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A hybrid optimization-simulation approach for robust weekly aircraft routing and retiming

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ABSTRACT

We address the robust weekly aircraft routing and retiming problem, which requires determining weekly schedules for a heterogeneous fleet that maximizes the aircraft on-time performance, minimizes the total delay, and minimizes the number of delayed passengers. The fleet is required to serve a set of flights having known departure time windows while satisfying maintenance constraints. All flights are subject to random delays that may propagate through the network. We propose to solve this problem using a hybrid optimization-simulation approach based on a novel mixed-integer nonlinear programming model for the robust weekly aircraft maintenance routing problem. For this model, we provide an equivalent mixed-integer linear programming formulation that can be solved using a commercial solver. Furthermore, we describe a Monte-Carlo-based procedure for sequentially adjusting the flight departure times. We perform an extensive computational study using instances obtained from a major international airline, having up to 3387 flights and 164 aircraft, which demonstrates the efficacy of the proposed approach. Using the simulation software *SimAir* to assess the robustness of the solutions produced by our approach in comparison with that for the original solutions implemented by the airline, we found that on-time performance was improved by 9.8–16.0%, cumulative delay was reduced by 25.4–33.1%, and the number of delayed passengers was reduced by 8.2–51.6%.

1. Introduction

Over the last few decades, the airline industry has become an essential pillar of the world's economy, as demonstrated by the ever-increasing number of air passengers and the volume of air freight. As a case in point, data disclosed by the International Air Transport Association (IATA) reveals that airlines transported nearly 3.5 billion passengers in 2015, and carried some 50 million metric tons of cargo across an impressive network of 50,000 routes. This huge connectivity has an overwhelming impact on the global economy, as demonstrated by the $2.4 trillion of business activity shared by nearly 260 airlines.[1] These companies are continuously striving to enhance their profitability in a highly competitive environment by providing both high-quality and low-cost services, where legacy airlines have played a pioneering role in extensively employing

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[1] http://www.iata.org/about/Documents/iata-annual-review-2015.pdf.

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Operations Research (OR) to efficiently manage their processes. In particular, OR analysts have spent a great deal of effort in developing effective models and algorithms for optimizing the following major airline planning processes:

1. Schedule design (Jiang and Barnhart, 2009; Sherali et al., 2011): This process is concerned with building a profitable flight timetable to serve the targeted markets. It requires specifying flight origins and destinations together with the corresponding frequencies and departure times, while taking into consideration market profitability, resource availability, and regulations. The generated schedule constitutes the basis for all subsequent airline operations.
2. Fleet assignment (Barnhart et al., 2003; Sherali et al., 2006; Barnhart et al., 2009; Dožić and Kalić, 2015): This deals with matching the expected number of passengers to the correct seat capacity, while seeking to minimize passenger spill as well.
3. Aircraft routing (Clarke et al., 1997; Gopalan and Talluri, 1998; Lacasse-Guay et al., 2010): This planning process aims to determine for each individual aircraft the most profitable routing while satisfying maintenance restrictions. In this context, an aircraft routing refers to a time-compatible sequence of flight legs, where two consecutive flight legs are connected by their departure and arrival stations.
4. Crew scheduling (Desaulniers et al., 1998; Cohn and Barnhart, 2003): This process requires assigning qualified cockpit and flight attendant crews to each scheduled flight leg while satisfying a wide range of mandatory duty rules.

In this context, a seemingly paradoxical fact is that, despite their overwhelming effectiveness, optimized schedules are scarcely implemented as planned. The predominant reason is that airlines operate in an extremely dynamic and unstable environment while dealing with many uncertain parameters and factors outside their control. Consequently, unexpected incidents often lead to disrupting the planned schedules, thereby forcing airlines to rely on contingency plans to implement changes to the publicized schedule. The causes of disruptions are numerous and include aircraft breakdowns, air-traffic congestion, crew shortages, aircraft arriving late, and inclement weather conditions, to quote just the most common ones. It is well documented that these disruptions have been plaguing airlines worldwide, and that the number of disrupted flights is ever on the rise due to the dramatic growth in the airline industry. In 2014, it has been reported that 23.75% of US airlines' flights were delayed by more than 15 min.[2] Consequently, flight delays place a significant strain on the air transportation sector. Ball et al. (2010) reported that the cost of domestic flight delays put a $32.9 billion dent into the U.S. economy in 2007.

In this state of art, the airline industry is in greater need than ever to implement robust optimization approaches and paradigms to mitigate, in a cost-effective manner, the lingering negative impact of disruptions. Thus far, two broad classes of strategies have been investigated in the literature: proactive strategies and reactive strategies. On one hand, the class of proactive strategies refers to a set of approaches that aim at building robust schedules that are less vulnerable to disruptions or are easy to recover. In other words, a proactive strategy seeks to attribute, at the planning stage and thereby in anticipation of any disruption, some robustness features into the planned airline schedules. On the other hand, the class of reactive strategies refers to a set of recovery policies that seek, by using optimization methodologies, to repair the delayed schedules after the occurrence of a disruption in a quick and cost-effective way. So far, a wide range of reactive strategies have been adopted by airlines including aircraft rerouting, flight cancellation, crew rescheduling, and transporting disrupted passengers to their final destinations using alternative routes and/or airlines. In-depth surveys of reactive strategies can be found in Ball et al. (2007) and Barnhart (2009).

In this paper, we address the following tactical aircraft routing problem that is usually solved well in advance of departures. Given a one-week set of flights to be flown during a specific season of the year, together with (narrow) time-windows associated with the different departure times, the problem requires setting a departure time for each flight and deriving periodic maintenance feasible aircraft routes while covering all flights. The objective is to build robust aircraft schedules that are less sensitive to delays caused by late-arriving aircraft. Our motivation for emphasizing this latter source of delays stems from the fact that this cause is predominantly responsible for delays worldwide. Indeed, 39.8% of the total delay recorded by US carriers in 2015 were caused by late-arriving aircraft.[3] More specifically, we describe a proactive approach for enhancing the robustness of a weekly flight schedule by judiciously reallocating aircraft connection buffer times while accommodating maintenance constraints. In this effort, we make the following contributions:

1. We propose a compact mixed-integer nonlinear programming (MINP) model to solve the robust weekly aircraft maintenance routing problem. To the best of our knowledge, this is the first compact model for this weekly variant, and is derived by extending the daily model of Haouari et al. (2013).
2. We apply the Reformulation-Linearization Technique (RLT) of Sherali and Adams (1990, 1994) to provide an equivalent mixed-integer linear programming formulation than can be solved using a commercial solver.
3. We describe a hybrid optimization-simulation approach that delivers robust aircraft routes having enhanced on-time performance, while accommodating maintenance constraints and stochastic delays. The proposed approach combines mixed-integer programming with Monte-Carlo simulation to derive robust aircraft schedules.

[2] http://www.bts.gov/xml/ontimesummarystatistics/src/index.xml.
[3] Understanding the Reporting of Causes of Flight Delays and Cancellations, {http://www.bts.gov/help/aviation/html/understanding.html}.