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A robust approach to airport gate assignment with a solution-dependent uncertainty budget

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ABSTRACT

Airport gate assignment (AGA) is a critical issue for airport operations management. It aims to assign flights to gates according to their arrival and departure times. To tackle flight delays in airports, we propose a robust airport gate assignment (RAGA) to minimize the $(1-\alpha)$-quantile of the total real-time overlap between consecutive flights at the same gate, namely, the total gate blockage time, so that the realized total gate blockage time is worse than its quantile with a probability, at most α. Given any constant, we develop an asymptotically tight upper bound for the violation probability that total gate blockage time is worse than the constant. Based on the upper bound, a solution-dependent uncertainty budget is introduced to develop a robust counterpart (RCP) for the RAGA. We further develop a solution technique for the RCP by transforming the problem into a finite number of tractable binary programmings. An empirical study of the Shuangliu International Airport (CTU) indicates that our proposed robust approach for AGA outperforms existing methods.

1. Introduction

Airport gate assignment (AGA) is a critical issue for airport operations management. In practice, flights are assigned to gates according to their schedules, that is, their scheduled arrival and departure times. With the increase in air traffic in the past decades, the significance of the assignment task has drawn more and more attention.

From arrival to departure, a flight needs to complete three activities: arrival, parking and departure. Each activity can be assigned to a distinct gate. Meanwhile, airports essentially consist of two types of gates: boarding gates and remote stands. For flights with short parking times, the three activities usually take place at one boarding gate. In comparison, for flights with long parking times, especially those overnight flights, parking takes place at a remote stand. Activities for a single flight assigned to different gates are accomplished by towing the aircraft. For simplicity of notation, we take each activity of a flight that can occupy different gates as three distinct flights, with each activity having its scheduled arrival time equal to its activity starting time and its departure time equal to its activity finishing time. The airport control tower typically locks the gate for a flight at its arrival time and releases the gate at its departure time.

Thus, a feasible AGA must satisfy the following two constraints:

1. Each flight (or activity) is assigned to exactly one gate.

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Table 1
Descriptive statistics of flight delays in CTU (min).

Statistics	Min	1st-Quartile	Median	Mean	3rd-Quartile	Max	Standard deviation
	−37	9	20	24	36	105	23

2. No two flights (or activities) can be assigned to the same gate concurrently according to their schedules.

However, in real-time operations, flight delays often occur. This situation is deteriorating in Chinese airports. For instance, according to a BBC report, in June 2017, among 344 airports around the world, the 12 airports with the lowest on-time rates are all in China. In terms of airlines, the three largest airlines in China, i.e., Air China, China Eastern, China Southern Airlines, have on-time rates within the range of 75%–80%, compared to the rate within the range of 94%–98% for Japanese Airline, the largest airline in Japan. Table 1 illustrates the flight delay statistics for Chengdu Shuangliu International Airport (CTU). Note that, excluding the outliers with a delay time of more than 105 min, the median flight delay is 20 min and the standard deviation is 23 min.

Therefore, considering real-time flight delays, we model the departure time of a flight as a random rather than a deterministic parameter, and design a robust airport gate assignment (RAGA) framework to protect the system from operational uncertainty. Our RAGA framework guarantees that the airport has no conflict in flight schedules, and that the $(1-\alpha)$-quantile of the total gate blockage time is minimized, i.e., the real-time total gate blockage time is greater than the resulting quantile with a probability at most α. In daily operations, once a flight is heavily delayed, it has to comply with re-assignment rules. Therefore, in our AGA model, we consider only those flights with a delay time no greater than 105 min.

AGA can be described as follows. Consider m gates and all gates have a uniform service starting time s and service finishing time t $(0 \le s < t \le 24)$. Consider a flight set $F = \{1, \dots, n\}$ of n flights, in which each flight i has a scheduled arrival time a_i and a scheduled departure time d_i $(s \le a_i < d_i \le t)$. Let $\tilde{d}_i$ denote the real-time departure time for flight i. Accordingly, let

$$\tilde{l}_{ij} = \begin{cases} 0, & a_j - d_i < 0; \\ \max\{0, \tilde{d}_i - a_j\}, & \text{otherwise}, \end{cases}$$

denote the real-time overlap between any two flights. According to the definition of $\tilde{l}_{ij}$, the real-time overlap has a non-negative value, and the value for the real-time overlap indicates the duration of the minimum delay for flight j due to gate conflict. If $a_j - d_i < 0$, indicating that flight j and flight i have a conflict according to their schedules, then the two flights are not assigned to the same gate for any feasible solution, and contribute zero total gate blockage time. If $a_j - d_i \ge 0$, then the real-time overlap between the two flights equals the real-time departure time for flight i minus the scheduled arrival time of flight j. The reason why we use the scheduled arrival time rather than the real-time arrival time of flight j is that the control tower locks the gate at a_j rather than $\tilde{a}_j$ in its operations management. We define a feasible solution to AGA as: n sequences, $\{S_1, \dots, S_n\}$, which consist of all elements of F, and each element of F appears exactly once in a sequence; there is no scheduled gate conflict between two consecutive flights assigned to the same gate, which implies that, for any two consecutive elements i and j in a sequence, the scheduled overlap $l_{ij} \le 0$, where $l_{ij} = d_i - a_j$.

1.1. Related work

Concerning airport stands, Ravizza et al. (2014) provided a realistic approach for airport ground movement optimization with stand holding. In Narciso and Piera (2015), a simulation-based experimental approach that evaluates the minimum number of stands at the terminal necessary to cope with the arrival/departure pattern traffic under a time delay limit was presented.

In the literature, AGA with the objective of minimizing the total walking distance of customers has been extensively researched. This type of problem has been studied by Mangoubi and Mathaisel (1985), Babić and Teodorović (1984), Xu and Bailey (2001), Zhu et al. (2003), Ding et al. (2005) and Haghani and Chen (1998) with binary integer programming, tabu search, and generic algorithm. For the assignment problem with the objective of minimizing total number of gates based on the cost of gates and delays, Wirasinghe and Bandara (1990) proposed a closed-form approximation.

An AGA with multiple objectives was formulated by Yan and Huo (2001) as multi-objective binary programming, and was solved by the simplex method, column generation and branch and bound technique. For a deterministic AGA, buffer times between two flights were adopted by Hassounah and Steuart (1993), and Yan and Chang (1998) to avoid real-time flight conflicts. Yu (1997) proposed a knowledge-based AGA system integrated with mathematical programming techniques to provide both static and dynamic solutions within a reasonable computing time. Gosling (1990) designed an expert system which considers multiple factors and rules. Cheng et al. (2012) assessed the performance of three meta-heuristics, namely, genetic algorithm, tabu search, simulated annealing and a hybrid approach in AGA. AGA with time windows was investigated by neighborhood moves in tabu search and memetic algorithms (Lim et al., 2005). Guépet et al. (2015) dealt with the AGA with the objective of maximizing the number of passengers/aircraft at contact stands and minimizing the number of towing movements.