Modelling and Solving the Airport Slot Scheduling Problem with Efficiency, Fairness, and Accessibility Considerations

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1. Introduction

The rapid growth of air transport demand coupled with inadequate provision of airport capacity has led to serious imbalance between demand for airport services and supply of the required airport resources. As a result, 170 of the busiest airports worldwide are schedule coordinated airports (IATA, 2014a). According to the IATA World Scheduling Guidelines (WSG), an airport is coordinated when the demand exceeds its capacity and its infrastructure cannot be expanded in the short term to meet the demand (IATA, 2014b).

Slots are used to express the capacity of schedule coordinated airports. Airport slot scheduling provides the means of managing effectively airport capacity. A commonly used metric for assessing airport scheduling efficiency is schedule delay or schedule displacement which is defined as the difference between the requested and actually allocated slot time. (Koesters, 2007; Zografos et al., 2012; Corolli et al., 2014; Jaquillat and Odoni, 2015). However, in addition to schedule efficiency, fairness and accessibility are metrics that can be used for lot scheduling.

The objective of this paper is to develop and solve a new airport slot scheduling model that considers simultaneously schedule efficiency, schedule fairness and airport accessibility objectives. Two alternative formulations are proposed. In the first formulation, the schedule displacement (schedule delay) metric is used to express schedule efficiency. In the second formulation, a weighted displacement metric is introduced to express schedule efficiency. The proposed metric weights the schedule displacement by aircraft seat capacity and flight distance. In both formulations we are using a schedule fairness metric which postulates that the schedule displacement for each aircraft operator (airline) should be proportional to the number of slots the specific airline has requested. The airport accessibility objective is modelled as a constraint which requires that a minimum number of slots should be allocated to airlines providing connections to small remotely located airports.

2. Model formulation

This section presents two integer programming formulations. The following notation is adopted. Let $T = \{0, ..., n-1\}$ be the set of coordination time intervals. The set of movements is denoted by M. For each movement m, the aircraft seat capacity, flight distance, and originally requested time interval are given by f_m, d_m, and t_m, respectively. Let P be the set of movement pairs and $\left(m_{arr}^p, m_{dep}^p\right) \in P$, such that m_{arr}^p is the arrival movement for movement pair p and m_{dep}^p is the corresponding departure movement. The minimum turnaround time corresponding to movement pair p is given by ω^p. Let A be the set of airlines and M_a be the set of movements requested by airline a. The set of movements connecting small remotely located airports from airline a is denoted by R. The minimum number of slots that must be satisfied for set R is specified by r. Denote by C the set of airport capacity constraints, where each constraint c starts from time interval τ_c and lasts δ_c consecutive intervals. The set of consecutive coordination time intervals over which constraint c is checked is denoted by $T_c = \{t \in T \mid \tau_c \leq t < \tau_c + \delta_c\}$. For constraint c, the declared capacity is u_c, and movement m consumes b_{mc} units declared capacity. Denote x_m^s to be one if movement m is allocated to interval t, zero otherwise. The bi-objective model with fairness, efficiency, and accessibility considerations is written as follows:

$$\min_{\mathbf{x}=\left[x_m^s\right]} Z^1(\mathbf{x}) = \left(\overbrace{\frac{1}{|A|}\sum_{a\in A}\left(\rho_a - \frac{\sum_{a'\in A}\rho_{a'}}{|A|}\right)^2}^{\text{Fairness}}, \overbrace{\sum_{m\in M}\sum_{t\in T}\left|t-t_m\right|x_m^t}^{\text{Efficiency}} \right)^T \tag{1}$$

Where:

$$\rho_a = \frac{\dfrac{\sum_{m\in M_a}\sum_{t\in T}\left|t-t_m\right|x_m^t}{\sum_{m\in M}\sum_{t\in T}\left|t-t_m\right|x_m^t}}{\dfrac{|M_a|}{\sum_{a\in A}|M_a|}}, \forall a \in A \tag{2}$$

subject to:

$$\sum_{m\in R}\sum_{t\in T_m} x_m^t \geq r \tag{3}$$

$$\sum_{m\in M}\sum_{t\in T_c} b_{mc}x_m^t \leq u_c, \forall c \in C \tag{4}$$

$$\sum_{t\in[0,k)} x^t_{m^p_{arr}} + \sum_{t\in[k-\omega^p,n)} x^t_{m^p_{dep}} \leq 1, \forall\left(m^p_{arr}, m^p_{dep}\right)\in P, k\in[\tau^p, n) \quad (5)$$

$$\sum_{t\in T} x^t_m = 1, \forall m\in M \quad (6)$$

$$x^s_m \in \{0,1\}, \forall m\in M, s\in T \quad (7)$$

The objective function (1) minimises the schedule delay as well as the variance of the fairness indicators for all airlines. Equation (2) expresses the fairness indicator for each airline. The denominator is the proportion of slots requested by an airline. The numerator is the proportion of schedule delays allocated to the airline. If $\rho_a = 1.0$, it means that the schedule delay experienced by airline *a* is proportional to the number of slots requested by this airline; otherwise it implies that airline *a* is allocated disproportional delay (either higher or lower schedule delay than the delay corresponding to the proportion of requested slots). Due to constraints (3) - (5), in general, it is not possible to achieve completely proportional schedule delay allocation. Therefore, the variance of ρ_a is used in (1) to express the fairness objective.

Equation (3) is the accessibility constraint that guarantees a minimum number of slots will be allocated to the flights connecting small remotely located regional airports with a major airport. T_m denotes the displacement (expressed in number of intervals) that an airline is willing to accept for the scheduling of flights connecting small remotely located airports with the hub airport under consideration, in case the initially made requests are displaced. The value of T_m can be the outcome of the negotiation between the airlines requesting slots to connect small remotely located airports and the rest of the airport stakeholders. The value of T_m should be set in such a way as to ensure feasibility for the problem under consideration. Equation (4) requires that the total number of movements scheduled during a given time interval cannot exceed the corresponding available capacity. Equation (5) expresses the aircraft turnaround time constraint and it requires that the time interval between the arrival and departure slot is greater than or equal to the aircraft turnaround time. Equation (6) stipulates that every movement must be allocated to only one time interval. For comprehensive discussions on the schedule delay objective and constraints (4) - (6), we refer to the model developed in Zografos et al. (2012).

In the second model, the efficiency measure used in (1) is replaced by a new efficiency metric that weights the displacement by aircraft size (number of seats per aircraft), and flight distance. The second model is expressed as follows:

$$\min_{\mathbf{x}=\left[x^s_m\right]} Z^2(\mathbf{x}) = \left(\overbrace{\frac{1}{|A|}\sum_{a\in A}\left(\rho_a - \frac{\sum_{a'\in A}\rho_{a'}}{|A|}\right)^2}^{\text{Fairness}}, \overbrace{\sum_{m\in M}\sum_{t\in T}\left|t-t_m\right| x^t_m f_m d_m}^{\text{Weighted efficiency}} \right)^T \quad (8)$$

subject to: Equations (3) to (7)

3. Concluding remarks

The existence of a feasible solution to the proposed models depends on the airport declared capacity profile. In order to guarantee feasibility, a dummy interval which allows sufficiently large schedule displacement is introduced. The model is solved hierarchically as in the case Zografos et al. (2012) giving the highest priority to the requests of airlines that have Grand Father Rights (IATA, 2014b), followed by the optimisation of slot requests of new entrants. Results obtained from the application of the proposed models to real world problem instances demonstrate the trade-off between the efficiency and fairness. Sensitivity analyses provide useful information on the relationship between declared capacity and schedule delay. The proposed models were applied to allocate slots in a medium size coordinated airport in order to compare the quality of the solutions and the computational performance of the different models.

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