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Innovative Applications of O.R.

Operational aircraft maintenance routing problem with remaining time consideration

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A R T I C L E I N F O

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The aircraft maintenance routing problem is one of the most studied problems in the airline industry. Most of the studies focus on finding a unique rotation that will be repeated by each aircraft in the fleet with a certain lag. In practice, using a single rotation for the entire fleet is not applicable due to stochasticity and operational considerations in the airline industry. In this study, our aim is to develop a fast responsive methodology which provides maintenance feasible routes for each aircraft in the fleet over a weekly planning horizon with the objective of maximizing utilization of the total remaining flying time of fleet. For this purpose, we formulate an integer linear programming (ILP) model by modifying the connection network representation. The proposed model is solved by using branch-and-bound under different priority settings for variables to branch on. A heuristic method based on compressed annealing is applied to the same problem and a comparison of exact and heuristic methods are provided. The model and the heuristic method are extended to incorporate maintenance capacity constraints. Additionally, a rolling horizon based procedure is proposed to update the existing routes when some of the maintenance decisions are already fixed.

1. Introduction

Operations research methods are widely used for different planning and scheduling problems in the airline industry. These problems can be divided into four major classes: Flight scheduling, fleet assignment, aircraft maintenance routing and crew scheduling (Liang & Chaovalitwongse, 2009). In general terms, the flight scheduling problem deals with the scheduling of flights so that the market demand is met. The fleet assignment problem sorts out the assignments of plane types to fleets for predetermined flights with the aim of maximizing the total profit. While the crew scheduling problem tries to handle the assignments of crew members to each aircraft, the aircraft maintenance routing problem (AMRP), which is the main focus of this study, deals with arranging routes for the aircrafts so that the maintenance regulation constraints are not violated. Although all of these problems have been widely studied for the last few decades, the challenge remains due to high complexity of airline networks and increasing size of the industry.

There are established thresholds for the number of consecutive flight days and the number of operating hours for an aircraft beyond which a predetermined maintenance check must take place. The maintenance checks have different frequencies and durations depending on their type (Clarke, Johnson, Nemhauser, & Zhu, 1997). A *type A* check is repeated every 65–125 hours of flying or every week and it involves visual inspection of major systems for about eight hours. A *type B* check is repeated every 300–600 hours of flying and lasts around 1–3 days. *Type C* and *type D checks* are repeated once in every one to four years and they can be only completed at specialized hangars in about one month (Sriram & Haghani, 2003). AMRP addresses short-term maintenance requirements with shorter maintenance frequencies. The rationale behind this is that longer checks which are less frequent directly affect the fleet capacity; hence, such maintenance checks must be considered while solving the fleet assignment problem.

Among the many studies that deal with AMRP, most of the early ones address the problem at a more tactical level, ignoring the operational level constraints and dynamic issues. In these studies, the aim is to find a unique rotation of flights (starting and ending at the same location) that will be repeated by each aircraft in the fleet with a certain lag. In practice, using a single rotation for the entire fleet may not be applicable due to stochasticity and operational considerations in the airline industry. Thus, AMRP has also been addressed at a more operational level to assign *maintenance feasible* flight sequences to each individual aircraft (identified by its tail number) of a given fleet by considering the current states of the aircrafts while covering all the flights in the flight schedule over a short-term planning horizon. A route is maintenance feasible when it contains no maintenance-free segment of flights whose

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accumulated duration is larger than the remaining time of the corresponding aircraft. The remaining time of an aircraft is defined as the difference between legal flying hour limit, which is the amount of time allowed between consecutive maintenance operations, and the accumulated flight duration since its last maintenance operation. In this study, our aim is to develop a fast and responsive methodology to solve the operational aircraft maintenance routing problem (OAMRP). For this purpose, a new ILP formulation is proposed for OAMPR. After attempting to solve this new model by exact methods, a heuristic method based on compressed annealing (CA) is proposed. The performance of the CA heuristic is validated with respect to exact solutions on a relatively small real-life flight network, then its applicability to larger networks is shown by using examples from the literature. Furthermore, the model and numerical examples are extended to incorporate capacity considerations for the maintenance facilities. Lastly, a rolling horizon based procedure is proposed to update the existing routes when some of the maintenance decisions are already fixed.

The paper is organized as follows: In Section 2, we present a literature review about AMRP and discuss the contributions of our study. In Section 3, OAMRP model is described and the new ILP formulation is proposed. In Section 4, the exact and the heuristic methods are presented in detail. Section 5 covers the numerical experiments and the comparison of the proposed methods. In Section 6, maintenance capacity related extensions are presented and a rolling horizon based routing method is introduced along with a discussion about the applicability of the heuristic method in real life. In Section 7, concluding remarks are provided.

2. Literature review and contribution

2.1. Literature review

In this section, we briefly describe and discuss some of the major studies in AMRP; however, one can refer to the surveys of Etschmaier and Mathaisel (1985), Gopalakrishnan and Johnson (2005) and Sherali, Bish, and Zhu (2006) for the flight scheduling, the fleet assignment and the crew scheduling problems, respectively. The focus of AMRP related studies can be operational or tactical. The studies with tactical focus find a unique rotation which can be repeated by the aircrafts in the fleet while ignoring the initial conditions of the aircrafts and dynamic changes (cancellations or delays) in the airline industry. At the operational level, all restrictions must be obeyed because the solutions at this level determine the plans to be followed in real life.

In some early studies, Daskin and Panayotopoulos (1989) present an ILP formulation to assign aircrafts to routes in a hub-and-spoke network with the objective of maximizing profits. Feo and Bard (1989) present a model that aims to both locate maintenance stations and develop flight schedules which better meet the cyclical demand for maintenance with minimum cost. Clarke, Hane, Johnson, and Nemhauser (1996) try to generalize the fleet assignment model of Hane et al. (1995) by considering maintenance and crew restrictions.

On the tactical side of AMRP, Kabbani and Patty (1992) propose a set partitioning model to solve the 3-day maintenance routing problem. Assuming that the checks are performed overnight, they generate *over-the-day* routings also known as *lines of flight*. After fixing over-the-day routings, they connect the route segments to solve their original problem. Gopalan and Talluri (1998) use *lines of flight (LOF)* logic of Kabbani and Patty (1992) on the k-day maintenance routing problem and develop a polynomial time algorithm for $k = 3$. They prove that even 2-day maintenance routing problem becomes NP-Hard when LOFs are not fixed and Talluri (1998) shows that 4-day maintenance routing problem is NP-Hard even with fixed LOFs. Clarke et al. (1997) use Lagrangian relaxation (LR) to find a unique, maintenance feasible rotation which yields the largest total *through value* where through value is defined as the total benefit obtained by connecting certain flights. Mak and Boland (2000) formulate AMRP as an asymmetric traveling salesman problem with *replenishment arcs* where a replenishment arc denotes a connection during which a maintenance operation can take place. They use LR to obtain lower bounds and simulated annealing (SA) to obtain upper bounds. Their SA method allows infeasible flight connections in solutions, but penalizes them with a large penalty cost. Liang, Chaovalitwongse, Huang, and Johnson (2011) consider k-day maintenance routing problem assuming that maintenances are overnight operations and the flight schedule is repeated every day. They construct a compact representation of time–space network, *Rotation Tour Network (RTN)*, and propose a new ILP formulation based on their new representation.

On the operational side, Argüello and Bard (1997) propose a greedy randomized adaptive search procedure (GRASP) to reconstruct aircraft routings in response to dynamic changes in the airline industry with the objective of minimizing costs incurred by flight cancellations and delays. The focus of the paper is not directly on maintenance. Sriram and Haghani (2003) use *Origin Destination (OD) pairs* similar to LOFs. Assuming that the OD pairs are already given and maintenances are overnight operations, their aim is to determine individual aircraft assignments to the routes that yield the minimum total cost. One of the proposed models in this study tries to keep track of the remaining flying times; however, the authors do not attempt to solve that model owing to its size. Afsar, Espinouse, and Penz (2006) determine routes for aircrafts to satisfy the already scheduled long-term maintenance checks over an acyclic horizon. Due to stochasticity, they do not fix routes several weeks in advance; instead they prepare the plan based on a rolling horizon of one week. They propose a two-step heuristic approach where the first step deals with *critical* aircrafts which have to undergo maintenance operations soon and the second step deals with the non-critical ones. In Afsar, Espinouse, and Penz (2009), different heuristic methods, including SA, and priority rules for non-critical aircraft selection are applied to the same problem. Note that the maintenance operations of the critical aircrafts are assumed to be already scheduled in these studies and the problem becomes easier with such an assumption. Grönkvist (2006) uses constraint propagation in order to accelerate the column generation for the tail assignment problem, which is closely related to OAMRP. Sarac, Batta, and Rump (2006) propose a set partitioning based formulation to minimize total daily maintenance costs without violating the flying hour limit of each aircraft. Their model considers maintenance resource availability and legal remaining times of aircrafts. Since the set partitioning based formulation contains exponentially many variables each of which represents a feasible route, column generation technique is used as the solution procedure. The time horizon of the model is one day and as stated in the study, longer time horizons can better utilize remaining times of aircrafts. In a more recent study, Haouari, Shao, and Sherali (2012) develop a polynomially sized nonlinear model for the same problem. They linearize the nonlinear model by using reformulation–linearization technique and obtain high quality results for fairly large instances. Orhan, Kapanoglu, and Karakoc (2011) propose an ILP which maximizes the utilization of the remaining times with respect to given maintenance schedules. Reiners, Pahl, Maroszek, and Rettig (2012) develop an auto-adapting algorithm that is based on ge-