Improving Slot Allocation at Level 3 Airports

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Abstract

Most of the busiest airports outside the United States, including the major connecting hubs, are classified as Level 3. At these airports, airlines need to be assigned slots by a schedule coordinator to schedule flights. Slot allocation is driven by a set of rules and priorities specified in the Worldwide Slot Guidelines (WSG) published by the International Air Transport Association (IATA). The process and rules for slot allocation at Level 3 airports carry enormous economic and regulatory implications for the global air transport sector. The objective of this paper is to contribute to the ongoing quest for improvements to the process that can be realistically implemented in practice. For that purpose, we have developed an optimization model, fully compliant with the WSG, for allocating airport slots to airlines and applied it at a few airports of varying sizes in Portugal, in order to compare the slot allocations performed by the coordinators with the best possible slot allocations under a variety of objectives and constraints, as well as to assess the impacts of potential changes to the WSG. The results obtained show that some even limited changes to the WSG can, on their own, bring considerable benefits in the short term to the slot allocation process. We have also identified and summarized a number of other potential changes to the WSG, with potential to make the slot allocation process even more efficient, fair, transparent and inclusive.

Keywords: Air Transport Policy, Demand Management, IATA Slot Allocation Process.
1 Introduction

According to current worldwide practice, airports offering commercial passenger service are subdivided into three “levels” (IATA, 2017). Level 1 airports are those “where the capacities of all infrastructure at the airport are generally adequate to meet the demands of users at all times”. Level 2 (or “facilitated”) airports are those where “there is potential for congestion during some periods of the day, week, or season which can be resolved by schedule adjustments mutually agreed between the airlines and a facilitator”. And Level 3 (or “schedule coordinated”) airports are those where “it is necessary for all airlines and other aircraft operators to have a slot allocated by a coordinator in order to arrive or depart at the airport during the periods when slot allocation occurs” [italics added]. Airports at the three levels can thus be characterized as “uncongested”, “mildly congested”, and “congested”, respectively. The focus of this paper is on Level 3 airports.

For the Summer season of 2017, 177 airports in the world were designated as Level 3. Of those, 37 were in the Asia/Pacific region, 103 in Europe, 10 in the Middle East and Africa, 13 in North Asia and 14 in the Americas. Despite their small number (only about 4.5% of the roughly 4,000 airports in the world with scheduled airline service), Level 3 airports play a truly critical role in global air transport. In 2016, they served approximately 3.15 billion airport passengers – or about 43% of the worldwide total of 7.4 billion and about 55% of the roughly 5.75 billion passengers outside the United States.1 A full 70% of all airport passengers in Europe used Level 3 airports. Of the 30 busiest airports, in terms of passengers, outside the US, 29 were Level 3.2 And, perhaps most important, practically all the major connecting hubs outside the US are Level 3 airports. Finally, the number of Level 3 airports worldwide will increase by 15%, from 177 to 203, for the Summer seasons of 2017 and 2018 and by 10%, from 161 and 177, for the respective Winter seasons, suggesting their steadily growing influence over time.

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1 As will be discussed later, the United States avoids designating airports as Level 3, to minimize the extent of schedule coordination. As of May 2017, the only one Level 3 airport in the US was JFK International, despite the fact that, by any standard, many airports in the US would be characterized as congested.

2 The only exception, surprisingly, was Jakarta’s Soekarno-Hatta, a notoriously congested airport, which was designated as Level 2.
For all these reasons, the process and rules under which access to Level 3 airports is determined carry enormous economic and regulatory implications for the global air transport sector. More generally, the issue of how to best allocate scarce capacity among airlines at congested airports has attracted much attention from academia and industry over the years, beginning as far back as the late 1960s, and generated much controversy.

Slot allocation at Level 3 airports was indeed one of the topics addressed by the Economic Commission of the International Civil Aviation Organization (ICAO) during ICAO’s 39th Assembly in Fall 2016. In its report at the end of the Assembly, the Commission welcomed the joint statement made by the International Air Transport Association (IATA) and the Airports Council International (ACI), “which recognized the need to optimize the use of scarce capacity, particularly at capacity constrained airports” (ICAO, 2016) and agreed to conduct a detailed review of the slot allocation process. The Commission further noted that “ACI and IATA would work with States and the industry stakeholders as partners and would report progress to the next session of the Assembly” in 2019.

This development has opened a ‘window of opportunity’ for improving existing slot allocation practices. With minor regional (e.g., in the European Union) or national (notably in the United States) variations, these practices follow closely and on a global scale the process described by IATA’s Worldwide Slot Guidelines (WSG henceforth) (IATA, 2017). This process and its rules are of a purely administrative nature at this time. In a Working Paper submitted in advance of the 39th Assembly to ICAO’s Economic Commission, IATA states that it “would oppose any consideration of market-based primary slot allocation mechanisms; these have been analyzed on many occasions in the past, by multiple independent academic and expert organizations, with no clear indications that such mechanisms improve the utilization of already-congested airport capacity or provide benefits to improving customer experience and choice in connectivity and fares” (IATA, 2016). While many would disagree with this statement, it is certainly true that airlines, through their representative bodies, have strongly opposed over the

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3 For reviews, see Chapter 12 of de Neufville and Odoni (2013) and, especially, a volume dedicated to the subject (Czerny et al, 2008).
years the use of congestion pricing, slot auctions, or other such market-based mechanisms for capacity allocation purposes. In view of this opposition, it is unlikely that the use of a purely administrative approach will be abandoned in the short- and medium-terms. IATA’s position in this respect is summarized in a statement on its website that refers to the ongoing ICAO-endorsed review: “The WSG Strategic Review is the ongoing process of enhancing the existing WSG, not rewriting from scratch, to ensure it remains the global, single slot standard for years to come – a major undertaking for 2017/18”.

The objective of this paper is to contribute to the ongoing quest for improvements to the slot allocation process that could be realistically implemented in the short term. Given the political realities just described, the paper’s scope will necessarily be limited to ways of enhancing significantly the efficiency, effectiveness and outcomes of certain key steps in the purely administrative process prescribed by the WSG. To this purpose, Section 2 will first provide a summary of the process, followed by brief descriptions of the capacity constraints that airports specify, the slot requests that airlines submit, and the decision-making rules that are used to allocate slots and develop the flight schedules at each Level 3 airport. Section 3 will then present a description of Priority-based Slot Allocation Model (PSAM), a state-of-the-art optimization model we have developed for allocating slots to airlines, and will illustrate through an example the types of insights that the model can offer. It will be seen that optimization models not only can identify slot allocations that are more compliant with airline scheduling preferences, but may also suggest mild modifications to the existing WSG rules that have the potential for reducing significantly the negative impact of airport capacity limitations on these scheduling preferences. This motivates an investigation, made possible by the use of PSAM, of the impacts of several such modifications to the WSG rules. The results are reported in Section 4, the lengthiest of the paper. Section 5 discusses two other areas where changes to existing practices may prove beneficial: (a) adding specificity to what qualifies an airport for designation as Level 3, as well as possibly refining the class of Level 3 airports by breaking it down into two more homogeneous subclasses; and (b) resolving potential network-level conflicts

between slot allocations made separately at each individual airport. Section 6 provides a more general context for this paper by discussing briefly a number of other issues, some of them of a fundamental nature, associated with the existing slot allocation process. Finally, in Section 7, we summarize the main contributions of our paper and indicate directions for future research.

2 The Slot Allocation Process

Figure 1 summarizes the main steps in the slot allocation process\(^5\) and indicates the associated timeline and the responsible entities (Kösters, 2007). The process is carried out bi-annually, for the “Summer” and “Winter” seasons, to provide airlines with access to Level 3 airports in the form of a landing or takeoff slot. A slot is defined as “the permission to use the full range of an airport’s infrastructure to perform aircraft arrivals or departures on a specific day and at a specific time” (IATA, 2017). First, each airport provides its “declared capacity”, specifying the number of arrival and departure slots made available in each time interval of a day. Second, the airlines submit their desired schedule of flights at each airport to the slot coordinator for the upcoming season. Third, the coordinator performs the initial slot allocation in an “unbiased, transparent and non-discriminatory” way and presents the results to the airlines. Fourth, adjustments are made during the Slot Conferences about four months before the start of each season, which are attended by airline representatives, slot coordinators, airport representatives and other interested parties. These adjustments involve primarily the resolution of conflicts stemming from the timing of slots allocated across multiple airports, and, if relevant, disputes among airlines competing for the same slots. Last, the airlines may “return” slots to the coordinator until two months before the start of each season, if they decide that they will not use them. They can also request last-minute adjustments and carry them out, if approved by the coordinator, up to the day of operations.

This paper focuses mainly on the third step, i.e., the initial slot allocation. This is a critical step, as it is the primary determinant of the final scheduling outcome. We first discuss the

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\(^5\) The slot allocation process is often more formally referred to as the “schedule coordination process”.

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specification of declared capacities and the form of airline slot requests, which define the inputs of initial slot allocation, and then present the rules and procedures underlying initial slot allocation in more detail.

Figure 1: Outline of the slot allocation process, as performed bi-annually at Level 3 airports.

2.1 Capacity Constraints

The declared capacity places an upper limit on the number of slots to be allocated to the airlines and other eligible operators at an airport in each time interval of a day. Ideally, declared capacities should be equal to the throughput the airport can achieve per hour (or any other unit of time). However, this is often not feasible due to the significant variability of airport throughput, which is driven by such factors as meteorological conditions, airport operating procedures, the mix of arrivals vs. departures, the mix of aircraft types, etc. While some of these factors are predetermined by the schedule of flights, others pertain to airport operating conditions at a given time and can only be described probabilistically at the time of slot allocation. It is therefore impossible to set a schedule of flights that will match the airport’s throughput capabilities exactly and with certainty. For this reason, the declared capacities are used by the airport to balance supply-side capabilities and airline demand during the schedule coordination process, with the objectives of maximizing their utilization and their responsiveness to airline requests, while maintaining an adequate level of service (e.g., acceptable delay levels).
In the simplest (and still most common) case, declared capacities take the form of a limit on the total number of aircraft movements (landings and takeoffs) that may be scheduled per hour, e.g., “up to 24 movements per hour”. However, a growing number of the busiest Level 3 airports now employ ever-finer levels of granularity. The example of Lisbon Airport in 2014 and in 2015 is shown in Table 1. Note, first, that separate capacities are specified for the runway system, the apron and the two terminals of the airport. Second, runway capacities are specified for each of four different time intervals in 2014 (15, 30, 60 and 180 minutes) and for each of two different time intervals in 2015 (15 and 60 minutes). Third, the limits may be broken down further into limits on total number of movements, number of arrivals and number of departures, and into limits on the number of arriving, departing, Schengen, and non-Schengen passengers in the case of the terminal buildings. Finally, the runway capacity limits (as at several other Level 3 airports) are treated as 5-minute rolling horizon limits. For instance, for 2014, no more than 38 total movements, 26 arrivals and 26 departures may be scheduled between 10:00 and 11:00, between 10:05 and 11:05, between 10:10 and 11:10, etc., no more than 12, 10 and 10, respectively, between 10:00 and 10:15, between 10:05 and 10:20, etc., and similarly for the 30-minute and 180-minute limits. Finally, as in the case of Lisbon 2015, capacity limits may vary by time of day, e.g., “up to 40 movements between 8:00 and 9:00, up to 34 movements between 9:00 and 10:00, etc.”. This can be used to specify lower limits during nighttime due to noise-related restrictions. Moreover, if the number of slot requests is much higher in certain periods of the day than others, the declared capacity may also be set higher during the peak demand periods to reflect airline preferences.

Declared capacities may thus include such complications as: time intervals of different length (e.g., of 15 and 30 and 60, etc., minutes); capacities applied over rolling time windows; and constraints that apply to different elements of the airport (e.g., runways, apron, terminals) and are expressed in terms of different units (i.e., limits on the number of movements or of aircraft or of various types of passengers). Only a small number of Level 3 airports now have a set of coordination parameters as extensive and complex as

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6 Passengers arriving from or departing for the “Schengen Area” (26 European nations) are not subject to passport and customs controls, i.e., are essentially treated as domestic passengers.
Lisbon’s, but the number of such airports is growing. For this reason, the optimization model to be described in Section 3.1 must be able to accommodate such complex constraints, if they exist, as well as consider constraints that vary by time of day.

Table 1: Declared capacities for Lisbon Airport.

<table>
<thead>
<tr>
<th>Declared Capacity Indicators</th>
<th>Lisbon Airport 2014</th>
<th>Lisbon Airport 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight Movements / hour</td>
<td>38</td>
<td>38</td>
</tr>
<tr>
<td>Arrival Departures / hour</td>
<td>26</td>
<td>38</td>
</tr>
<tr>
<td>Flight Movements / 15 min</td>
<td>12</td>
<td>38</td>
</tr>
<tr>
<td>Arrival Departures / 15 min</td>
<td>12</td>
<td>38</td>
</tr>
<tr>
<td>Flight Movements / 30 min</td>
<td>21</td>
<td>38</td>
</tr>
<tr>
<td>Arrival Departures / 30 min</td>
<td>19</td>
<td>38</td>
</tr>
<tr>
<td>Flight Movements / 180 min</td>
<td>113</td>
<td>38</td>
</tr>
<tr>
<td>Arrival Departures / 180 min</td>
<td>77</td>
<td>38</td>
</tr>
<tr>
<td>Terminal 1</td>
<td>2500</td>
<td>2500</td>
</tr>
<tr>
<td>Arrivals / hour</td>
<td>1500</td>
<td>2000</td>
</tr>
<tr>
<td>Terminal 1</td>
<td>2300</td>
<td>2300</td>
</tr>
<tr>
<td>Departures / hour</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>Terminal 2</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Departures / hour</td>
<td>300</td>
<td>450</td>
</tr>
<tr>
<td>Apron / Nr. aircraft</td>
<td>63</td>
<td>63</td>
</tr>
</tbody>
</table>

2.2 Airline Slot Requests and the Rules of Slot Allocation

In the second step of the slot allocation process shown in Figure 1, the airlines submit their slot requests to the slot coordinators in the format specified in Chapter 6 of the IATA Standard Schedules Information Manual (IATA, 2014). Table 2 shows a sample of five slot requests at the airport of Madeira, Portugal. Each row of Table 2 contains a request by an airline for one or more slot series for the Summer 2014 season (March 30 – October 25, 210 days). A slot series consists of “at least 5 slots requested for the same time on the same day-of-the-week, distributed regularly in the same season” (IATA, 2017). Requests for fewer than 5 slots are not eligible for consideration during the initial slot allocation step; they may be considered after the slot return deadline (Step 5 in Figure 1) should any slots remain available at that time.

For an example, Request 1 characterizes a request for a series of flights that will take place on Sundays only (as indicated by the “1000000” entry in Column 7) during the entire season, i.e., for the 30 Sundays between March 30 (Column 5) and October 25 (Column 6).
Note that this particular request is actually for a pair of slots on each Sunday, that is, for an arrival at 08:00 (Column 12) and a departure, by the same aircraft, at 08:30 (Column 13), i.e., for a total of 60 individual slots. The request also specifies the type of aircraft involved and the number of seats in it (Columns 9 and 8), as well as the airport from which the aircraft will begin its itinerary of the day (Column 10), the airports visited immediately prior to and after Madeira (Columns 11 and 14) and the airport where the itinerary will be completed at the end of the day (Column 15). Finally, it also indicates (Columns 16 and 17) whether the request is for a scheduled passenger flight ("J"), a chartered flight ("C"), etc.

Table 2: An example of slot requests.

<table>
<thead>
<tr>
<th>Req. no. (1)</th>
<th>Priority (2)</th>
<th>Arr. ID (3)</th>
<th>Dep. ID (4)</th>
<th>Start Date (5)</th>
<th>End Date (6)</th>
<th>Days of week (7)</th>
<th>Seats (8)</th>
<th>Aircraft (9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F</td>
<td>XY001</td>
<td>XY002</td>
<td>30MAR</td>
<td>25OCT</td>
<td>1000000</td>
<td>180</td>
<td>320</td>
</tr>
<tr>
<td>2</td>
<td>CR</td>
<td>XY003</td>
<td>XY004</td>
<td>30MAR</td>
<td>31MAY</td>
<td>1234567</td>
<td>180</td>
<td>320</td>
</tr>
<tr>
<td>3</td>
<td>CL</td>
<td>XY005</td>
<td>XY006</td>
<td>01APR</td>
<td>21OCT</td>
<td>1030507</td>
<td>180</td>
<td>320</td>
</tr>
<tr>
<td>4</td>
<td>B</td>
<td>XY007</td>
<td>---</td>
<td>01JUL</td>
<td>23SEP</td>
<td>0200500</td>
<td>170</td>
<td>320</td>
</tr>
<tr>
<td>5</td>
<td>N</td>
<td>---</td>
<td>XY008</td>
<td>30MAR</td>
<td>25OCT</td>
<td>0004000</td>
<td>120</td>
<td>319</td>
</tr>
</tbody>
</table>

In contrast to Request 1, Requests 2, 3 and 4 in Table 2 comprise more than a single series. Request 2, for example, comprises 7 different series of slots, one for each of the seven days of the week, all requested at the same time of the day – arrival at 10:00 and departure at 11:00. In addition, an arrival and a departure pair may be requested in the same slot request (as in Requests 1, 2 and 3), or a request may be solely for arrivals (Request 4) or solely for departures (Request 5). The requests that are made specifically for one type of movement typically come from bigger airlines, which derive operating flexibility from the large number of aircraft they may be operating at the airport. The optimization model of slot allocation must be able to accommodate these various specificities of slot requests.
2.3 Initial Slot Allocation Rules and Request Priorities

We now summarize the rules and priorities for slot allocation at Level 3 airports (Step 3). The first two of the rules below are often referred to as the *schedule regularity constraints*:

(i) All slots belonging to the same series (i.e., slots for the same flight on the same day of the week, at least five times over the season, such as Request 1 in Table 2) must be given the same time of the day.\(^7\)

(ii) It is *recommended* that, unless the airline requests otherwise, identical series of slots for different days of the week which are submitted together as part of the same request (e.g., as in Request 2 of Table 2) should be given slots at the same time of the day across multiple days of the week.

(iii) The requested turnaround times between the arrival and departure pair of slots assigned to the same aircraft (e.g., 30 minutes in the case of Request 1) must be maintained (or, at worst, adjusted with minimal changes) to avoid any increases in ground time and dilution of the connectivity of an airline’s networks of flights.

(iv) Slots must be allocated in accordance with a set of priorities specified in the WSG as “primary criteria” for allocation. If necessary, “additional criteria” may also be used, usually for tie-breaking purposes, in cases when two slot series are equally eligible for assignment to a particular slot. The primary criteria are described in more detail in the remainder of this section.

Requests for slot series are classified into four main classes: requests for *historic* slots (abbreviated as ‘H’ henceforth), *change-to-historic* slots (‘CH’), *new entrant* slots (‘NE’) and ‘other’ slots that do not belong to any of the aforementioned three priority classes (‘O’). This is shown in Column 2 of Table 2: Request 1 is for a H slot series (Code F), Requests 2 and 3 for CH slot series (Codes CR and CL), Request 4 for a NE series (Code B), and Request 5 for an ‘O’ slot series (Code N).

Top priority is accorded to requests for H slots. Under the rules of the WSG, “an airline is entitled to retain a series of slots on the basis of historic precedence” as long as it satisfies

\(^7\) IATA’s WSG states that, “if that is not possible, [all the slots in a series should be allocated] at approximately the same time” (IATA, 2017, §1.7.2.e). In practice, however, allocation to the *exact* same time is typically enforced. Our optimization model also treats this as a requirement.
the slot usage requirement (IATA, 2017). These are called the “grandfather rule” and the “use-it-or-lose-it rule”: if an airline operated any particular slot series during the previous Summer (resp., Winter) season for at least 80% of the time during which the series was authorized, then that airline is entitled to operate the same slot series during the next Summer (resp., Winter) season. For instance, the airline responsible for Request 1 in Table 2 would be entitled to this “historic” slot series in Summer 2014, if it had operated the same slot series on at least 24 of the 30 Sundays in Summer 2013. Second priority is accorded to CH requests. This corresponds to airlines holding H series of slots, but requesting a change in the time of the H slot series, or in other attributes of the H series, such as a different aircraft type, route or type of service.

After slots have been allocated to H and CH slot series, the remaining slots, if any, constitute the slot pool that will be allocated to NE slot series and to O slot series, in that order. According to the WSG, an airline qualifies for designation as a new entrant (NE) airline at an airport A, if it is “requesting a series of slots [at A] on any day when, if the airline’s request were accepted, it would hold fewer than 5 slots [at A] on that day”. According to the WSG, 50% of the slots in the slot pool must be allocated to new entrants at the initial slot allocation period, unless the total number of slots requested by new entrants is less than 50% of the slots in the pool. Any remaining slots after the allocation to new entrants are finally made available to the ‘other’ slot series requests. At the end of the initial slot allocation process, either all the slot requests will have been accommodated (albeit possibly not at the time requested by the airline) or some requests will have been rejected outright because total demand for slots exceeded the airport’s declared capacity.

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8 The difference between ‘CR’ and ‘CL’ codes (Table 2) is that, when an airline submits a CR code, it is willing to accept any time between the (new) requested time and the historic time. By contrast, when an airline submits a CL code, it is only willing to accept the (new) requested time, if available, or the historic time.

9 In the European Union, the definition of a new entrant airline is somewhat less restrictive under certain circumstances (Council Regulation (EEC) No 95/93).

10 The objective, obviously, is to facilitate access to airports by more airlines. However, the largest number of slots a new entrant can end up with in a day under the 50% provision is 4, i.e., two slot pairs – for instance, one flight in the morning and one in the evening.
2.4 Case Study Data

We shall provide several examples based on data from three Level 3 airports in Portugal, those of Madeira, Porto and Lisbon. These are airports of very different size: in 2017, Lisbon served close to 27 million passengers, Porto close to 11 million and Madeira 3.2 million. We use slot request and allocation data for the Summer season of 2014 in Madeira and Porto and for the Summer seasons of 2014 and 2015 in Lisbon. Slot allocation in Portugal is performed by ANA Aeroportos de Portugal. The declared capacities for Lisbon were shown in Table 1. Madeira and Porto operate with runway capacity limits for each 15-minute period and 60-minute period applied on a 5-minute rolling horizon basis. In Madeira, the declared capacities are 6 movements, 4 arrivals and 4 departures per 15-minute period, and 14 movements, 7 arrivals and 7 departures per hour. In Porto, the declared capacities are 7 movements per 15-minute period and 20 movements per hour, with no separate limits on the number of arrivals and of departures. In addition, Madeira and Porto are also subject to terminal and apron capacity constraints and to noise restrictions, but these are typically not binding.

3 Determining the Initial Slot Allocation

We now describe briefly our optimization model for slot allocation, and illustrate, through an example, its capabilities and the questions it motivates. Since this paper focuses on the application of this model to support the Initial Slot Allocation (Step 3 of Figure 1) and potential enhancements to the existing IATA guidelines, we only provide here a short overview of the model. More technical details on its formulation and its solution procedure can be found in the appendix and, especially, in (Ribeiro et al., 2018).

3.1 The Optimization Problem

The task of the slot coordinator at a Level 3 airport during the initial slot allocation step can be viewed as an optimization problem that can be stated, in general terms, as follows: “given a set of airline requests for slots during a season of operations and a set of constraints resulting from the airport’s declared capacities, propose a combination of slot assignments (i.e., a “slot allocation”) that minimizes the difference between the proposed
schedule of flights and the schedule that would have resulted from the airlines’ requests in the absence of capacity constraints, while respecting the relative priorities of the different classes of requests”. Henceforth, we will refer to this optimization problem as the Slot Allocation Problem (SAP).

In practice, coordinators do not currently employ formal optimization tools. Instead, they use a variety of approaches to perform slot allocation, often assisted by special-purpose software (e.g., PDC SCORE), which processes slot requests sequentially according to their priority class – H first, followed by CH, NE and O. Requests in each priority class are processed one-at-a-time on an ad hoc basis, thus not affording an opportunity to consider simultaneously the complete set of slot requests and explore the interactions among requests and the full set of combinations of potential slot assignments. The resulting slot allocation may therefore be sub-optimal.

On the other hand, the SAP is not easy to formulate as a mathematical optimization problem or to solve optimally. The first formulation that captures much of the complexity of the SAP is quite recent (Zografos et al, 2012). That same paper presents a solution of the SAP for a medium-size airport of approximately 5 million annual passengers in Greece. More recently, we have developed a new model formulation for solving the SAP called the Priority-based Slot Allocation Model (PSAM). Some of its novel features include: consideration of a complete list of capacity constraints; consideration of all types of slot requests; and the ability to solve the SAP to optimality for much larger airports than had hitherto been possible. The remainder of this subsection describes briefly the PSAM.

The PSAM takes as inputs the complete set of capacity constraints (Section 2.1) and the full list of airline slot requests (Section 2.2). The decision variables determine the slot time allocated to each request. This essentially defines the displacement of each request, i.e., the difference between the slot time allocated to a slot series and the slot time requested by the airline. For example, if the slot times allocated to the slot series of Request 1 of Table 2 are 08:45 and 09:15, for the arrival and departure, respectively, of the associated

11 The general version of the PSAM also includes variables to determine whether each slot request is rejected, or not to capture instances where total demand exceeds total capacity. However, this is not the case at the vast majority of Level 3 airports, including those considered in this paper.
aircraft, then the displacement of each slot in this slot series is equal to 45 minutes.\textsuperscript{12} Note that the displacement can be positive or negative value depending on whether the slot series is assigned to a later time or an earlier time than requested.

Qualitatively, the PSAM is formulated as follows, where $MaxD$, $TotD$ and $NoD$ denote the maximum displacement, the total schedule displacement and the number of slots displaced, respectively. Its full mathematical formulation is provided in the Appendix and in (Ribeiro et al., 2018).

\begin{equation}
\text{Minimize } w_1MaxD + w_2TotD + NoD
\end{equation}

subject to

- Capacity constraints
- Flight connection constraints
- Slot displacement constraints
- Schedule regularity constraints
- Technical constraints

Let us first discuss the model's objective function. The PSAM minimizes an aggregate measure of schedule displacement. This, however, is not unambiguous. Indeed, there may exist trade-offs between conflicting objectives such as, for instance, displacing many slots by a relatively small amount vs. displacing a smaller number of slots by a larger amount. In order to quantify, and optimize, such trade-offs, slot coordinators must minimize a measure of the overall displacement contained in a proposed schedule of flights. The PSAM is thus formulated as a multi-objective optimization problem that comprises three terms: (i) the maximum displacement imposed on any slot series on any day of the season, (ii) the total displacement associated with all allocated slots throughout the season, and (iii) the number of slots that were scheduled at a different time than requested.

The user-specified weighting constants ($w_1$ and $w_2$) provide flexibility in prioritizing the three displacement metrics. For example, setting $w_1 >> w_2 >> 1$ minimizes, first, the largest flight displacement, then the total displacement and then, among all the solutions that achieve these two objectives, the number of slots displaced. This corresponds to a

\textsuperscript{12} This maintains the connection time of 30 minutes between the arrival and departure times of the aircraft.
**lexicographic** solution, where each objective is given priority over the subsequent one. It is consistent with current practices of slot coordinators, with the interests of the airlines, and with the existing literature (Zografos et al., 2012; Jacquillat and Odoni, 2015a; Pyrgiotis and Odoni, 2016). It is motivated by the underlying goal to achieve an equitable treatment of all slot requests by ensuring that no slots will incur a disproportionately large displacement, and to minimize the overall impacts of the slot allocation process, measured by the total displacement. The third objective may be helpful in cases where there still remain tied solutions. In such cases, selecting among them the solution with the smallest number of displaced slots facilitates implementation by simplifying negotiations between the coordinator and the airlines during Slot Conferences.

Note, however, that other priorities can be captured in the objective function. To this end, we will characterize the Pareto-optimal frontiers between the different objectives, that is, the set of solutions such that no other solution can improve one of these objectives without worsening the others. This can be achieved by changing the weights $w_1$ and $w_2$ in the objective function or by an $\varepsilon$-constraint approach. The latter involves, first, minimizing the maximum displacement, and, then, minimizing the total displacement while ensuring that the maximum displacement lies below a target that is initially set to the optimal value of the maximum displacement, and then progressively increased by increments of 5 minutes until the optimal value of the total displacement is attained. We can repeat the same procedure for the number of slots displaced, albeit at higher computational costs.

Turning to the constraints of PSAM, the capacity constraints specify the limitations imposed by the declared capacities of the runway system, apron and passenger terminals. For example, the runway capacity constraints (possibly specified on a rolling horizon basis) ensure that arrival, departure and total runway capacities are not exceeded during the course of any day in the season. Flight connection constraints ensure that the airline-requested time between the arrival of a flight and the departure of a flight performed by the same aircraft is not changed.$^{13}$ Slot displacement constraints identify the slot series

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$^{13}$ A more flexible alternative (see Section 4.2.1) is to require that the connection time will not increase or decrease by more than user-specified limits $T_{\text{max}}$ and $T_{\text{min}}$. 

15
that are displaced and calculate the corresponding displacement of each slot series. Schedule regularity constraint assign the same time-of-the-day to the slots belonging to the same series and to the slot series belonging to the same request, as specified or recommended in the WSG. Finally, some of the technical constraints specify the domains of the decision variables (e.g., integer or binary), while others serve to speed up greatly the solution of PSAM.

The solution procedure used by PSAM leverages the strict priorities across airline slot requests (see Section 2.3): requests for H slot series first, followed by CH, NE and O, in this order. The PSAM solution procedure therefore breaks down the SAP into four sub-problems, one for each of the four types of requests. A lexicographic approach is then used to solve these sub-problems sequentially, one-at-a-time, according to the priority of the requests, with H slots allocated first, and so on. The solution to the sub-problem of allocating H slots is usually trivial: each requested slot series is given its requested slots, with a resulting displacement of zero. We then solve each of the next three sub-problems, with some additional constraints specific to each class. From a computational standpoint, this lexicographic approach improves the tractability of the PSAM by decomposing it into four smaller problems. On the negative side, it does not search for alternative solutions that could potentially meet the airlines' slot requests more effectively by making only modest adjustments to the priority rules specified in the WSG. We explore this issue further in Section 4.2.3 by considering solutions to the PSAM that allocate all four types of requests simultaneously in a single step, instead of sequentially.

3.2 An Illustrative Example

We consider in this section the application of the PSAM to solve the SAP for the airport of Madeira, Portugal. The intent is to illustrate the impact of various constraints and rules associated with the existing slot allocation process and suggest promising questions to explore later on. The focus here will be on successive solutions to the SAP as more constraints and priority rules are considered. Figure 2 shows the Pareto-optimal frontiers

---

14 An exception may occur in the rare cases in which the declared capacity of a Level 3 airport is, for some reason, smaller in the next season than in the previous one.
for the two objectives of minimizing the maximum displacement and minimizing the total displacement under four different sets of conditions (see details below), as well as the coordinator's solution for Summer 2014 (diamond-shaped point at the upper right side). The coordinator's solution involved maximum displacement and total displacement of 80 minutes and 12,140 minutes, respectively. This solution did modify in a few cases the airline-requested connection times between the arrival and departure pair of slots flown by the same aircraft. However, these requested connection times were treated as mandatory in the PSAM tests described below and adhered to exactly. In this sense, the PSAM solved, in this case, a somewhat more constrained problem than the coordinator.

Figure 2 - Coordinator’s solution of the SAP for Madeira Airport and four Pareto-optimal frontiers.

We now discuss the Pareto frontiers obtained with PSAM and shown in Figure 2. First, the blue frontier corresponds to the extreme case in which there are no schedule regularity constraints and no priorities concerning the allocation of slots to different classes of requests (see Section 2.3). In other words, each day of the season is treated independently.

\[\text{15} \] The impact of allowing for flexibility in turnaround times is discussed in Section 4.2.1.
of all other days and, for each day separately, PSAM allocates slots irrespectively of whether a request comes from an H slot series, CH series, etc. The only restriction is that connection times must be maintained. As shown in Figure 2, the leftmost of the four points of the Pareto frontier is at (15, 7385). Thus, if days could be optimized independently and the priorities of slot requests disregarded, maximum and total displacement could be reduced by 81% (80 vs. 15 minutes) and 39% (12140 vs. 7385), respectively, compared to the coordinator’s allocation.

The yellow frontier enforces schedule regularity constraints, but still disregards the priorities among the different classes of requests. Specifically, identical series of slots for different days of the week, which are submitted together as part of the same request (such as those in Request 2 of Table 2), must be allocated at the same time of the day across the different days of the week. The regularity constraints imply that allocations on different days become interdependent: the 210 days of the season must now be considered all at once, greatly increasing the computational complexity of the SAP. The regularity constraints will typically increase the maximum displacement and/or the total displacement needed to accommodate the slot requests. For example, the fourth point from the left of the six points that define the yellow frontier is at (30, 9,755), with a 62.5% reduction in maximum displacement and 16% reduction in total displacement, compared to the coordinator’s allocation.

Up to this point, slot allocations have not considered a request’s priority class. For instance, in the solutions that define the blue and yellow frontiers up to 20-30% of historic slots are displaced, in violation of the grandfather rights accorded to these slots. We now add the restriction that H slots cannot be displaced and obtain two Pareto-optimal solutions with a maximum displacement equal to 55 and 60 minutes, respectively, and a total displacement of 11,145 minutes and 10,805 minutes, respectively (shown in green in Figure 2). Thus, the H slot constraints result in significant increases of about 10% in total schedule displacement, compared to the yellow frontier, and more notably, in very large increases in the maximum flight displacement (from 30 minutes to 55 and 60 minutes). This is not surprising, as historic slots typically occupy the most desirable slot
times and therefore tend to displace significantly slot series belonging to the three lower priority classes, especially requests for slots during times of the day when demand peaks. Finally, we add consideration of the remaining priorities and allocate slots hierarchically to the three lower-priority classes. For this purpose, we implement the full lexicographic solution approach described in Section 3.1, where each priority class is treated sequentially. In this case, we obtain a single Pareto-optimal solution, shown in grey in Figure 2. In other words, the maximum displacement and the total displacement are jointly minimized and there is no trade-off between these two objectives. This solution has a maximum displacement of 70 minutes (a 12.5% improvement compared to 80 minutes in the slot coordinator’s solution) and a total displacement of 11,620 minutes (a 4.3% improvement compared to 12,140 minutes in the slot coordinator’s solution). The PSAM solution with full consideration of requirements and priorities is therefore similar to the slot coordinator’s – thus confirming the realism of the model – but also results in a smaller maximum flight displacement and a smaller total schedule displacement, despite leaving all the connection times unchanged, unlike the solution implemented in practice. More generally, this example illustrates vividly how schedule regularity requirements and priority rules increasingly constrain the slot allocation decisions and lead to significant increases in the maximum and/or the total displacement. Note, finally, that the final PSAM solution for Madeira consists of a single point that minimizes the maximum displacement and the total displacement simultaneously. This is unusual: generally, there will be two or more Pareto-optimal solutions and decision-makers will have to consider trade-offs among measures such as maximum displacement, total displacement and number of displaced slots, as will be seen in Section 4.1.

4 The Power of Optimization Models

Optimization models, such as PSAM, offer several major benefits and opportunities. The most immediate and obvious is that they may produce improved allocations, compared to the ones that can be obtained through the heuristic approaches currently in use. They can also generate solutions that reflect different rankings of alternative objectives, such as minimizing maximum displacement, minimizing total displacement or minimizing the
number of displaced slots. An equally important benefit is the opportunity the models provide for exploring ways to improve current practice in the long run. For example, they can quantify the impacts of potential changes to the rules and priorities that are currently used for slot allocation, or quantify how the total displacement is affected by small increments in declared capacity. All these points will be discussed in this section.

4.1 Improving Initial Slot Allocations

Table 3, based on the application of PSAM at Porto, provides an example of the potential of optimization models to generate improved slot allocations and produce solutions that reflect the priorities that decision makers attach to different objectives. The table shows a summary of the results of four different PSAM solutions for Porto, where different priorities are assigned to the three objectives considered in the model specified in Section 3.1. The trade-offs among these objectives are quantified in this way. Sol. 1 follows the order typically considered by the coordinators, i.e., “maximum displacement first, then total displacement, then number of slots displaced”, whereas Sol. 2 follows the order “total displacement first, then maximum displacement, then number of slots displaced”, Sol. 3 the order “number of slots displaced, maximum displacement, total displacement” and Sol. 4 “number of slots displaced, total displacement, maximum displacement”.

Table 3: Tradeoffs among different objectives at Porto.

<table>
<thead>
<tr>
<th>Solution</th>
<th>Maximum Displacement (min)</th>
<th>Total Displacement (min)</th>
<th>Slots Displaced (slots)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CH</td>
<td>NE</td>
<td>O</td>
</tr>
<tr>
<td>Coordinator</td>
<td>45</td>
<td>15</td>
<td>80</td>
</tr>
<tr>
<td>Sol. 1</td>
<td>25</td>
<td>25</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>-44%</td>
<td>+66%</td>
<td>-31%</td>
</tr>
<tr>
<td>Sol. 2</td>
<td>45</td>
<td>25</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>0%</td>
<td>+66%</td>
<td>-25%</td>
</tr>
<tr>
<td>Sol. 3</td>
<td>25</td>
<td>25</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>-44%</td>
<td>+66%</td>
<td>-31%</td>
</tr>
<tr>
<td>Sol. 4</td>
<td>25</td>
<td>25</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>-44%</td>
<td>+66%</td>
<td>-25%</td>
</tr>
</tbody>
</table>

First, note that all four solutions improve all three objectives by significant margins when compared to the coordinator’s solution. For instance, Sol. 1 reduces maximum displacement by 31%, total displacement by 27% and the number of displaced slots by
7%. These are much more substantial reductions than the ones previously reported for Madeira (Figure 2) of 12.5%, 4.3% and 1.1%, respectively. This is not surprising because Porto is a much busier airport, as it allocated 40,597 slots versus 13,196 for Madeira in Summer 2014. It is therefore much harder for the slot coordinators to find close-to-optimal solutions for Porto, without the use of an advanced optimization model, such as PSAM. Second, the trade-offs resulting from prioritizing different objectives are noteworthy. For instance, minimizing the number of displaced slots (Sol. 3 and Sol. 4) is achieved at the cost of increasing total displacement. Finally, observe that the benefits of the PSAM solution are not evenly distributed among the different priority classes. For instance, for Sol. 1 the displacement of the CH slots, which are of primary interest to incumbent airlines, decreases greatly in every respect – by 44%, 67% and 42%, respectively, for each of the three measures of performance – but the opposite is the case for NE slots (+66%, +16%, -1.7%). The reason is that the large improvements in the scheduling of CH slots constrain the allocation of slots to the two lower priority classes by limiting the number of slots available at the busiest hours.

Motivated by this last observation we also analyzed an additional scenario that follows the same order of objectives as Sol. 1, but places a limit of 15 minutes on the maximum displacement that can be assigned to NE slots. In this case we reduce the improvements of the CH slots – from 45%, 67% and 42% to 45%, 59% and 36%, respectively, for each of the three measures of performance – while, at the same time, the total displacement and the number of slots displaced are now improved by 9% and 14%, respectively, compared to the coordinator’s solution. This demonstrates that PSAM can also be used to explore the tradeoffs faced by the different priority classes and to determine the most desirable solution accordingly. This point will be further explored in Section 4.2.3.

The busiest airport to which we have applied PSAM to date is Lisbon, where the number of slots allocated in the Summer of 2014 and 2015 was 109,938 and 114,119, respectively – almost three times as many as at Porto. To our knowledge, Lisbon is by far the busiest

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16 The number of displaced slots for Madeira was not reported in Section 3.2, as the discussion was limited to the maximum displacement and total displacement objectives.
airport for which an optimization model has obtained an exact solution to date.\textsuperscript{17} Table 4 summarizes the model’s results for Summer 2014 and Summer 2015, indicating the number of slots requested by each priority class and the corresponding amount of total displacement for each of the two seasons. Note that in this analysis we only considered capacities for the runway of 15 and 60 minutes. Comparing the results for the two years, it is interesting to observe that the number of CH slots requested in 2015 was much greater than in 2014, but the total displacement of these slots is smaller in the 2015 solution than in the one for 2014. The reason is that the number of H slots in 2015 was much smaller than in 2014, thus making more capacity available for CH slots. However, once the CH slots are assigned optimally, a smaller pool of slots remains for the NE and O requests, leading to increased total displacement for these two classes. Unfortunately, we could not compare our results with the coordinator’s solution for the Summer 2014 and 2015 seasons because of inconsistencies in the data about the coordinator’s solution.

Table 4: Lisbon solutions of PSAM for Summer seasons of 2014 and 2015.

<table>
<thead>
<tr>
<th>Type of Slot</th>
<th>Lisbon Airport 2014</th>
<th>Lisbon Airport 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nr. Slots</td>
<td>Total Displacement (min)</td>
</tr>
<tr>
<td>H</td>
<td>47,616 (43%)</td>
<td>0</td>
</tr>
<tr>
<td>CH</td>
<td>38,503 (35%)</td>
<td>27,790</td>
</tr>
<tr>
<td>NE</td>
<td>2,362 (2%)</td>
<td>2,990</td>
</tr>
<tr>
<td>O</td>
<td>21,457 (17%)</td>
<td>352,100</td>
</tr>
<tr>
<td>Total</td>
<td>109,938</td>
<td>382,880</td>
</tr>
</tbody>
</table>

One of the principal conjectures that have emerged from this research is that as the number of slots allocated at an airport increases, so will the likelihood that the solution to the SAP computed by PSAM (or other optimization models) will be significantly better than the solution proposed by the coordinator with the approaches and tools currently used in practice. Stated simply, the busier the airport, the more beneficial will the use of

\textsuperscript{17} Lisbon was the 21\textsuperscript{st} busiest airport in Europe in 2017 and served 186,000 movements. The top four airports (London Heathrow, Paris CDG, Amsterdam, and Frankfurt) all served around 480,000.
an optimization model be. This was certainly true in the case of Porto and Madeira airports. The model’s solution for Madeira, with a small number of slots, was only marginally better than the coordinator’s (Section 3.2), whereas, in the case of Porto with twice as many slots as Madeira, it was better by a wide margin. This is to be expected as the number of possible allocations increases exponentially with the number of slots to be allocated and with the number of slots requested by the airlines. The number of possible allocations thus becomes huge for airports of the size of Porto and much more so for those of the size of Lisbon or greater. Heuristic approaches may perform reasonably well for smaller airports but, unless they are highly sophisticated, are likely to generate far less efficient solutions at the larger airports than exact optimization models.

It is important to note that the validity of our conjecture will additionally depend strongly on the “mix” of the four classes of slot requests (H, CH, NE, O), as well as on the relationship between the total number of slots requested and the number of slots available at the subject airport. Consider, for example, a Level 3 airport where, at the end of the Summer season of 2017, close to 100% of the existing slots (i.e., the entire declared capacity of the airport) are occupied by flights having historic rights and assume that the airlines that hold these rights have all met the 80% “use-it-or-lose-it” limit for the season. (This is a scenario that resembles the current situation at London Heathrow.) If all the airlines choose to keep exactly the same slots in Summer 2018 (i.e., in the extreme case where there are virtually no CH requests) and if the declared capacity of the airport remains the same for Summer 2018, then the solution to the SAP will be trivially simple (i.e., repeat, essentially, the schedule of Summer 2017) and the solution generated by an optimization model will be very close to the coordinator’s. But the opposite would be true in a situation where, in Summer 2018, (i) many airlines holding historic rights choose to submit CH requests or (ii) in Summer 2017, only 85% of declared capacity was occupied (i.e., slack capacity existed at off-peak periods) and many NE and O requests were also submitted.

As already discussed, the PSAM was implemented at three Portuguese airports: Madeira, Porto and Lisbon. At Madeira and Porto, it was applied using data for the Summer Season of 2014, without considering apron and terminal constraints. In the case of Lisbon, it was implemented once for the Summer season requests of 2014, without considering apron
and terminal constraints and only the runway capacities for 15 and 60 minutes, and twice for the Summer season requests of 2015, one time without apron and terminal constraints and the second time with these constraints. To solve PSAM we used CPLEX 12.5 with the GAMS programming language. The model was run with an i7 processor @3.6 GHz, 8Gb RAM computer, with a Windows 10 64-bit operating system. The complexity of the model, in terms of number of binary (0, 1) variables, integer variables, and constraints, is summarized in Table 5, along with computational performance, measured by the CPU time required until the optimal solution was found.

Table 5: Computational statistics for a GAMS/CPLEX implementation of PSAM.

<table>
<thead>
<tr>
<th>Model Indicators</th>
<th>Madeira Airport</th>
<th>Porto Airport</th>
<th>Lisbon Airport</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2014(^1)</td>
<td>2014(^1)</td>
<td>2014(^1)</td>
</tr>
<tr>
<td>Number of slots requested</td>
<td>13,106</td>
<td>40,597</td>
<td>109,938</td>
</tr>
<tr>
<td>Number of binary variables</td>
<td>176,346</td>
<td>347,346</td>
<td>735,939</td>
</tr>
<tr>
<td>Number of integer variables</td>
<td>1,212</td>
<td>2,388</td>
<td>5,058</td>
</tr>
<tr>
<td>Number of constraints</td>
<td>899,462</td>
<td>1,993,956</td>
<td>2,567,255</td>
</tr>
<tr>
<td>CPU Time</td>
<td>2 minutes</td>
<td>8 minutes</td>
<td>1 hour</td>
</tr>
</tbody>
</table>

Table 5 indicates that CPU time is extremely sensitive to the size of the airport, i.e., the number of slots requested. While the PSAM was solved relatively quickly for Madeira and Porto (2 and 8 minutes, respectively), Lisbon 2015 took 7 days when not considering apron and terminal constraints, and had not been completed after 15 days when these constraints were included. Thus, at the present level of development, PSAM can compute guaranteed optimal solutions at airports with traffic volumes up to Lisbon’s (i.e., of the order of 200,000 movements per year). There are only roughly 15 airports in Europe at which this volume was clearly exceeded in 2017. Another aspect that impacts CPU time significantly is the distribution of slots across priority classes. The larger the share of historic slots, the easier it is to solve the PSAM, since historic slots are, first, automatically allocated to the requested time and, second, reduce the number of available times at which the requests in the other three priority classes can be accommodated. Thus, Lisbon
2015 is significantly harder to solve than Lisbon 2014 since, in addition to having more requested slots (+4%), the share of historic slots was only 31% versus 43% in 2014.

Overall, we have found that the benefits of optimization models such as PSAM increase at airports with larger number of slot requests and at airports with lower shares of historic slots. At the same time, these airports are precisely the ones that involve greater computational complexity. Ongoing research is focusing on trying to improve the computational performance of PSAM and on developing heuristic approaches that enable PSAM to obtain near-optimal solutions reasonably quickly at these airports.

4.2 The Value of Flexibility

One particularly important area for investigation is the impact of potential changes to some of the rules and slot priorities in the current World Slot Guidelines. We are particularly interested in quantifying the benefits that may be obtained by introducing a limited level of flexibility into these rules and priorities. Recent versions of the WSG recognize implicitly that some flexibility may yield significant benefits. The most recent version invites airlines requesting slots at Level 3 airports to indicate any flexibility they may have with respect to: (i) requested slot times and (ii) “minimum and maximum turnaround times and any other such constraints” (IATA, 2017, §9.7.3).

One of the principal advantages that optimization models offer is, in fact, the opportunity to explore the potential impacts of rule “relaxations” such as (i) and (ii). In this section, we shall explore, by using the PSAM, the sensitivity of slot allocations to small changes to the rules and priorities that are mandated by the WSG and applied in practice. This type of analysis can also inform potential future adjustments to the WSG and enhance the outcomes of the slot allocation process. The specific changes to be examined are:

(i) Flexibility in the setting of “connection times”, as in (ii) above.
(ii) Consideration of aircraft size as a factor in allocating slots
(iii) Flexibility in the slot times assigned to historic slot series, as in (i) above.
(iv) “Weighted priorities” of the different classes of slot requests.
(v) Relaxation of some schedule regularity requirements in allocating slots.
4.2.1 Connection Times

The default assumption in PSAM (and in practice) is that the airline-requested connection times (or ‘turnaround times’) between the arrival and departure of flights performed by the same aircraft must be strictly respected. If, for example, an airline has requested an arrival-departure slot pair for a slot series at 12:10 and 12:55, respectively, then the slot pair allocated to this series must have a 45-minute time difference between the arrival slot and the departure slot. This requirement can be relaxed by specifying two connectivity parameters, $T_{max}$ and $T_{min}$, which represent respectively the maximum permissible increase and decrease to the requested connection times, respectively. For instance, setting $T_{max} = 10$ min and $T_{min} = 5$ min means that the connection time in the above example can be equal to 40, 45, 50 or 55 minutes. Note that the default assumption corresponds to $T_{max} = T_{min} = 0$. Table 6 summarizes results for Porto for five scenarios in which $T_{max} = T_{min}$ and both are set equal to 0, 5, 10, 15 or $\infty$, with the last case meaning that there is no connection time constraint, as long as this time is non-negative.

Several observations can be made. Most importantly, even limited flexibility in connection times may generate large reductions in total displacement. The first 5 minutes of flexibility (Scenario 2) result in an 11% overall reduction, with most of the benefits accruing to CH and NE slot requests. Even more remarkably, the total displacement of CH and NE slots is improved much more (by 30% and 46%, respectively) by varying the connectivity parameters by up to 15 minutes than by varying them from 15 minutes to infinity (an additional 9% and 4%, respectively). In fact, only the O slots may benefit significantly from any increase in the flexibility of the connectivity parameters beyond 15 minutes. This can be explained intuitively: because of their higher priority, the CH and NE slot requests will be assigned to the slots for which demand is highest, therefore “pushing” the O slots to less busy times. Thus, the O slots need additional flexibility in the connectivity parameters to obtain large benefits. Finally, it is interesting to note that the maximum displacement does not change as flexibility in connection times increases up to 15 minutes. Again, the reason is that demand for slots is concentrated around peak times and, therefore, any O requests for slots at peak times can be accommodated only after displacing them by a significant amount of time (55 minutes in this case).
Table 6: Sensitivity of displacement to flexibility in connection times at Porto.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Tmax−Tmin (min)</th>
<th>Maximum Displacement (min)</th>
<th>Total Displacement (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CH</td>
<td>NE</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>55</td>
<td>0%</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>55</td>
<td>0%</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>55</td>
<td>0%</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>55</td>
<td>0%</td>
</tr>
<tr>
<td>5</td>
<td>∞</td>
<td>25</td>
<td>0%</td>
</tr>
</tbody>
</table>

4.2.2 Size of Aircraft

Aircraft size is not one of the primary criteria considered in assigning priorities to slot requests under the existing WSG rules. The priority of a request for a slot series is not affected by whether the associated flight is performed by a narrow-body aircraft with 120 seats or a wide-body with 300. However, this may conceivably change in the future, especially at Level 3 airports that have almost reached the full limits of their capacity and cannot accommodate any additional aircraft movements (see also Section 5). In such cases, the only way to grow the number of passengers served is by incentivizing the use of larger aircraft by the airlines. Several Level 3 airports are now at or near this point.\(^\text{18}\)

The PSAM can be used to explore the implications of including aircraft size as a criterion in allocating slots. For this purpose, the model can be modified, in a simple way, by modifying the objective function to consider the displacement per passenger (measured as the number of aircraft seats). Qualitatively, the new objective function is written as follows. Specifically, the second and third term are now formulated as the total number of passenger-minutes of displacement and the number of passengers suffering nonzero displacement, respectively (the letter S stands for aircraft seats). The full mathematical formulation is provided in the Appendix.

\(^{18}\) Note that, under current practice, airports charge weight-based landing fees that are higher for larger aircraft. The consideration of aircraft sizes in PSAM would therefore effect a significant shift toward incentivizing the use of larger aircraft to reflect their positive impact on passenger throughput.
In Table 7, we compare the results obtained when total displacement of slot requests is minimized with those when total passenger displacement is minimized at Porto. Aircraft have been divided into 10 classes according to number of seats. The second column shows the number of slots occupied by each class in Summer 2014, while Columns 3 and 4 show the minimum total displacement in minutes for the season under the two objective functions (i.e., without and with consideration of aircraft sizes). As expected, slot requests associated with smaller aircraft now experience more displacement, while the opposite is true for those associated with larger aircraft. For instance, the total displacement of the larger aircraft (i.e., aircraft with more than 150 seats) is reduced by 3.1%, while the total displacement of the smaller aircraft is increased by 6.5%. One might plausibly argue that this may be more consistent with the best interests of passengers and, possibly, of the airport operator and of the airlines (see also Section 5.2).

Table 7: PSAM results at Porto when minimizing slot displacement vs. passenger displacement.

<table>
<thead>
<tr>
<th>Aircraft Class (seats)</th>
<th>Number of Slots</th>
<th>Total Displacement (min)</th>
<th>Difference</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Minimize Slot Displacement</td>
<td>Minimize Passenger Displacement</td>
<td></td>
</tr>
<tr>
<td>0-30</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>31-60</td>
<td>3,847</td>
<td>2,700</td>
<td>3,120</td>
<td>420</td>
</tr>
<tr>
<td>61-90</td>
<td>14</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>91-120</td>
<td>4,128</td>
<td>150</td>
<td>150</td>
<td>0</td>
</tr>
<tr>
<td>121-150</td>
<td>6,411</td>
<td>11,800</td>
<td>12,400</td>
<td>600</td>
</tr>
<tr>
<td>151-180</td>
<td>8,413</td>
<td>9,735</td>
<td>9,625</td>
<td>-110</td>
</tr>
<tr>
<td>181-210</td>
<td>15,756</td>
<td>13,935</td>
<td>13,600</td>
<td>-335</td>
</tr>
<tr>
<td>211-240</td>
<td>178</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>241-270</td>
<td>450</td>
<td>305</td>
<td>0</td>
<td>-305</td>
</tr>
<tr>
<td>271-300</td>
<td>300</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

4.2.3 Weighted Priorities of the Classes of Slot Requests

We study next the third and fourth of the questions posed in the introduction to Section 4. This amounts to examining the impact of potential changes in the way the four classes of slot requests are prioritized. According to existing rules, the four classes are processed in a strict order of priority – H slots first, followed by CH, NE and O requests, in that order. The example of Section 3.2 suggested that this strict order of priorities contributes significantly to increases in displacement. We explore here the consequences of relaxing...
partially this strict order through a system of “weighted priorities”. Particular emphasis will be given to the possibility of adding some flexibility to the assignment of historic slots by allowing some of these slots to be displaced marginally, i.e., by small amounts of time.

The weighted priorities approach requires two adjustments to the original version of PSAM. First, the objective function of PSAM is reformulated to solve the model in a single stage, instead of solving it lexicographically as four sequential sub-problems, as described in Section 3.1. Specifically, as shown in (3) below, we now state the objective function as the weighted sum of four quantities, $HVal$, $CHVal$, $NEVal$ and $OVal$, which denote, respectively, the value of the objective function (1) for the H, CH, NE and O slots. In other words, each of the four quantities corresponds to the minimization of the displacement for each priority class. Second, the constraints on the timing of H slots is relaxed by permitting some displacement of these slots by up to a pre-specified limit (e.g., 5 minutes, 10 minutes, etc.). Constraint (4) restricts the amount of displacement suffered by any H slot, $D_{H,i}^H$, to be less than a user-specified value, $D_{H}^{MAX}$.

\[
\text{Minimize } \alpha \cdot HVal + (1 - \alpha)\{\beta \cdot CHVal + (1 - \beta)\{\gamma \cdot NEVal + (1 - \gamma) \cdot OVal\}\} \tag{3}
\]

\[
|D_{H,i}^H| \leq D_{H}^{MAX} \tag{4}
\]

The weights $\alpha$, $\beta$ and $\gamma$ in [0.5,1) measure the relative weight of each priority class in relation to the following class. For example, values of $\alpha = 0.5$ and $\beta = 0.99$ signify that the H and CH slots are weighted almost equally, but are given high priority over the remaining classes. In order to maintain the current priority order, each weight is at least equal to 0.5. The parameters should not be set equal to one because this would mean no cost for the displacement of slots with lower priority, and thus not result in a Pareto-optimal outcome.

To illustrate the impact of these changes, we now solve the PSAM at Porto with the weighted objective function (3) and the relaxed displacement constraints (4) for the H slot series. To simplify the analysis, we restrict our experiments to the case where the objectives $HVal$, $CHVal$, $NEVal$ and $OVal$ consider only the total displacement of the class
The displacement results are reported in Table 8, with $\alpha$ varying between 0.99 and 0.5 by increments of 0.1, and $\beta$ equal to 0.99, 0.9, 0.7 or 0.5. The value of $\gamma$ was always set equal to 0.99, so we did not test the trade-off between NE and O slots. We considered values of $D_{H}^{\text{MAX}}$ of 5 and 15 minutes, i.e., historic slots can be displaced by a maximum of 5 or 15 minutes. We discuss these results in the remainder of this section.

Table 8: Total displacement results for Porto for different values of the weight $\alpha$ and $\beta$.

<table>
<thead>
<tr>
<th>$D_{H}^{\text{MAX}}$</th>
<th>$\beta = 0.99$ or $\beta = 0.9$</th>
<th>$\beta = 0.7$</th>
<th>$\beta = 0.5$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H</td>
<td>CH</td>
<td>NE</td>
</tr>
<tr>
<td>0.99</td>
<td>3.560</td>
<td>5.220</td>
<td>29.845</td>
</tr>
<tr>
<td>0</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>0.9</td>
<td>1.950</td>
<td>5.220</td>
<td>29.775</td>
</tr>
<tr>
<td>-45%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>0.8</td>
<td>1.210</td>
<td>5.220</td>
<td>28.875</td>
</tr>
<tr>
<td>-62%</td>
<td>0%</td>
<td>0%</td>
<td>-3%</td>
</tr>
<tr>
<td>-66%</td>
<td>0%</td>
<td>0%</td>
<td>-3%</td>
</tr>
<tr>
<td>0.7</td>
<td>1.210</td>
<td>5.220</td>
<td>28.875</td>
</tr>
<tr>
<td>-66%</td>
<td>0%</td>
<td>0%</td>
<td>-3%</td>
</tr>
<tr>
<td>0.6</td>
<td>1.210</td>
<td>5.220</td>
<td>28.875</td>
</tr>
<tr>
<td>-66%</td>
<td>0%</td>
<td>0%</td>
<td>-3%</td>
</tr>
<tr>
<td>0.5</td>
<td>1.210</td>
<td>5.220</td>
<td>28.875</td>
</tr>
<tr>
<td>-66%</td>
<td>0%</td>
<td>0%</td>
<td>-3%</td>
</tr>
<tr>
<td>0.9</td>
<td>1.350</td>
<td>5.220</td>
<td>28.875</td>
</tr>
<tr>
<td>-62%</td>
<td>0%</td>
<td>0%</td>
<td>-3%</td>
</tr>
<tr>
<td>0.8</td>
<td>0</td>
<td>2.565</td>
<td>2.820</td>
</tr>
<tr>
<td>-72%</td>
<td>0%</td>
<td>0%</td>
<td>+4%</td>
</tr>
<tr>
<td>0.7</td>
<td>1.735</td>
<td>2.820</td>
<td>26.575</td>
</tr>
<tr>
<td>-72%</td>
<td>0%</td>
<td>0%</td>
<td>+4%</td>
</tr>
<tr>
<td>0.6</td>
<td>1.355</td>
<td>2.820</td>
<td>29.575</td>
</tr>
<tr>
<td>-72%</td>
<td>0%</td>
<td>0%</td>
<td>+4%</td>
</tr>
<tr>
<td>0.5</td>
<td>1.355</td>
<td>2.820</td>
<td>29.575</td>
</tr>
<tr>
<td>-72%</td>
<td>0%</td>
<td>0%</td>
<td>+4%</td>
</tr>
</tbody>
</table>

**Impact of limited flexibility in historic slot times**

We begin by studying the case in which (i) H slots may be displaced by up to 5 or 15 minutes, and (ii) $\alpha$ can vary between 0.99 and 0.5 by increments of 0.1, keeping $\beta=0.99$, i.e., CH slots still have full priority in relation to NE and O slots (left side of the table). By
introducing limited flexibility to the timing of H slots, we provide an opportunity to move some slot series from the other three priority classes into more desirable times. Thus, we expect that, as the values of $D_{H}^{\text{MAX}}$ and of $\alpha$ increase, the displacement of H slots will increase and the one of the other slots will decrease. We explore this trade-off below.

The most obvious observation suggested by the leftmost part of the Table 8 is that significant improvements in the displacement of CH slots may be achieved by increasing the displacement of H slots by only a small amount. For instance, increasing the displacement of H slots by 90 minutes (i.e., displacing just 18 historic slots during the entire season by only 5 minutes each) reduces CH displacement by 45%, or by 1,610 minutes (a “benefit/cost ratio” of 17.9) to 1,950 minutes. Increasing the displacement of H slots by another 150 minutes, to 240 minutes, leads to a further reduction of 600 minutes in CH displacement, or an additional 17% reduction – but with a diminished marginal benefit/cost ratio of 4.0 (=600/150).

Second, most of the benefits from increasing $D_{H}^{\text{MAX}}$ are obtained by increasing the maximum permitted displacement of historic slots from 0 to 5 minutes. Beyond this point (i.e., when increasing further $D_{H}^{\text{MAX}}$ to 15 minutes) the solution is not particularly sensitive to the additional flexibility provided by the larger $D_{H}^{\text{MAX}}$. In fact, for values of $\alpha$ up to 0.8, the displacements obtained by setting $D_{H}^{\text{MAX}}$ to 5 or 15 minutes are identical.

Third, the NE and O slot series derive only small benefits from the flexibility of the H slot times, as almost all the benefits are captured by the CH series. In fact, note that when we allow a larger displacement for H slots (small $\alpha$ and $D_{H}^{\text{MAX}} =15$) we actually worse solutions for the O slots, the ones with the lowest priority. This is because the H and CH slot requests now enjoy essentially the same level of priority and jointly occupy most of the slots at the busiest times, thus leaving fewer desirable slots for NE and O slots.

Impact of relaxing the priority of change-to-historic slots

Motivated by this last observation, we now analyze the case when the CH slot requests do not enjoy full priority over the two lower priority classes, NE and O. We therefore vary $\beta$, considering values of 0.9, 0.7 and 0.5. We expect that, for smaller values of $\beta$ (i.e., for lower priority of the CH slots), the displacement of the NE and O slots will be lower. In Table 8,
the first row shows the displacements when the priority given to CH slots is lowered without allowing displacement of historic slots (i.e., \( \alpha = 0.99 \)), and the other rows show the effects of varying \( \alpha \) and \( \beta \) simultaneously.

First, note that \( \beta \) trades off the displacement of CH slots against the displacement of NE and O slots. For instance, increasing the CH displacement by 17% leads to a decrease of 46% and 11%, respectively, in the displacement of NE and O slots. Note that the results for the CH slots are worse than in the original solution when we consider \( \alpha \) equal to 0.99, i.e., prioritize fully the H slot series. However, when we allow increases to the displacement of H slots, we always obtain solutions that decrease the displacement of CH slots, no matter how much we decrease \( \beta \).

Second, most of the benefits obtained by reducing the priority of CH slots are captured by the NE requests. For instance, the NE displacement can be reduced by up to 88%, but that of O slots by up to only 15%.

Finally, the effect on the displacement of O slots exhibits complex behaviors. For large values of \( \alpha \), the slot allocation process is highly constrained by the H and CH slot requests, so few benefits are captured by the O slot requests. On the other hand, for the smallest values of \( \alpha \) practically all the reductions in displacement are shared by the CH and NE slots because these two classes now enjoy much more flexibility and the model is able to accommodate them better (especially given that we set \( \gamma = 0.99 \)). Thus, as far as the O slots are concerned, the benefits of the weighted priorities process considered here are largest for moderate values of \( \alpha \), such as \( \alpha = 0.8 \).

The main conclusions from the “weighted priorities” approach can now be summarized. First, a small increase in the displacement of H slots may lead to a large decrease in total displacement and can be beneficial to all three other classes of requests, depending on the values of \( \alpha, \beta \) and \( \gamma \). Second, and importantly for policy, most of the benefits obtained by displacing H slots are obtained with a small total displacement of the H slots. Large additional displacements of H slots provide only marginal additional benefits, compared to the benefits obtained from the initial small displacements. And, third, a “domino effect” can also be observed: the benefits obtained by displacing H slots are primarily captured
by the CH slots and, to a much more moderate extent, by the NE slots. In turn, if priorities are weighted in a way that CH slots are prevented from capturing most of the benefits accruing from the displacement of H slots, then NE slots can experience significant decreases in displacement. An analogous observation can be made for the case of O slots.

4.2.4 Relaxing Schedule Regularity Requirements

Another area for potential changes to the current rules and practices pertains to the requirements for schedule regularity over a season, as specified in the WSG. We consider here combinations of two types of schedule regularity constraints, one with respect to time-of-the-day and the other with respect to the length of the scheduling period.

Concerning the first, we consider two possibilities: (i) all slots belonging to identical series of slots for different days of the week, which are submitted together as part of the same request, must be scheduled at the same time of the day across the different days of the week; (ii) all slots belonging to the same slot series must be scheduled at the same time of the day (but not necessarily all slots belonging to “identical series of slots for different days of the week, which are submitted together as part of the same request”). As noted in Section 2.3, current practice at most Level-3 airports is consistent with (i), the stricter of the above two possibilities, so we treat (i) as the choice under the status quo. The default choice in the PSAM is also (i).

When it comes to the length of the scheduling period, we consider three possibilities: (a) the scheduling period spans the entire season of interest (“Summer” or “Winter”), as in current practice; (b) the scheduling period is subdivided into more homogeneous sub-periods of one or more months each; (c) the scheduling period is subdivided into sub-periods of one month each. Alternatives (b) and (c) are intended to account for the fact that at many airports, especially ones with highly seasonal demand, the airlines may have different slot requirements in different parts of a “season”. For example, in the case of the Summer season airline schedules (and thus slot requirements) in April, May and October may differ significantly from those in July and August.

---

20 The WSG actually states proposition (i), concerning identical series for different days of the week, as a recommendation, rather than a requirement (Section 2.3).
Table 9 reports the PSAM results at Porto under a set of scenarios related to the above variations for the Summer season of 2014. Scenario 1 combines (i) and (a) and Scenario 2 combines (ii) and (a). For Scenarios 3 and 4, we combine (i) and (ii), respectively, with (b), assuming that the Summer season is subdivided into three parts – April-May-June, July-August, and September-October. This particular subdivision is motivated by the fact that the number of slots requested by the airlines at Porto in July and August is about 15% higher than in the other 5 months of the Summer season, each of which has roughly the same number of requests. Scenarios 5 and 6 assume monthly scheduling periods (i.e., (c)) combined, respectively, with time-of-the-day requirements (i) and (ii). Finally, Scenario 7 represents the extreme case of no interdependences among slots. In other words, slots are now scheduled by treating each day of the season independently of all other days by minimizing the objective function (1) for the requests submitted for that particular day.

**Table 9: Sensitivity of the displacement at Porto to changes in the schedule regularity constraints.**

<table>
<thead>
<tr>
<th>Scheduling Period</th>
<th>Scenario</th>
<th>Maximum Displacement (min)</th>
<th>Total Displacement (min)</th>
<th>Slots Displaced (slots)</th>
<th>Requests with Violations (%)</th>
<th>Maximum Amplitude (min)</th>
<th>Average Amplitude (min)</th>
<th>Standard Deviation Amplitude (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entire Season</td>
<td>1 All series in same request 55</td>
<td>38.625</td>
<td>2.379</td>
<td>0.0%</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>2 Only each individual series 55</td>
<td>33.885</td>
<td>1.897</td>
<td>2.0%</td>
<td>30</td>
<td>8.2</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>3 periods</td>
<td>3 All series in same request 55</td>
<td>27.415</td>
<td>2.025</td>
<td>10.8%</td>
<td>110</td>
<td>17.3</td>
<td>19.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 Only each individual series 55</td>
<td>21.790</td>
<td>1.425</td>
<td>7.0%</td>
<td>110</td>
<td>17.6</td>
<td>19.1</td>
<td></td>
</tr>
<tr>
<td>Monthly</td>
<td>5 All series in same request 55</td>
<td>26.170</td>
<td>1.880</td>
<td>11.3%</td>
<td>110</td>
<td>18.8</td>
<td>18.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6 Only each individual series 55</td>
<td>20.845</td>
<td>1.295</td>
<td>7.3%</td>
<td>110</td>
<td>18.6</td>
<td>18.8</td>
<td></td>
</tr>
<tr>
<td>Daily</td>
<td>7 Each day independently 55</td>
<td>19.310</td>
<td>1.206</td>
<td>11.6%</td>
<td>110</td>
<td>19.8</td>
<td>19.2</td>
<td></td>
</tr>
</tbody>
</table>

In the left half of Table 9 we see the impact of the various combinations of regularity constraints on the three objectives of PSAM – maximum displacement, total displacement, and number of slots displaced. On one hand, we observe that consideration of these constraints does not increase the optimal solution for the maximum displacement, which is always equal to 55 minutes. On the other, they have a very significant impact on total
displacement and number of slots displaced, as relaxing them could reduce the total displacement and the number of slots displaced by up to 50%.

The right half of the table presents indicators of the impact that the non-consideration of the constraints has on schedule regularity. First, it shows the percent of slot requests whose regularity constraints are violated in each scenario (e.g., in Scenario 2, only 2% of the slot requests do not have all their slot series scheduled at the same time). Second, we provide information about the amplitude of the time between slots belonging to the same slot request across the season (e.g., in Scenario 2, there are at least two slot series belonging to the same slot request that are scheduled at times differing by 30 minutes – for instance, the slots may be scheduled at 08:45 on Mondays and at 09:15 on Tuesdays). Finally, we show the average and standard deviation of this amplitude for the slot requests where a violation occurs (i.e., for Scenario 2, the average amplitude for the 2% of slot requests with a violation is 8.2 minutes and the standard deviation is 7.5 minutes).

Table 9 suggests that there may be good reasons to consider adopting changes (ii) and (b) for the schedule regularity constraints. If requirement (ii), instead of (i), were adopted with respect to the time-of-the-day regularity (Scenario 1 vs. Scenario 2), the total displacement at Porto would be reduced by 12% and the number of slots displaced by 20%. Moreover, only 2% of the slot series in the set of “identical series of slots for different days of the week” would violate requirement (i) and the maximum amplitude between times allocated to slots belonging to the same slot request would be only 30 minutes, with the average and standard deviation of only 8.2 and 7.5 minutes, respectively.

Table 9 similarly points to the potential benefits of subdividing “seasons” into shorter, more homogeneous (as far as demand is concerned) sub-periods. This can make it possible to account more effectively for the detailed characteristics of seasonality in demand. In the case of Porto, forcing slot times in April, May, June, September and October to be identical to those in July and August, as done today, means that some slot series in these five “low” months suffer significant displacement just in order to ensure regularity throughout the season. As Table 9 shows, Scenario 3 that subdivides the summer season into three independent sub-periods reduces total displacement by 29% and the number
of slots displaced by 15%, compared to the status quo Scenario 1. Note that, within each sub-period, all schedule regularity constraints are satisfied, i.e., comply with (i), so that any violations of current regularity constraints under Scenario 3 only occur between sub-periods. If, in addition, we allow compliance with only (ii) during each of the sub-periods, total displacement and the number of slots displaced are reduced by 44% and 40%, respectively (Scenario 4). Interestingly, little further benefit is obtained by breaking down the season into monthly periods, as seen by comparing the results for Scenario 5 with those for Scenario 3 and for Scenario 4 with Scenario 6. Moreover, and importantly, this observation holds even for the extreme case of Scenario 7 in which each day is treated as a separate and independent sub-period!

Although the maximum amplitude between scheduled times for Scenarios 3 through 7 is 110 minutes\(^{21}\), amplitudes of this magnitude are very rare. For example, for Scenario 3, only one slot request had a difference of 110 minutes, while all the others had amplitudes of 55 minutes or less, with more than 70% at less than 15 minutes. This suggests that the addition to PSAM of some additional constraints that limit the maximum amplitude between the scheduled times of slot series belonging to the same slot request may lead to even better results in terms of the average and standard deviation of the amplitude.

Finally, we observed that the impacts of the changes in schedule regularity constraints are shared across all the priority classes of slot requests\(^{22}\) and therefore do not raise any issues regarding the distribution of potential benefits.

### 4.3 The Impact of the Declared Capacity on Slot Allocation

While the effects of flight schedules on airport on-time performance have been well documented, the impact of declared capacities on slot allocation has been the subject of more limited attention. We now use the PSAM to demonstrate through an example the strong impact of declared capacities on the displacement of slot requests. Specifically, we

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\(^{21}\) This means that a slot may be scheduled at 10:50 in July and August, and at 09:00 in the other months. Note that the differences between scheduled slot times are now measured across different sub-periods of the season.

\(^{22}\) Historic slots are not impacted anyway.
perform a sensitivity analysis of the total displacement at Porto as a function of its declared capacity. Recall that Porto was subject, in the Summer season of 2014, to a limit of 20 movements per rolling hour and of 7 movements per rolling 15-minute period, with no separate limits for arrivals only and departures only, and no terminal or apron capacity limits. We vary these two values (C60' and C15', respectively) and report the resulting total displacement in Table 10. Note that this does not consider the potential existence of latent demand, i.e., the possibility that the airlines may request more slots at peak hours, or more slots altogether, in response to increases in declared capacities.

Table 10: Total displacement results (in minutes) for different declared capacities

<table>
<thead>
<tr>
<th>C60'/C15'</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>Infeasible</td>
<td>Infeasible</td>
<td>Infeasible</td>
<td>Infeasible</td>
<td>Infeasible</td>
<td>Infeasible</td>
<td>Infeasible</td>
</tr>
<tr>
<td>20</td>
<td>Infeasible</td>
<td>38,625</td>
<td>27,090</td>
<td>19,660</td>
<td>14,460</td>
<td>12,690</td>
<td>12,470</td>
</tr>
<tr>
<td></td>
<td>0%</td>
<td>-30%</td>
<td>-49%</td>
<td>-63%</td>
<td>-67%</td>
<td>-68%</td>
<td>-68%</td>
</tr>
<tr>
<td>21</td>
<td>Infeasible</td>
<td>30,760</td>
<td>18,410</td>
<td>10,430</td>
<td>4,900</td>
<td>3,080</td>
<td>2,560</td>
</tr>
<tr>
<td></td>
<td>-20%</td>
<td>-52%</td>
<td>-73%</td>
<td>-87%</td>
<td>-92%</td>
<td>-93%</td>
<td>-93%</td>
</tr>
<tr>
<td>22</td>
<td>Infeasible</td>
<td>29,480</td>
<td>16,210</td>
<td>8,110</td>
<td>2,640</td>
<td>820</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>-24%</td>
<td>-58%</td>
<td>-79%</td>
<td>-93%</td>
<td>-98%</td>
<td>-99%</td>
<td>-99%</td>
</tr>
<tr>
<td>23</td>
<td>Infeasible</td>
<td>29,180</td>
<td>15,910</td>
<td>7,810</td>
<td>2,340</td>
<td>520</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>-24%</td>
<td>-59%</td>
<td>-80%</td>
<td>-94%</td>
<td>-99%</td>
<td>-100%</td>
<td>-100%</td>
</tr>
<tr>
<td>24</td>
<td>Infeasible</td>
<td>29,180</td>
<td>15,910</td>
<td>7,810</td>
<td>2,340</td>
<td>520</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>-24%</td>
<td>-59%</td>
<td>-80%</td>
<td>-94%</td>
<td>-99%</td>
<td>-100%</td>
<td>-100%</td>
</tr>
<tr>
<td>25</td>
<td>Infeasible</td>
<td>29,180</td>
<td>15,910</td>
<td>7,810</td>
<td>2,340</td>
<td>520</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>-24%</td>
<td>-59%</td>
<td>-80%</td>
<td>-94%</td>
<td>-99%</td>
<td>-100%</td>
<td>-100%</td>
</tr>
</tbody>
</table>

The main insight from Table 10 is that the optimal total displacement is highly sensitive to the value of the declared capacity. For instance, an increase in the total hourly capacity by one slot (from 20 to 21 movements per hour) would reduce the total displacement by 20%. A simultaneous increase in the total 15-minute capacity by one slot (from 7 to 8 movements per period), while still keeping the hourly limit to 21, would result in a displacement 52% smaller than under the current setting! Note, moreover, that any reduction in the declared capacities from the current values results in an infeasible problem. This is due to the hard constraints associated with H and CH slots. Finally, further increases in declared capacities would further reduce the total displacement, until all slot requests can be met exactly with a capacity of 12 movements per rolling 15-minute period and 23 movements per rolling hour. Note, however, that reductions in
displacement are marginally decreasing. For instance, increasing declared capacity from 21 to 22 movements per hour, or from 8 to 9 movements per 15-minute period, would result in significantly smaller reductions in the optimal value of the total displacement than respective increases from 20 to 21 movements per hour or from 7 to 8 movements per 15-minute period.

At the same time, it is well known that air traffic delays and airport on-time performance are also highly sensitive to the values of declared capacities (Pyrgiotis et al., 2011; Jacquillat and Odoni, 2015b). Therefore, capacity declaration is of paramount importance in slot allocation. Declared capacities can lead to high levels of congestion and deteriorated levels of service if set too high, and to high displacement of slot requests if set too low. This suggests opportunities to define a transparent and standardized process for declaring capacities across Level 3 airports, supported by up-to-date analytical models, as well as frequent performance re-assessment by collecting appropriate data and reporting critical metrics in view of strategic goals. We summarize here the principal guidelines concerning capacity declaration that have emerged from recent research and the analysis above that could form a basis for such a process (Jacquillat and Odoni, 2015a; Zografos et al., 2017).

(i) Should be set with respect to the full spectrum of the operating conditions observed at the airport (e.g., good/poor weather conditions, different runway configurations, etc.). Focusing solely on poor weather conditions bears the risk of declaring overly conservative capacities resulting in unnecessarily low scheduling levels, while scheduling practices based on good weather alone can lead to excessive delays in poor weather.

(ii) Should be defined, ideally, at high levels of granularity. For instance, existing practices that declare separate limits for arrivals and departures, or that specify separate runway, terminal and apron capacities, tend to lead to a better matching of the scheduling levels with the airport’s operating capabilities.

(iii) Should balance the supply-side operating capabilities and the demand-side characteristics of airline slot requests to achieve a targeted level of service, and account for the nonlinear relationships between schedule displacement and
airport delays, on one hand, and declared capacities, on the other. For instance, two hypothetical airports, with the same supply-side characteristics, might end up with different declared capacities if airline demand characteristics at the two airports are very different.

(iv) Can vary from one period of the day to another to accommodate higher volumes of operations at peak hours, which can be compensated, in part, by schedule valleys at off-peak hours. This could lead to a better matching with airline demand, while maintaining high levels of service. Declared capacities that vary by time-of-day have become common practice at some of the busiest Level 3 airports (e.g., Amsterdam Schiphol, London Heathrow).

(v) Can vary from one week of the season to another to accommodate higher volumes of operations during the busiest periods of the year and/or the periods with the (historically) most favorable conditions. This is motivated by variations in airline demand and weather conditions over time (e.g., demand is 15% higher in Porto in July and August than during the rest of the “Summer” season).

4.4 The Issue of Fairness

Objective functions such as (1) or (3) minimize aggregate displacement costs. Airlines, however, are also greatly interested in how these costs are distributed among them. It is clearly undesirable to allocate a disproportionate amount of displacement to one airline or a small number of airlines. This issue has given rise to several recent studies on the subject of ensuring inter-airline equity (or “fairness”) in assigning slots at Level 3 airports.

A “fair” allocation, in this context, can be defined as one in which the share of total displacement assigned to any airline is roughly the same as that airline’s share of the total number of slots allocated at the airport. This definition can be easily expressed mathematically and incorporated into optimization models, such as PSAM, in ways that force rejection of solutions in which an airline receives an unacceptably large or small share of total displacement compared to its share of slots (Zografos and Jiang, 2016; Zografos et al., 2017).

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23 This assumes that no request is rejected; if this is not the case, the definition can be modified accordingly.
Jacquillat and Vaze, 2018). Several more refined variations of the definition of fairness have also been proposed and studied. For example, one may wish to assign more weight to the displacement of larger aircraft (thus implicitly prioritizing such aircraft) by taking into consideration the number of seats on the aircraft associated with each requested slot series (Zografos and Jiang, 2016). Or, one may require that the share of displacement assigned to any airline should be proportional to the share of slots this airline has requested during peak demand periods, thus not penalizing airlines that submit requests for slots during off-peak periods (Fairbrother and Zografos, 2018).

Several attempts have already been made to assess the impact of equity-related requirements on the efficiency of slot allocation and flight scheduling at Level 3 and other congested airports. An interesting pair of observations has emerged from this work (Jacquillat and Vaze, 2018). First, inter-airline equity can be achieved at only a small loss (or at no loss) in efficiency under a wide range of realistic conditions and hypothetical scenarios. Thus, fairness in the distribution of displacement does not necessarily mean a significant increase in total displacement. However, the reverse is also true: solving an optimization model by considering exclusively the efficiency objective, while ignoring inter-airline equity, risks the possibility of reaching highly inequitable slot allocations. In other words, the most efficient solution may be one with a very “unfair” distribution of displacement costs, whereas other solutions may exist that achieve the same (or a similar) level of efficiency, while also ensuring adequate equity. Thus, whenever issues of fairness may potentially arise, it is important to incorporate explicitly into models that support the allocation of slots, such as PSAM, the consideration of inter-airline equity.

5 Further Areas for Improvement

We now extend the scope of the search for improving the existing slot allocation process by examining two other important issues: the designation of airports as Level 3; and the solution of the SAP at a network level – as opposed to solving it for each airport separately.
5.1 Designation as Level 3

The airports currently designated as Level 3 constitute a highly non-homogeneous group. At one extreme, they include a number of airports that served more than 50 million passengers in 2017 and received more requests for slots than their declared capacities for many hours of the day and many days of their peak Summer or Winter seasons. At the opposite end, they also include many others that handle fewer than 10 or even 5 million passengers annually and with only a small number of hours in a season when the number of slot requests exceeded declared capacities. These differences reflect the vagueness of the current definitions of Level 3 (and Level 2) airports in the WSG, as well as the absence of consistent national policies concerning the designation of airports as Level 3. This state of affairs leaves much room for arbitrary and divergent local practices and has led to proliferation in the number of Level 3 airports in some countries.

According to the WSG, Level 3 airports are those where “a) demand for airport infrastructure significantly exceeds the airport’s capacity during the relevant period; b) expansion of airport infrastructure to meet demand is not possible in the short term; [and] c) attempts to resolve the problem through voluntary schedule adjustments have failed or are ineffective” (IATA, 2017). But the WSG offers very limited guidance for ascertaining whether these three conditions are met. Concerning a) – the most fundamental among the three – it calls for a “demand and capacity analysis using commonly recognized methods” that “should objectively consider the ability of the airport infrastructure to accommodate demand at desired levels of service, such as queue times, levels of congestion or delay” (§6.1). It does not, however, provide any guidance for determining whether “demand significantly exceeds capacity” or any benchmarks for what constitute “desired levels of service”.

A few airports or national organizations have attempted over the years to develop such benchmarks mostly for planning purposes. However, much of the available information on these benchmarks is anecdotal and has been rarely used in determining whether an

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24 Roughly 50% of the 103 European airports designated as Level 3 in Summer 2017 were in this category. All of these airports served fewer than 8 million passengers in 2017 with the great majority at lower than 5 million.
airport should be designated as Level 3. Historically, in the early 1960s, the US Federal Aviation Administration (FAA) set an average delay of 4 minutes per aircraft movement during peak hours as the threshold at which an airport would be considered to have reached its “practical hourly capacity” – essentially, the equivalent of being designated as a “congested” airport (de Neufville and Odoni, 2013). This threshold was abandoned after delays at many major airports in the US exceeded it, by a wide margin, in the late 1970s and 1980s. A number of other more recent examples of benchmarking include the following: (1) the declared capacity of London Heathrow is believed to be determined with the aid of a detailed simulation that uses a 10-minute average delay per movement during a peak day as the target level-of-service; (2) China’s Civil Aviation Agency is said to be currently using an average delay of 8 minutes per movement in a peak day as the upper limit on acceptable level of service at the country’s major airports; (3) in connection with several consulting projects at major airports in North and South America, Europe and Asia/Pacific, one of the authors of this paper has been using, with agreement from local decision-makers, a 5-minute average delay per movement during a typical day of operations and a 10-minute average delay for peak-hour movements as thresholds (when either of these levels is reached, the airport is considered to have reached its limits for acceptable level of service); and (4) the FAA has recently defined “significant congestion” as delays of 7 minutes or more per movement during more than 30 percent of the hours between 07:00 and 22:59 and “severe congestion” as delays of 15 minutes or more per movement during more than 50 percent of the hours in that time window (FAA, 2017).

Although these above thresholds vary in terms of both numerical value and level of sophistication, they all share the perspective that the maximum acceptable average level of delay in a day is in the range of 5-10 minutes per movement. This suggests that future versions of the WSG could offer some quantitative guidelines regarding “desired levels of service”, a step that could contribute to more uniformity in practices around the world. A broad range of target values for delays could be stated (e.g., average of 5 – 10 minutes per movement). Decision-makers at each airport could then: (i) select a specific target value from that range based on local preferences; (ii) perform an analysis to determine whether the airport can meet that target in the absence of any slot limits; and (iii) in the event that it cannot, request designation as Level 3, so it could meet the target by declaring capacity
limits and allocating slots accordingly among the airlines requesting them. Similarly, if the target level of service can be met without interfering with airline requests (or after limited interference) at an airport that has already been designated as Level 3, the airport could revert back to Level 1 (or Level 2). The underlying analyses could be supported by readily available queuing models and simulation tools. In addition to the benefits resulting from more standardized and internally consistent practices concerning designation, this process would be transparent, verifiable and objective.

5.2 A New Class of “Level 4” Airports?

Most Level 3 airports have sufficient capacity to accommodate virtually all slot requests, albeit often at the cost of significant slot displacement and forcing certain flights to operate at other than their most desirable times. However, a few critical airports are operating at saturation or near-saturation levels. The overwhelming majority of slots at these airports are “historic”, so they have little room for accommodating additional requests. Coordinators are thus forced to reject some new slot requests year after year. Moreover, much latent demand exists at these airports: airlines that would otherwise initiate or increase service at these airports do not bother submitting slot requests being aware of the unavailability of free slots. Should the capacity of these airports ever increase significantly, it is certain that numerous additional slot requests would be immediately submitted to claim the new slots. London Heathrow (LHR), Paris Orly (ORY) and Hong Kong International (HKG) are prominent examples of such Level 3 airports, but several others are increasingly experiencing similar conditions, in some cases due to agreed limits on annual numbers of movements in response to environmental concerns.

It may be useful to classify these extremely congested airports into a separate class of “Level 4” airports, as they face different types of decisions and underlying tradeoffs concerning slot allocation than the large majority of Level 3 airports. A new set of allocation rules may be called for at these airports, which might differ in significant ways from the set of rules that currently applies at Level 3 airports. For example, the emphasis in the new rules may be on criteria for accepting or rejecting requests for slots, rather than minimizing displacement. It is probable that this would translate into assigning more importance to what today are called “additional criteria”, for example, giving preference
to slot requests for high capacity aircraft and to slot series of long duration, such as series with year-round operations. In this way, for any given maximum number of movements that an airport could accommodate per year (or per season), the airport would maximize the number of passengers it serves or some other measure of utilization. As shown in Section 4.2.2, the PSAM is capable of taking aircraft capacity (i.e., number of seats) into account as a criterion in slot allocation. The example given in Table 7 also demonstrated that doing so might result into a different fleet mix than under the current Level 3 slot allocation rules and priorities. Other “additional criteria” whose importance may be elevated in the case of “Level 4” airports, include consideration of the type and number of markets served and ensuring and promoting the existence of a competitive environment.

5.3 Network Considerations

Another important area for improvements to the state-of-the-art is the resolution of network-level issues during the slot allocation process. This is currently done in an ad hoc manner, mostly during the Slot Conferences, as initial slot allocations at all Level 3 airport are carried out from an entirely local, airport-level perspective. The coordinator makes the initial slot allocation decisions with little or no knowledge of the decisions made by other coordinators at other airports. It is only after all the decisions are communicated to the airlines that problems of incompatibility between allocations made at different airports become known. The likelihood of such incompatibilities for any specific flight depends on the priority class to which the associated slot request belongs. Consider, for example, a flight from a Level 3 airport, A, to another Level 3 airport, B, that a particular airline, X, wishes to schedule through two different slot series requests submitted separately at A and at B. If both the departure slot at A and the arrival slot at B are H slots, there will almost certainly be no problem of compatibility between the two slots, as (i) the schedulers at the airline will have made sure that the scheduled time between the two slots is equal to the block time necessary to fly from A to B and (b) airline X is guaranteed to receive the two slot times requested. However, any other combination of slot priority classes (e.g., the slot requested at A belongs to the CH class and the one requested at B to the O class) runs the risk that, after the initial slot allocation, there will be an inconsistency between the slot times allocated at A and at B, i.e., the time between the scheduled
departure from A and the scheduled arrival at B will be different from any feasible A-to-B block time. Thus, the “decentralized” slot allocation process currently in use may yield solutions that are incompatible with one another at the network level. An additional issue (which, however, is easier to deal with in practice) may arise when an aircraft is ultimately headed to an airport C, that imposes a curfew after a certain time of the day. It is again possible that the timing of a slot assigned to that aircraft at a Level 3 airport may make it impossible to eventually reach C before the curfew begins.

Problems of this type are currently resolved by adjusting and revising the initial slot allocations at the Slot Conferences and follow-up exchanges. But these issues have also motivated interest in models for optimizing slot allocation at the network level, a topic that has attracted some attention during the current decade. Because of its great complexity, it is generally accepted that the exact solution of a network-wide PSAM-like model is intractable at this time, i.e., it is impossible to solve optimally, in reasonable computational times, the SAP for networks of airports of realistic size, while respecting all the slot priorities, capacity constraints and, especially, schedule regularity requirements at each and all airports. Recent research has therefore focused on heuristic approaches. To our knowledge, two efforts represent the state-of-the-art. Pellegrini et al (2017) have developed SOSTA (Simultaneous Optimization of airport SloT Allocation), a model that optimizes exactly and in reasonable computational times, the simultaneous allocation of slots for a single day at all airports in a large Europe-wide network, while respecting most slot allocation rules in the WSG. The slot allocation recommendations made by SOSTA for a peak day in the entire European network seem realistic and compare favorably with the allocations made in practice. The main weakness of SOSTA is that it does not consider schedule regularity requirements, i.e., by solving the slot allocation problem for a single day, rather than simultaneously for all days of a season, it does not necessarily schedule all slots of a series at the same time of the day across a season. The paper’s authors have suggested a heuristic approach for partially addressing this problem by solving SOSTA sequentially for a carefully selected set of days. Benlic (2018), on the other hand, does consider schedule regularity requirements and, unlike Pellegrini et al (2017), adopts an entirely heuristic approach to solve a number of instances of network-wide slot allocation problems. These instances involve large numbers of flights, comparable to the total
number of commercial flights in Europe in a season, and are solved in about 1 minute each. The instances, however, are not based on field data and are computer-generated under a number of assumptions, some of which simplify the problem greatly, including the assumption that all airports have similar or identical seasonal and daily demand distributions. A more definitive assessment of this approach must therefore await its application to more realistic problem instances.

In summary, the network-wide solution to the SAP is an important and still open problem.

6 The Larger Context

Any discussion of improvements to the existing slot allocation process at Level 3 airports would be incomplete without at least a brief mention of some of the major policy issues that are raised by current practices. In this section, we summarize, first, a selected subset of potential mild changes to the rules concerning historic slot rights, new entrants, and slot series, as well as to practices concerning participants to the decision-making process and their roles. We then touch very briefly on a couple of more fundamental questions that deserve, at the very least, a full debate at a time of rapid growth in demand for air travel and increasing pressures on airports.

Historic Slot Rights

The rules and rights associated with historic slots are probably the most controversial aspect of existing slot allocation practices. Earlier in this paper, a number of ways were mentioned for introducing limited flexibility in the way historic slots are scheduled (e.g., by permitting small displacements of historic slot times, Section 4.2.3). The impacts of such more flexible rules were studied and their benefits assessed. At a more basic level, however, much criticism has been directed to the practice of assigning historic slots in perpetuity to airlines, with violations of “use-it-or-lose-it” rules being the only way a slot can be lost. Clearly, this severely limits change at the most popular airports, where most slots are already historic ones, and places non-incumbent airlines at a competitive disadvantage.
One of the most often mentioned potential changes to the status quo is an increase in the minimum percent of time (currently set at 80%) that a slot should be used. Presumably, such an increase (e.g., to 85% or 90%) would make it more difficult for some airlines to continue the tactic of “sitting on” their slots. Even in the (likely) case that airlines will simply increase their use of slots to meet the new threshold, the change to a higher limit will, at the very least, reduce the number of unused and wasted slots. It would also be useful to add specificity to the definitions in WSG of when a slot “is not used because of the airline’s fault” and when it “is not used for reasons outside the control of the airline” (IATA, 2017).

A more drastic change might mandate the expiration of some specified fraction of historic slots each year. For example, 5% of the slots might be allowed to expire each year, meaning that the expected lifetime of historic rights to a slot would be 20 years. The expiring slots would be returned to the pool of “open” slots for re-allocation. Which specific slots would expire in any particular year might be determined through a lottery, or through an administrative procedure, possibly with inputs from the airlines (e.g., each airline would be asked to indicate the 5% of its slots it would give up), or, conceivably, through market mechanisms (e.g., airlines might trade slot elimination requirements with each other). Similarly, the newly open slots would be allocated each year through an administrative procedure or through a hybrid of administrative rules and market mechanisms. In 2008, the FAA proposed, but never implemented, an approach along these lines that included auctioning a specified fraction of the newly opening slots each year.25

New Entrants

New entrants may, in principle, act as the catalysts of increased competition at an airport, as well as contribute to the opening of new routes and markets. In this respect, the principal criticism of the existing slot allocation system is that it is too restrictive. It has often been argued that (i) more than (the current) 50% of the pool of “open” slots should be allocated among new entrants and, far more importantly, (ii) the definition of a new

entrant as “an airline requesting a series of slots at an airport on any day where, if the airline’s request were accepted, it would hold fewer than 5 slots at that airport on that day” should be changed by increasing significantly the limit of 4 slots a day. With regard to (i), not only the 50% limit might be increased, but consideration might also be given to assigning higher priority to some slot requests by new entrants (e.g., those proposing the use of large aircraft to serve new markets) than to change-to-historic requests. As for (ii), the limit of two slot pairs per day essentially relegates new entrants to the role of airlines that provide one connection in the morning and another in the evening in a single market, or a single connection per day to each of two markets. This precludes the possibility that a carrier (legacy or low-cost) would move aggressively into a Level 3 airport and offer a package of flights that would enable it to compete with the main incumbents at the airport for a significant share of overall originating, terminating and connecting traffic. Thus, this restriction propagates the status quo at so-called “fortress airports” that are typically dominated by a single carrier.

Slot Series

A series of slots is currently defined as “at least 5 slots requested for the same time on the same day-of-the-week, distributed regularly in the same season”. Increasing this number (for example, to a minimum of 9 slots so as to offer service during a minimum of roughly one-third of a season) might prove beneficial by contributing to a more “regular” schedule of flights over a season and making more slots available for the longer series. Such a change would also simplify and facilitate the allocation process itself.

Participants to the Process

A striking aspect of the existing process is the limited role of airport operators in decision-making on slot allocation. The only step in which airport operators are formally involved

26 The EU has modified slightly this definition for special cases, such as flights between a Level 3 airport and a small regional airport.

27 This was the traditional, pre-liberalization role of “flag carriers” that offered service to/from their home bases.

28 In many well-known instances at major US airports, air carriers have adopted this type of aggressive strategy, with strong positive effects on competition and on travel options at the subject airports.
is Step 1 of Figure 1, the setting of declared capacities. The only other responsibility of the airport operator mentioned explicitly in the WSG is to “provide relevant information to the coordinator” concerning some of the “additional criteria” for slot allocation (IATA, 2017). Nor is there a role for airport operators in setting up the rules and priorities in the WSG. Preparation of the WSG is overseen by the Joint Slot Advisory Group (JSAG). Despite the claim that “the composition of JSAG reflects the global nature of international air transport” (IATA, 2017), the JSAG “is comprised of an equal number of IATA Member airlines and airport coordinators”, with no representation of airport operators. A significant upgrading of the institutional role of airport operators in the process of Level 3 slot allocation would seem called for in view of (i) their deep understanding of local operating conditions and constraints and (ii) the growing role that airports play in promoting connectivity and, more generally, economic and social welfare at the local and regional levels.

A similarly limited role is also typically played by national governments. Coordinators (whether as individuals or as organizations) are typically appointed by governmental agencies or ministries, but they often operate with limited governmental input, despite the fact that decisions concerning slots, as well as those concerning the designation of airports as Level 2 or 3, are not purely “technical” matters, but have important national socio-economic implications.

**Fundamental Questions**

Finally, for the sake of completeness, it is essential to emphasize here that a number of fundamental questions about slot allocation at congested airports are still open ones. We mention only two of these here and note that they have already attracted a huge amount of attention by academics and practitioners alike.

First is the question of the property rights associated with historic slots (see, e.g., Czerny et al (2008), with numerous references to additional publications). An airport slot is defined as “a permission given by a coordinator for a planned operation to use the full range of airport infrastructure necessary to arrive or depart at a Level 3 airport on a specific date and time” (IATA, 2017). Yet, for most practical purposes, slots are treated as property of the airlines, with the right to sell, lease or exchange. The “secondary trading”
of slots, a practice which is spreading – slowly but steadily – internationally, has brought to the fore these two conflicting views (“permit” vs. “property”) and may force aviation policy-makers to finally attempt to resolve the relevant issues, such as the incentives that airlines perceive when slots are treated as property (Fukui, 2014; Gillen and Starkie, 2015). Haylen and Butcher (2017) present a good review.\textsuperscript{29}

A second fundamental question concerns the use of market mechanisms – in combination with an administrative process or alone – in airport slot allocation (see Gillen et al (2016) with numerous references to additional publications). Contrary to the statement of IATA cited in this paper’s introduction, many economists and other researchers that have studied the issue have concluded that such mechanisms can, under many circumstances, improve the utilization of already-congested airport capacity or provide benefits to improving customer experience and choice in connectivity and fares.

7 Conclusion

The policy issues raised by slot allocation at the busiest (Level 3) airports are vast and complex. In this paper, we have addressed several of them to various extents, with the main focus on the analysis of possible improvements to IATA’s World Slot Guidelines (WSG) that could be realistically implemented in the short term. To our knowledge, the analyses we have performed on the current slot allocation process surpass, both in breadth and in depth, those previously reported in the literature and provide valuable insights for the discussions that the International Civil Aviation Organization (ICAO) has encouraged on this subject.

For carrying out the analyses, we have relied on an optimization model that is fully compliant with the WSG, i.e., that takes into account all the objectives considered in the WSG as well as the runway, apron, and terminal constraints faced by the airports. The application of the model allowed us to compare the slot allocations performed by the coordinators at a few airports in Portugal with the best possible slot allocations under a

\textsuperscript{29} See also The Economist, Winning the Slottery, November 17, 2017.
variety of objectives and constraints, and to assess the impacts of potential changes to the rules and priorities that are currently used.

The results obtained through our model suggest, first, that the solutions found by slot coordinators can be close to optimal at small airports, but could probably be improved significantly at midsize and large airports. Second, and most importantly, our results show that even limited adjustments in the WSG rules could lead to a use of airport capacity that would match better the requests of the airlines (though not necessarily for all kinds of requests at the same time). This was observed for all types of changes analyzed. For instance, at the Porto airport, improvements of 66% in the displacement of change-to-historic slots were observed when the historic slots were allowed to be displaced by only 5 minutes, instead of being completely immovable as currently mandated by the WSG. Another example is the reduction in displacement when the slot allocation is performed, not for a full season as today, but for shorter and more homogeneous (as far as demand is concerned) sub-periods. In the case of the Porto airport, an improvement of 29% in total slot displacement was observed when the Summer season was divided into three sub-periods, to distinguish the two peak months (July-August) from the non-peak ones (May-June and September-October).

The changes to the WSG we have analyzed in detail could, on their own, bring considerable benefits in the short term. However, they are not the only changes to consider. We have identified and summarized in this paper a large number of other potential changes that could make the slot allocation process at Level 3 airports more efficient, fair, transparent and inclusive. In the future, we plan to devote a substantial part of our research efforts to the study of the impacts of such changes.

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References


**Appendix**

We provide in this appendix the full formulation of the PSAM, described in qualitative terms in Section 3.1. For a more complete description of the model and its solution procedure, we refer the reader to (Ribeiro et al., 2018).

**Sets**

\[ T = \{1, \ldots, T\} : \text{set of time periods, indexed by } t \]
\[ D = \{1, \ldots, D\} : \text{set of days, indexed by } d \]
\[ S = \{1, \ldots, S\} : \text{set of slot requests, indexed by } i \text{ or } j \]
\[ S_{arr} (\text{resp. } S_{dep}) \subset S : \text{set of arrivals (resp. departures)} \]
\[ P \subset S \times S : \text{set of pairs } (i, j) \in S \times S \text{ such that there is a connection between } i \text{ and } j \]
\[ C = \{1, \ldots, C\} : \text{set of capacity time scales, indexed by } c \]
\[ K = \{1, \ldots, K\} : \text{set of terminal capacities} \]

**Parameters**

\[ A_{it} = \begin{cases} 1, & \text{if slot } i \text{ is requested to operate no earlier than period } t \\ 0, & \text{otherwise} \end{cases} ; \]
\[ B_{id} = \begin{cases} 1, & \text{if slot } i \text{ is requested to operate on day } d \\ 0, & \text{otherwise} \end{cases} \]
\[ C^{dep}_{tdc} (\text{resp. } C^{arr}_{tdc}, C^{T}_{tdc}) = \text{departure (resp. arrival, total) declared capacity at the airport in period } t, \text{ day } d \text{ and time scale } c \]
\[ C^{term}_{tdc} = \text{terminal capacity } k \text{ in period } t, \text{ day } d \text{ and time scale } c \]
\( C_{td}^{\text{Apr}} \) = apron capacity in period \( t \) and day \( d \)

\( L_c \) = length of time scale \( c \)

\( T^{\text{max}} \) (resp. \( T^{\text{min}} \)) = maximum decrease (resp. increase) in the connection time between \( i \) and \( j \) in relation to the requested connection time

\( S_i \) = number of seats of the aircraft requested for slot \( i \);

\( I_{ik} \) = \( 1 \), if slot \( i \) accounts for the terminal capacity \( k \)

\( 0 \), otherwise

\( L F_i \) = load factor for the flight requested by slot \( i \)

**Decision Variables**

\( Y_{it} \) = \( 1 \), if slot \( i \) is rescheduled to operate no earlier than period \( t \)

\( 0 \), otherwise

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

\( W_i^+ \) (resp. \( W_i^- \)) = \( 1 \), if slot \( i \) is displaced for a later (resp. earlier) time

\( 0 \), otherwise

\( Q_{td} \) = Number of aircraft in the apron during period \( t \) and day \( d \).

\( N_{id} \) = Number of aircraft needed in the apron in the first period of day \( d \)

**Model Formulation**

\[
\begin{align*}
\min w_1 \max_{i \in S} \left( X_i^+ + X_i^- \right) + w_2 \sum_{i \in S} \sum_{d \in D} \left( X_i^+ + X_i^- \right) \times B_{td} + \sum_{i \in S} \sum_{d \in D} \left( W_i^+ + W_i^- \right) \times B_{td} \\
\end{align*}
\]

\( w_1 \) (1)

\[
\begin{align*}
\min w_1 \max_{i \in S} \left( X_i^+ + X_i^- \right) + w_2 \sum_{i \in S} \sum_{d \in D} \left( X_i^+ + X_i^- \right) \times B_{id} + \sum_{i \in S} \sum_{d \in D} \left( W_i^+ + W_i^- \right) \times B_{id} \times S_i \\
\end{align*}
\]

\( w_2 \) (1a)

\[
\begin{align*}
Y_{it} = 1 \quad \forall i \in S \quad (2)
\end{align*}
\]

\[
\begin{align*}
Y_{it} \geq Y_{i,t+1} \quad \forall i \in S, t \in T \quad (3)
\end{align*}
\]

\[
\begin{align*}
\sum_{t \in T} (1 - A_{it}) Y_{it} = X_i^- \quad \forall i \in S \quad (4)
\end{align*}
\]

\[
\begin{align*}
\sum_{t \in T} A_{it} Y_{it} = X_i^+ \quad \forall i \in S \quad (5)
\end{align*}
\]

\[
\begin{align*}
W_i^+ \geq Y_{it} - A_{it} \quad \forall i \in S, t \in T \quad (6)
\end{align*}
\]
Equation (1) formulates the multi-objective problem of minimizing the maximum slot displacement, the total displacement and the number of slots displaced. The first two objectives are weighted by user-defined scalars \( w_1 \) and \( w_2 \), as discussed in Section 3.1. Equation (1a) formulates an alternative objective function that replaces equation (1) in Section 4.2.2, to consider the number of passengers as weight for the displacement. This new objective function formulates the multi-objective problem of minimizing the maximum slot displacement, the total number of passenger-minutes of displacement and the number of passengers suffering nonzero displacement.

Constraints (2) ensure that all the slots requested are allocated to some period. Constraints (3) ensure that the variables \( Y \) are non-increasing in \( t \), which is consistent.
with their definition. Constraints (4) to (7) define the logical relationships between the variables (i.e., each slot request can be either scheduled at the requested time, displaced to a later slot, or displaced to an earlier slot). Constraints (8), (9) and (10) ensure that the airport capacities for arrivals, departures and total number of movements are never exceeded over any day $d$. Constraints (11) ensure that the number of passengers in the terminals of the airport never exceeds their capacities. Constraints (12), (13) and (14) ensure that the number of aircraft in the apron never exceeds their capacity. Constraints (15) and (16) ensure that the time between two connected flights does not increase/decrease by more than the allowable limits. Finally, Constraints (17) and (18) specify the domain of definition of the decision variables.