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An adaptive large neighborhood search heuristic for solving a robust gate assignment problem

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ABSTRACT

With the rapid growth of air traffic demand, airport capacity becomes a major bottleneck within the air traffic control systems. Minor disturbances may have a large impact on the airport surface operations due to the overly tight schedules, which results in frequent gate conflict occurrences during airport's daily operations. A robust gate schedule that is resilient to disturbances is essential for an airport to maintain a good performance. Unfortunately, there is no efficient expert system available for the airport managers to simultaneously consider the traditional cost (the aircraft tow cost, transfer passenger cost) and the robustness. To fill this gap, in this paper, we extend the traditional gate assignment problem and consider a wider scope, in which the traditional costs and the robustness are simultaneously considered. A mathematical model is first built, which leads to a complex non-linear model. To efficiently solve this model, an adaptive large neighborhood search (ALNS) algorithm is then designed. We novelly propose multiple local search operators by exploring the characteristics of the gate assignment problem. The comparison with the benchmark algorithm shows the competitiveness of proposed algorithm in solving the considered problem. Moreover, the proposed methodology also has great potential from the practical perspective since it can be easily integrated into current expert systems to help airport managers make satisfactory decisions.

1. Introduction

During the past thirty years, the air transport traffic has roughly doubled. Because of the hub-and-spoke structure of air traffic network, most of hub airports are run close to the capacity. As a result, minor disturbances can cause large-scale delays in the overall air traffic system. A major consequence is that flights have to be rescheduled. One negative impact of the flight schedule variation on terminal area is the gate conflict, which occurs when two or more aircraft are expected to use a common gate at the same time. Maintaining a stable gate operation is very important as gate connects air-side and land-side at the airport. On the air-side, gate provides service during aircraft's parking. On the land-side, passengers wait, board, disembark, and transfer near the gate area. This indicates that the gate assignment plans insensitive to disturbances are beneficial with respect to both aircraft operating cost and passenger satisfaction level. Therefore, in this study we focus on creating a gate assignment plan taking possible future disturbances into consideration.

Gate assignment problem (**GAP**) is to assign a gate to the flight *activities* (include arrival, parking, and departure) for a set of aircraft. A typical hub airport has over one hundred gates and more than one thousand flight activities at an operation day. The typical objectives of GAP include maximizing one-day throughput of the airport, maximizing airline preference, minimizing towing time, etc. In addition, passenger service satisfaction level (affected by waiting time and transfer distance) is tightly related to airline revenue, and thus should also be considered.

In the literature, the static gate assignment problem, in which possible variations are not taken into account when making decisions, has already attracted a lot of attention. For example, Hu and Di Paolo (2007) proposed a genetic algorithm to solve multi-objective gate assignment problem. Drexl and Nikulin (2008) proposed a simulated annealing heuristic to solve a multi-objective variation that aims to minimize the number of ungated fights and total passenger walking distance, and meanwhile maximizing the total preferences. Based on this research, the authors further incorporated another objective to minimize the absolute deviation

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of the new gate assignment from a so-called reference schedule, which was then solved by a tabu search heuristic (Nikulin & Drexl, 2010). A stochastic neighborhood search approach was proposed to minimize the duration of all ungated flights by Genc, Erol, Eksin, Berber, and Güleryüz (2012). Ramp congestion and taxi time were integrated when making gate plans in Kim, Feron, and Clarke (2013); Neuman and Atkin (2013), where tabu and genetic algorithms were adopted as solution approaches. Marinelli, Dell'Orco, and Sassanelli (2015) proposed a bee colony optimization algorithm to minimize passenger total walking distance and remote gate usage. Guépet, Acuna-Agost, Briant, and Gayon (2015) proved that GAP is NP-hard by a reduction from circular arc graph coloring problem. A comprehensive review for GAP and some of its extensions can be found in Dorndorf, Drexl, Nikulin, and Pesch (2007).

To deal with the disrupted situations, some researches consider a *gate reassignment problem* (**GRP**), which aims to recover the disturbed schedule while maintaining a minimal deviation from the original one (Maharjan & Matis, 2011; Tang, 2011; Tang, Yan, & Hou, 2010; Yan, Chen, & Tang, 2009; Zhang & Klabjan, 2017). This reassignment plan is usually only conducted when large disruptions occur. However, such recovery processes are likely to result in additional costs and a waste of resources, and recovery measures generally cannot push the schedules back to normal completely.

Compared with GRP (which a reactive action), making a schedule that is insensitive to minor disturbances is more beneficial to the whole airport's performance. Seeing this requirement, recent researches considered *robustness* in making gate assignment plans. Dorndorf et al. (2007) modeled a robust gate assignment problem with three objectives, one of which is to avoid the assignment of two flights with low buffer times to the same gate. Specifically, each buffer time between two successive assignments are scheduled as close as possible to a predefined threshold. Based on this work, the authors further considered a deviation of the resulting solutions with respect to a reference schedule (Dorndorf, Jaehn, & Pesch, 2012). Seker and Noyan (2012) introduced a stochastic programming formulation to incorporate stochastic disruptions. Castaing et al. (2016) considered four different objective functions representing four different measures of robustness, and then evaluated them using real-world data. In our previous work (Yu, Zhang, & Lau, 2016), several math-heuristics have been proposed and tested in the context of robust GAP, while the methods cannot solve practical-size instances efficiently.

To the best of our knowledge, there is no paper simultaneously considered robustness, cost induced during tows, and passenger transfer distance. As discussed aforementioned, these three factors are all very important to a favorable assignment plan, and a good plan should make a good trade-off among the three factors. To fill this gap, in this paper, we consider a GAP that takes three cost factors in the objectives, namely, (i) *conflict cost* that measures the robustness of the original schedule as well as the effort saved to re-schedule the original assignment; (ii) *tow cost* that measures the staff and facility cost required when changing the position of aircraft; and (iii) *passenger transfer cost* that measures the passengers' satisfaction level. An *adaptive large neighborhood search* (**ALNS**) heuristic is proposed to solve this problem efficiently. The major contributions are listed as follows:

- We propose a comprehensive gate assignment model, in which robustness, aircraft tow and transfer passengers are simultaneously considered;
- An efficient ALNS heuristic for solving the robust GAP model is proposed. Considering the problem characteristics, we propose multiple deconstruction and construction operators;
- Extensive numerical studies are conducted to validate the high efficiency and effectiveness of the proposed approach over the tabu search algorithm.

Table 1
Notations.

Sets and Parameters	
$\mathcal{A}$	Set of arrival activities, indexed by i and j
$\mathcal{P}$	Set of parking activities, indexed by i and j
$\mathcal{D}$	Set of departure activities, indexed by i and j
$\mathcal{G}$	Set of gates, indexed by k
Δ_{ij}	Separation time between activity i and j
$\sigma(i)$	Successive activity of i
N_{ij}	Number of passengers transferring from flight i to j
D_{kl}	Distance between gate k and l
S_i	Start time of activity i
E_i	End time of activity i
C^{TOW}	Unit cost of a tow
α, β, γ	Weight coefficient for objectives
Decision Variable	
x_{ik}	$= 1$, if activity i is assigned to gate k, $= 0$ otherwise

This paper is organized in the following manner. In Section 2, we describe the background and the formulations of the robust GAP considered in this paper. In Section 3 the ALNS heuristic is described in detail. Section 4 shows the extensive numerical studies. Section 5 concludes the paper and provides some future directions for research on this topic.

2. Problem description

In this section, we present a formal specification of the robust GAP, based on which the robust GAP model and an ALNS algorithm are proposed in the following sections. There are three objective components: robustness measured by the expected conflict cost, tow cost, and passenger transfer distance. The denotations used in this paper are described in Table 1.

The robust GAP considered in this paper aims to schedule the activities of a set of aircraft $\mathcal{F}$ near the terminal. The whole turnaround time for an aircraft at the terminal area is divided into three periods: an arrival activity, a parking activity and a departure activity. An arrival activity is counted from gate reaching time to the end of the disembarking process. A departure activity is counted from the start of boarding process to off-block. A parking activity includes the time between the arrival activity and departure activity. Arrival and departure activities are also called (arrival and departure) flights in this paper.

- **Expected conflict cost**: The conflict duration is the overlapped time between successive flights assigned to the same gate. Under normal conditions, conflict duration should be zero. When the departing aircraft is postponed or the arriving aircraft reaches the gate earlier, a gate conflict occurs. The expected conflict duration among all flights at the gate is used to measure the robustness of a gate assignment plan. A high robustness is achieved when the expected conflict duration is low among aircraft. The flight delay usually follows some pattern at an airport due to the specific infrastructure conditions, positions in the air traffic networks and the original schedules. We analyzed the delay data in HKIA from 5 May to 8 May 2014 with 2191 arrivals and 2253 departures and found both arrivals and departures follow a log-normal distribution. Then the expected conflict duration between an arrival and a departure is approximated to an exponential function of the scheduled separation time.

$$z^{CFT} = \sum_{i \in \mathcal{D}, j \in \mathcal{A}} f(\Delta_{ij}) \sum_{k \in \mathcal{G}} x_{ik} x_{jk} \tag{1}$$

in which

$$f(\Delta_{ij}) = a \cdot b^{\Delta_{ij}} \tag{2}$$