Computers & Operations Research 51 (2014) 130–145

Contents lists available at ScienceDirect

Computers & Operations Research

journal homepage: www.elsevier.com/locate/caor

Recoverable robust single day aircraft maintenance routing problem

Stephen J. Maher [a,*], Guy Desaulniers [b], François Soumis [b]

[a] School of Mathematics and Statistics, University of New South Wales, Sydney, NSW 2052, Australia
[b] École Polytechnique de Montréal and GERAD, Department of Mathematics and Industrial Engineering, Montréal, Québec, Canada H3C 3A7

ARTICLE INFO

Available online 27 March 2014

Keywords:
Airline planning
Maintenance
Robustness
Recoverability

ABSTRACT

Aircraft maintenance planning is of critical importance to the safe and efficient operations of an airline. It is common to solve the aircraft routing and maintenance planning problems many months in advance, with the solution spanning multiple days. An unfortunate consequence of this approach is the possible infeasibility of the maintenance plan due to frequent perturbations occurring in operations. There is an emerging concept that focuses on the generation of aircraft routes for a single day to ensure maintenance coverage that night, alleviating the effects of schedule perturbations from preceding days. In this paper, we present a novel approach to ensure that a sufficient number of aircraft routes are provided each day so maintenance critical aircraft receive maintenance that night. By penalising the under supply of routes terminating at maintenance stations from each overnight airport, we construct a single day routing to provide the best possible maintenance plan. This single day aircraft maintenance routing problem (SDAMRP) is further protected from disruptions by applying the recoverable robustness framework. To efficiently solve the recoverable robust SDAMRP acceleration techniques, such as identifying Pareto-optimal cuts and a trust region approach, have been applied. The SDAMRP is evaluated against a set of flight schedules and the results demonstrate a significantly improved aircraft maintenance plan. Further, the results demonstrate the magnitude of recoverability improvement that is achieved by employing recoverable robustness to the SDAMRP.

1. Introduction

The aircraft routing problem is typically solved following the fleet assignment, many months in advance of the day of operations. At this stage, maintenance planning is performed to ensure that each aircraft in the fleet is checked at regular intervals. The resulting maintenance plans can span multiple days, making them susceptible to schedule perturbations. While robust planning is becoming more popular for airline problems, perturbations occurring in operations can still significantly alter the planned solution. As such, any schedule disruptions may restrict maintenance critical aircraft from entering a maintenance base, unless costly intervention is provided by the operations control centre.

There have been numerous approaches presented for solving the aircraft maintenance routing problem, with and without considering the effects of schedule perturbations. Lacasse-Guay et al. [19] provides a good review of current business practices that shape the formulation of the Aircraft Routing Problem (ARP). In [19], the authors explain that the various approaches fall into three broad categories, *Strings*, *Big-cycle* and *One-day routes*. The *string* model involves the construction of flight routes spanning between visits to maintenance stations. The flight routes, or strings, are constructed to be maintenance feasible and can be performed by all aircraft of the one fleet. The *big cycle* model has the objective of identifying one single route that covers multiple days and includes every scheduled flight. This modelling approach is most common for schedules that are identical every day. In the resulting solution, each overnight stop in the cycle represents a possible starting point for an aircraft. Also, the cycle is constructed to be maintenance feasible by scheduling maintenance visits at appropriate intervals throughout.

Finally, the *one-day routes* approach is designed under the assumption that disruptions from preceding days render the maintenance planning for an airline infeasible most of the time. Given this assumption, aircraft routing can be seen as a two-stage decision process. In the first stage (the planning stage), one-day routes are planned to ensure aircraft maintenance feasibility. This is achieved by providing a sufficient number of routes out of each overnight airport that terminate at maintenance stations. In the second stage, which is performed every night before the operations, specific aircraft are assigned to the one-day routes. Specifically, this process ensures that each maintenance critical aircraft at the start of the day terminate at a maintenance station. The one-

* Corresponding author.
E-mail address: maher@zib.de (S.J. Maher).

http://dx.doi.org/10.1016/j.cor.2014.03.007
0305-0548/

day routes model used in the first stage differs from the string and big-cycle models discussed above by constructing flight routes that only span a single day. Routes originating from each overnight airport are constructed for each day of the planning horizon. The one-day routes planning model will be developed further throughout this paper.

Traditionally, the aircraft maintenance routing problem is presented using either a big-cycle or string formulation. Examples of maintenance routing problems solved to identify a big-cycle are presented by Feo and Bard [12], Clarke et al. [6] and Gopalan and Talluri [16]. Alternatively, examples of the string formulation are presented by Barnhart et al. [3] and Sriram and Haghani [33]. The aircraft routing problems developed using these two approaches schedule aircraft maintenance over multiple days under the expectation that few disruptions will occur. Given the prevalence of disruptions to airline operations, there is a high probability that planned maintenance schedules will be affected each day. While the maintenance schedule can be corrected by the operations control centre with the use of aircraft swaps during the day, this can be very costly to the airline. Performing an aircraft swap helps to reduce the number of delayed flights, but it can also cause infeasibility in the maintenance plan. Consequently, further modification is generally required to the planned aircraft routes, possibly impacting on the crew schedules and passenger itineraries. Ideally any intervention by the operations control centre is performed at night to provide ample time to correct any changes to maintenance schedules.

The one-day routes approach to the ARP is an attempt to address the down-the-line impacts that disruptions have on maintenance scheduling. In practice, an optimisation problem using the one-day routes approach is solved each night, focusing on the aircraft requiring maintenance the following night. This approach attempts to generate a sufficient number of routes that terminate at maintenance stations, which will be allocated to maintenance critical aircraft. Heinhold [18] presents an approach employed by Southwest Airlines that calculates the expected number of aircraft at each overnight airport requiring maintenance the following day. This expectation is used to form a model to ensure that an adequate number of aircraft routes departing from each overnight airport terminate at maintenance stations. By solving this problem for close-in planning, only small modifications are required in response to disruptions from preceding days to recover the planned maintenance schedule.

The concept of one-day routes is investigated further by Lapp and Cohn [21], proposing the use of a multi-stage optimisation problem to improve maintenance reachability. Lapp and Cohn [21] develop a model using the concept of a line-of-flight (LOF), which is a sequence of flights performed by an aircraft during a single day. The optimisation problem modifies LOFs to provide maintenance visits for maintenance critical aircraft stationed at each overnight airport. This is similar to the approach presented by Heinhold [18], however the multi-stage approach improves the tractability of the problem. The input for this problem is the set of originally planned LOFs departing from each overnight airport. A subset of these LOFs terminate at maintenance stations and are described as a maintenance line-of-flight (MLOF). The proposed optimisation model identifies overnight airports that have an inadequate number of MLOFs. By selecting a LOF and MLOF from airports with an under and over supply of MLOFs respectively, a single swap is performed to allow the LOF to terminate at a maintenance station. This process is performed to increase the maintenance reachability from all airports in the network. The authors demonstrate an increase in the maintenance reachability compared to the originally planned LOFs, reporting reasonable runtimes. Since only one swapping opportunity is identified along each LOF, there is a possibility to further improve the maintenance routing by allowing more rerouting options for each aircraft. The single day aircraft maintenance routing problem (SDAMRP) developed in this paper employs the one-day routes approach to provide an adequate number of MLOFs in the aircraft routing stage. A major contribution of this paper is the novel approach developed for considering aircraft maintenance for a single day schedule.

The development of the one-day routes approach for the ARP is motivated by the impact of schedule disruptions on medium and long term maintenance plans. While the one-day routes approach aims to provide a feasible maintenance schedule at the start of each day, disruptions throughout the day can still affect this maintenance plan. Robust planning is a common approach employed to reduce the susceptibility of an aircraft routing solution to schedule disruptions. There are two main types of robust planning, *proxy* and *feedback* robustness, each displaying individual strengths and weaknesses.

Proxy robust approaches attempt to improve the operational performance of an aircraft routing solution by enhancing favourable planning characteristics. Examples of proxy robust approaches are presented by Lan et al. [20], Weide et al. [35], Borndorfer et al. [5] and Dunbar et al. [10], each attempting to minimise the expected propagated delay. An alternative form of proxy robustness identifies features from the planning solution that are expected to aid the recovery process. This form of robust planning focuses on the concept of recoverability, which is defined as the amount of effort required by operational controllers during recovery as a result of planning stage decisions. Proxy robust approaches that explicitly attempt to improve the recoverability of aircraft routing solutions are presented by Ageeva [1], Eggenberg [11] and Rosenberger et al. [30].

By comparison, feedback robust approaches explicitly evaluate the robustness, or recoverability, of the planning stage solution during the optimisation process. The evaluation stage of a feedback robust approach helps to develop a less conservative robust planning solution compared to equivalent proxy robust models. Recoverable robustness, introduced by Liebchen et al. [22], is an example of a feedback robust approach that attempts to improve the planning stage recoverability. In particular, the objective of recoverable robustness is to identify a planned solution that is recoverable with *limited effort*. This concept is applied to the tail assignment problem in Froyland et al. [14], which is solved to identify a single day tail assignment with a minimum expected recovery cost. This paper presents an extension upon the recoverable robust tail assignment problem presented in [14] by applying this approach to real-world, large-scale airline schedules. Additionally, we present an aircraft routing problem that is solved with direct consideration of maintenance requirements for a single fleet type. This same level of maintenance planning is not provided in the tail assignment problem presented by Froyland et al. [14]. The aircraft routing problem with maintenance considerations is a novel approach modelled using one-day routes and the recoverable robustness technique further strengthens this planning method. A further contribution of this paper is the analysis of connection cost functions regarding their impact on the recoverability improvements and solution runtimes on the recoverable robust problem.

This paper is presented in two stages, the formulation of the single day aircraft maintenance routing problem and the application of recoverable robustness. The purpose of this structure is to highlight the individual strengths of each of these techniques. Section 2 develops the model for the single day aircraft maintenance routing problem, providing a full description of the techniques used in the problem formulation. A description of recoverable robustness for the single day aircraft maintenance routing problem is presented in Section 3. Using the recoverable robustness technique, the planning aircraft routing solution is evaluated by solving a recovery subproblem. The description of the