A Modelling Framework for Solving the Network-Wide Airport Slot Allocation Problem

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1 INTRODUCTION

Many airports around the world are overly congested. These airports are classed as coordinated airports and access to these airports is controlled through the International Air Transport Association Worldwide Airport Slot Guidelines (IATA WASG) (IATA, 2021). The capacity of coordinated airports is expressed in slots. A slot is defined as a time interval during which airlines can have access to the airport infrastructure to operate their flights. Therefore, airlines submit slot requests for each scheduling season. An independent coordinator allocates slots to requests using a set of rules described in IATA WASG aiming to satisfy the submitted requests as close as possible to their requested time by minimizing slot displacement, i.e., the difference between the requested and allocated time. A similar process is followed for the facilitated airports, for which there is a potential for congestion only during some periods of the day, week, or season, and the necessary adjustments are made by the facilitators, similar to the coordinators at coordinated airports (IATA, 2021).

The slot allocation problem has been studied for single airports and at network level. Single airport models (Zografos et al., 2012; Ribeiro et al., 2018) allocate slots independently at each airport without taking into account network level interactions. Network level models, on the other hand, allocate slots simultaneously to all airports to capture the inherent flight connectivity interactions throughout the network (Pellegrini et al., 2017; Benlic, 2018). Existing network level slot allocation models use as input the requests made by the airlines at each individual airport and extend the single airport models by introducing flight connectivity constraints to ensure network-wide flight schedule compatibility. Owing to the complexity of the network level problem, the proposed network level formulations use simplified approaches, e.g., consider only primary slot allocation criteria, do not capture the interaction between airport airside and terminal capacity constraints, and do not capture peculiarities of the slot allocation process emerging from the local interpretation of the IATA WASG.

In this paper, we are introducing a novel approach in modeling network level slot allocation. In contrast with existing models, our modeling approach is using as input the initial schedules that have been generated at each individual airport and optimally adjusts them to ensure network-wide flight connectivity. Thus, the proposed approach mirrors better the current network-wide practice. It ensures the autonomy of the slot allocation process at each individual airport and affords the generation of context specific individual airport schedules, while guaranteeing the network-wide flight connectivity. Another important feature of the proposed approach is the incorporation of the connectivity importance of each airport in optimizing the adjustment of the schedules of the individual airports. This modeling feature can assist decision makers to allocate the cost of the network-wide schedule adjustment (total schedule displacement) among the airports by ensuring that the schedules of key airports will not be overly disturbed.

2 NETWORK WIDE SLOT ALLOCATION MODELLING AND SOLUTION FRAMEWORK

We propose a framework where the slot allocation at each individual coordinated airport is performed first (as it also happens in practice) by considering the IATA WASG and the complexities and peculiarities associated with the allocation of slots at each airport. The schedules of the individual coordinated airports are then used to allocate the slots at network level, such that capacity limits of each airport, turnaround times for the aircraft, and flight times are respected. The allocation of slots at network level is achieved by ensuring network-wide flight connectivity while optimizing objective(s) expressing the network-wide slot allocation performance. In this paper we are introducing two bi-objective optimization models. Model 1 considers the minimization of the: i) total displacement encountered by all flights throughout the network (network-wide schedule efficiency), and ii) maximum displacement, i.e., interflight-equity. Model 2 considers the optimization of the network-wide schedule efficiency as in the case of the first model, while the second objective optimizes the inter-airline fairness by allocating the total network-wide displacement to all airlines proportionally to the number of their requested slots at all coordinated airports. For both models we are introducing variants that: i) do not consider the importance of the airports in ensuring the network connectivity, ii) incorporate the connectivity importance of the airports through the consideration of alternative connectivity indices.

2.1 Incorporating Airport Importance

Although there are several indices to quantify the importance of an airport in the air transport network, we focus on two measures. The first is the betweenness centrality measure (Guimera et al., 2005), which is defined as the ratio of number of shortest paths connecting any two airports that involve a transfer at the airport in consideration to the number of all shortest paths connecting them. Each arc connecting two airports in the network represents a direct flight between these airports and can be assigned a weight to illustrate the characteristics of the airports' relationship. We use the number of flights throughout the season as the weight of an arc, and define its distance as the reverse of its weight. The shortest paths between two airports are calculated using these distances. Betweenness centrality is a measure showing the potential of an airport to funnel the flow of the flights in the network, and is calculated for airport i as follows:

$$c_i = \sum_{j,k \in A | j,k \notin A} \frac{g_{jk}(i)}{g_{jk}} \tag{1}$$

where A is the set of airports, and g_{jk} and $g_{jk}(i)$ stand for the number of shortest paths between airports j and k, and among them, the number of those that include a stop at airport i, respectively (Guimera et al., 2005).

The second measure we use is the connectivity index proposed by IATA (2020). It is a measure of the degree of integration of an airport into the network in terms of number of passengers travelling. It is mathematically expressed for airport i as follows:

$$CI_i = \sum_{j \in D_i} s_{ij} w_j \tag{2}$$

where D_i is the set of airports to which there is a direct flight from airport i, and s_{ij} and w_j stand for the total number of seats belonging to the flights from airport i to j and the size of airport j in terms of number of passengers handled, respectively.

2.2 Proposed Solution Approach

To solve the proposed bi-objective models and generate the associated efficient frontiers, we use the ε −constraint method (Ehrgott, 2005). The algorithmic framework for Model 1 is presented in Algorithm 1. A similar approach is followed for Model 2 with different objective functions.

Algorithm 1: Description of the proposed solution framework

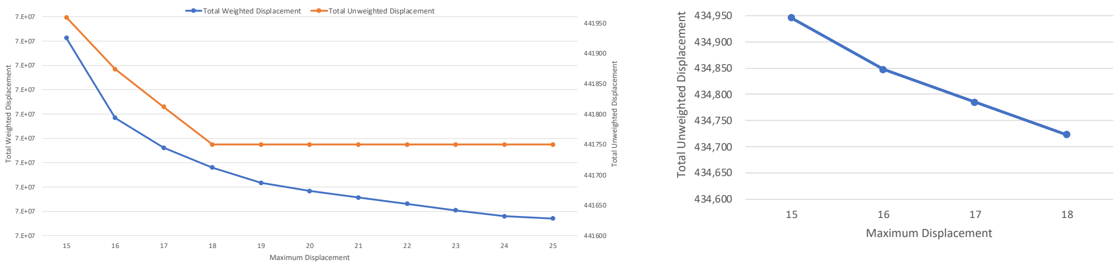
Input: Mathematical model for the bi-objective problem, airport schedules obtained from the single airport slot allocation models, airport importance measures

1. Solve the model using a single objective to minimize the total displacement
2. Let Δ_{single} be the optimal total displacement
3. Solve the model using a single objective to minimize the maximum displacement
4. Let z_{single} be the optimal maximum displacement
5. Initialize ε: $\varepsilon \leftarrow z_{single}$
6. Solve the model using a single objective to minimize the total displacement with an additional constraint $z \leq \varepsilon$, where z is the maximum displacement
7. Let Δ be the optimal total displacement
8. Store the total and maximum displacement information of this solution
9. Update ε with a step size δ: $\varepsilon \leftarrow \varepsilon + \delta$
10. Repeat Step 6 until $\Delta = \Delta_{single}$
11. Construct the efficient frontier with the stored solutions obtained in Step 8

Output: Network-wide schedules to be evaluated and selected using the key performance indicators

3 RESULTS AND DISCUSSION

We present the results from the application of Model 1, which seeks to minimize the total displacement and the maximum displacement received by any flight, to an instance that includes 56 airports, 16 of which are either coordinated or facilitated airports and the network has 479,307 flights in total. We use the default settings of CPLEX 12.10 solver on a workstation with Intel Xeon E5 2.60 GHz processor and 32 GB RAM. We perform two sets of experiments by weighting the displacement by the betweenness centrality measures (case 1) and without weighting the displacement (case 2). Figure 1 shows the trade-off between maximum displacement and total displacement, where the displacements are reported in 5-minute time intervals, for the two cases under consideration. For both cases, we observe that there is not a strong trade-off between the maximum and total displacements, i.e., increasing the maximum displacement does not pay off regardless of whether the airport importance coefficients are used or not. Specifically, when the displacements are weighted by the betweenness centrality measures, a 66.7% increase in the maximum displacement results in an improvement of 5% in total weighted displacement, while the number of displaced flights is decreased from 137,082 to 136,021. Similarly, when the displacements are not weighted, the improvement in total displacement is only 0.05% when the maximum displacement is increased by 20%, from 15 to 18 intervals, corresponding to 15 minutes, while the number of displaced flights decreased from 139,689 to 139,321. Furthermore, we observe that the resulting total displacement values are similar between the two analyzed cases. However, the airports are affected differently depending on their importance profiles. For instance, in the schedules with maximum displacement of 15 intervals, which is equivalent to 75 minutes, when the displacements are weighted by the betweenness centrality measures, the airport with the highest centrality value receives only 6% of the total actual displacement, whereas when the displacements are not weighted, this airport is allocated 32% of the total actual displacement. These results shed lights on the decision making process regarding the adjustments to the initial slot allocations. If the decision makers would like to prioritize some of the airports, then using airport importance coefficients makes sure that "important" airports receive less displacement.



a. Using betweenness centrality measures b. Not using the centrality coefficients

Figure 1 – *Trade-offs between maximum and total displacements*

Work under way includes i) incorporating airport importance using the IATA connectivity indices and analyzing the trade-off between total and maximum displacements through Model 1, and ii) analyzing the trade-off between slot allocation efficiency and fairness both at airport and airline level through solution of Model 2 using both importance measures proposed.

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