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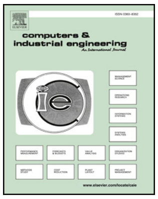

Mathematical models for flight-to-gate reassignment with passenger flows: State-of-the-art comparative analysis, formulation improvement, and a new multidimensional assignment model

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A B S T R A C T

This study explores the mathematical programming formulation of Flight-to-Gate Reassignment with passenger connections, one of the most critical problems in airport and airline recovery operations. Motivated by the intractable increase in problem size when passenger flows are considered, combined with the need for low solution time, we perform three main tasks: (a) We compare and analyze both theoretically and experimentally the different types of state-of-art formulations, and identify the limitations of each one. (b) We improve the performance of existing models by modifying their formulations and introducing valid inequalities. (c) We propose a novel mathematical formulation that accounts for passenger connections considering the layout of the airport and the available time between connecting flights. For the purpose of our experiments, we generate a number of cases of various sizes and schedule scenarios, as well as a set based on a real European airport. We then use our results to identify the most efficient formulations under different objective functions and problem assumptions. We expect that our work can provide researchers with a valuable tool for formulating efficient models that can be embedded in mathematical programming-based heuristics.

1. Introduction

One of the most critical airport management problems is the Gate Assignment Problem (GAP), which deals with the optimal allocation of flights to gates. Optimality is defined according to a variety of cost factors regarding both the schedule of airport operations and the desired level of service provided to passengers. A specific case of the Gate Assignment Problem is the Gate Reassignment Problem (GRAP), which refers to the re-allocation of flights to gates in real time when delays and other types of disruptions make the original schedule infeasible or impractical.

The concept of passenger flows plays a major role in the aircraft-to-gate reassignment problem, with different types of passengers generating different flow patterns: For example, passengers whose trip begins at the airport generally move from the entrance to the gate of the departing flight; passengers whose trip ends at the airport move from the gate of their arriving flight to the airport exit. Finally, connecting passengers move from the gate of the arriving flight to the gate of the departing flight of their transfer. In every case, flow patterns, as well as the resulting walking distance and time, vary according to layout of the airport (e.g. terminal location, existence of people movers and moving walkways) and the processing procedures (e.g. passport control) for passengers with different origins and destinations.

Motivated by the intractable size of mathematical models which consider passenger flows, we study different types of state-of-art formulations, improve them by introducing valid inequalities, and propose a novel assignment model that considers the layout of the airport and the available time between connecting flights. Our experiments demonstrate that we achieve significant improvements in optimization time and indicate the conditions under which each formulation is preferable.

2. Literature review: Mathematical modeling of passenger flows

2.1. State-of-art overview

Literature exhibits a variety of studies on both planned and real-time gate assignment. A comprehensive survey of GAP can be found in Dorndorf, Drexl, Nikulin, and Pesch (2007). Most studies focus on planned assignment (Haghani & Chen, 1998; Dorndorf, 2002; Ding, Lim, Rodrigues, & Zhu, 2004; Lim & Wang, 2005;
Genç, Erol, Eksin, Berber, & Güleryüz, 2012; Seker and Noyan,

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2012; Neuman and Atkin, 2013; Tang & Wang, 2013; Castaing et al., 2016; Guépet, Acuna-Agost, Briant, & Gayon, 2015; Marinelli, Dell'Orco, & Sassanelli, 2015; Narciso & Piera, 2015), while the number of studies on GRAP is significantly smaller.

From a mathematical perspective, GAP and GRAP are quite similar: Researchers formulate GRAP either as an assignment model with side constraints (Tang, Yan, & Hou, 2010; Maharjan & Matis, 2011; Yan, Tang, & Hou, 2011; Wang, Luo, & Shi, 2013; Yu & Lau, 2015) or as a network flow problem (Yu & Lau, 2015; Zhang & Klabjan, 2017). Also, Dorndorf, Jaehn, and Pesch (2017) recently formulated a clique partitioning problem (CPP), which they solved using a modified Ejection Chain Algorithm.

However, few studies present exact mathematical formulations for modeling passenger flows between gates. This aspect of the solution has either been overlooked in the literature or handled indirectly. The main reason is that modeling passenger connections increases significantly the size of the problem and therefore the required computational time. The problem is more evident in cases where the operator determines not only the gate of each flight, but also the exact occupancy time interval. Here, we will focus on the assignment and network flow formulations, which are the most common ones.

2.1.1. GRAP as an assignment model

While assignment models have been used in both planned and real-time assignment, they have rarely been expanded to accommodate passenger connections. The main problem arising in this case is the increase in the size of the problem due to the introduction of quadratic constraints. Nevertheless, a study of this type that models passenger flows directly is the one by Maharjan and Matis (2011), who develop a quadratic model to minimize the total walking distance of originating and connecting passengers whose boarding passes were issued prior to gate changes.

2.1.2. GRAP as a network flow problem

In a typical network flow approach of GAP, one network is created for each gate, with nodes corresponding to time windows. A feasible flow corresponds to a sequence of flights occupying the gate throughout the planning horizon: Starting from the source, the order of the incident nodes of arcs with positive flow corresponds to the sequence of flights assigned to the gate, as well as their respective time windows. The problem is then solved as a minimum cost network flow problem.

However, the model requires extensions to capture passenger flows, as in Yu and Lau (2015) and Zhang and Klabjan (2017). The reader shall refer to these studies for details. Yu and Lau (2015) minimize the total assignment cost and maximize the number of passengers who miss their connecting flight. Their formulation relies on a single network for the whole problem with separate flow conservation constraints for each gate. To solve the problem, they iteratively divide passenger connections into a hard set and a soft set. Zhang and Klabjan (2017) build an assignment network for each gate, and a passenger network for each connection. Each network is associated with its own set of variables and constraints, while an additional set of constraints establishes the relationship between the two. The authors propose a diving and a rolling horizon heuristic. In the diving heuristic, flights are iteratively fixed in cliques, i.e. groups of neighboring gates, according to the solution of the linear relaxation, while in the rolling horizon heuristic the planning horizon is divided into smaller windows based on the number of connecting passengers.

For simplicity, in the rest of the paper, the formulations by Yu and Lau (2015) and Zhang and Klabjan (2017) will be referred to as YL and ZK, respectively.

2.2. Common modeling assumptions

In gate assignment, the decision maker (airport or airline) aims to determine the optimal allocation of flights to airport gates, subject to physical, operational and practical constraints, where optimality is defined according to the incurred monetary costs and/or the priorities of the decision maker.

Every flight can be assigned to a subset of the gates, based on criteria such as the airline, the size of the aircraft, and the type of the flight (e.g. domestic/international, or Schengen/Out-of-Schengen for international European airports). Certain studies additionally include the assignment time as a decision variable. In general, arrival and departure times are planned weeks or months in advance. However, using updated information about arrival/departure times and gate availability to modify the time when a flight begins to occupy its gate allows for more precise flight configuration. In this context, the decision maker can delay the arrival of a flight to its designated gate, or hold an outbound flight at the gate to prevent missed connections.

The planning horizon is divided into discrete time windows, each 5–10 min long; for every flight, the time window of planned arrival/departure is known in advance. Based on the airport/airline policies for maximum holding time, each flight is associated with the earliest and latest time windows at which it may start occupying a gate. The duration of gate occupancy depends on the type of the flight, the number of passengers, and the size of the aircraft, and is known in advance. As a result, every flight occupies a gate for a fixed number of consecutive time windows, the first of which is the assignment window, and is associated with two sets: (a) The set of gates to which it can potentially be assigned, and (b) The set of time windows where it can potentially be assigned.

2.3. Contributions of this research

As can be seen, even when mathematical models are developed, researchers apply heuristics to find good solutions to GRAP. Both Yu and Lau (2015) and Zhang and Klabjan (2017) develop mathematical programming-based heuristics, in the sense that they use the model formulation to obtain solution bounds by solving restricted versions of the linear relaxation based on specific branching rules. From this perspective, the development of efficient heuristics requires an appropriate formulation that can handle the modeling assumptions and restrictions of the problem in hand fast and effectively. However, developing strong mathematical formulations is an aspect of the solution that has been neglected in the context of gate reassignment, especially when passenger flows are involved.

In addition, current research on modeling passenger flows is occasionally based on unrealistic assumptions. Most importantly, with the exception of the study by Zhang and Klabjan (2017), the chance of passengers missing their connecting flight is generally treated as independent of the walking distance between the gates of the inbound and the outbound flight. In reality, a tight connection is more likely to be missed if the required walking time between the gates is long, given the layout and the available transportation modes, as well as the required mandatory passenger processing procedures.

In this paper, we focus on the mathematical formulation of the gate reassignment problem with passenger flows. To tackle the issues explained above, the key contributions of this study are the following:

- We compare and analyze existing formulations of the gate Reassignment Problem with time as a decision variable and passenger flows in the objective function. To achieve this, we examine the mathematical models both from a theoretical (Section 4) and a practical-experimental perspective (Section 5). We also study the limitations and underlying assumptions of each formulation and provide guidelines for selecting a suitable formulation accordingly.
- We extend and improve existing formulations: We take advantage of the properties of the problem, such as the set partitioning constraints, to develop strong integer formulations that result in significant time savings when solved to optimality.
- We propose a new, time-indexed assignment formulation for dealing