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Aircraft routing with generalized maintenance constraints ☆

Nima Safaei [a,*], Andrew K.S. Jardine [b]

[a] Data Science and Analytics, Scotiabank, 40 King St. W, Toronto M5H 1H1, ON, Canada
[b] Department of Mechanical and Industrial Engineering, University of Toronto, 5 King's College Road, Toronto M5S 3G8, ON, Canada

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ABSTRACT

The literature on aircraft maintenance routing generally ignores the full range of maintenance requirements by only considering the most frequent maintenance type. The range of maintenance types and variety of individual aircraft's ages and utilization rates means the maintenance demand for each aircraft differs from one period to another, thus complicating aircraft routing decisions. This study proposes a new formulation of the aircraft maintenance routing problem in which maintenance requirements are built as generalized capacity constraints, ensuring sufficient maintenance opportunities are available within the planned routes to satisfy the maintenance demands of individual aircraft. Our new approach suggests minimizing maintenance misalignment using an interactive mechanism between aircraft routing and maintenance planning decisions. The computational results using real datasets reveal continuous reduction and convergence in maintenance misalignment through the proposed interactive mechanism. The lack of an effective interaction between the abovementioned decisions significantly increases the maintenance misalignment costs.

1. Introduction

The Aircraft Maintenance Routing Problem (AMRP) determines the route of individual aircraft (tail number) in a sequence of revenue flight legs, so that each route will have sufficient opportunities for the required maintenance tasks to be performed. A *Maintenance Opportunity* occurs when an airplane spends a sufficiently long period at a maintenance station, whether or not maintenance is actually performed. For the most part, the theoretical literature and common AMRP practices have focused on two policy types. The first ignores the maintenance requirements of individual aircraft and only considers generic maintenance routes, e.g., cyclic or *n*-day rotation policy [16,18,21,24,26]. The second schedules the periodic maintenance activities and plans the route of individual aircraft on a day-to-day basis [15,25]; Keysan et al., 2010; [14,23], a policy favoring "feasibility" over "optimization". The majority of past studies simplify maintenance requirements by only considering the more frequently occurring maintenance tasks (type A). In practice, each aircraft has many maintenance tasks, with over 50 different checks, which must be done on a regular basis during the life cycle. Past studies argue that "other aircraft maintenance checks are spaced over longer durations and, being more time intensive, are therefore usually planned at a higher decision level whereby aircraft are appropriately periodically pulled out of and reinserted into service" [14]. However, in the real world, the variety of maintenance tasks, ages and utilization rates of individual aircraft means the *maintenance workload due* (MWD) for each aircraft differs from one period to another. This, together with the variety of resource requirements (time and labour) for different maintenance tasks, will constrain the way we build cyclic maintenance rosters. Henceforth, we will use the definition "MWD" representing the total man-hours required to perform a list of maintenance tasks which are due over the upcoming horizon. Some of tasks may need to be performed multiple times depending on the aircraft usage rate over the horizon.

1.1. Problem statement

Fig. 1 represents the maintenance planning, i.e., projected MWD, of a fleet of 10 identical aircraft over a 52 week horizon in terms of man-hour. The age of the fleet ranges from 1330 to 1700 days and utilization rates range from 6900 to 8800 flight hours (FH). Each aircraft needs more than 50 types of maintenance checks with cycle intervals ranging from 50 to 40,000 FH. The significant variability of MWD of individual aircraft in Fig. 1 is due to the age variety, flight hours flown, maintenance history and the time and labour requirements of the various checks. In this case, solving AMRP becomes challenging because of the feasibility problem, i.e., finding a feasible routing to cover all flights with

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* Corresponding author.
E-mail addresses: nima.safaei@scotiabank.com, safaei@mie.utoronto.ca (N. Safaei), jardine@mie.utoronto.ca (A.K.S. Jardine).

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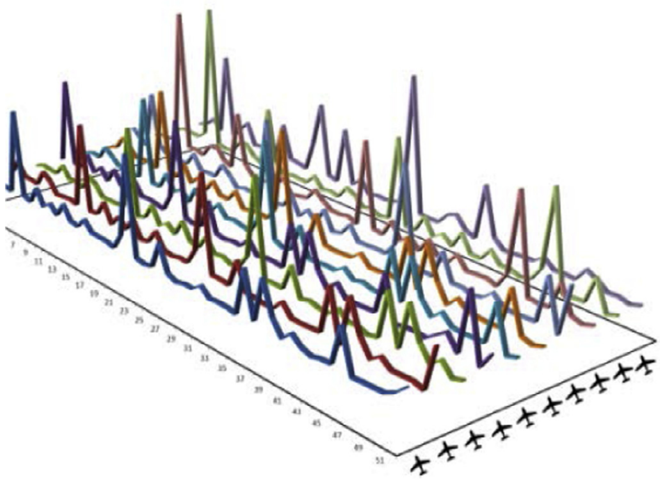

Fig. 1. Projected MWD of a fleet of 10 identical aircrafts with various operational history – weekly planning.

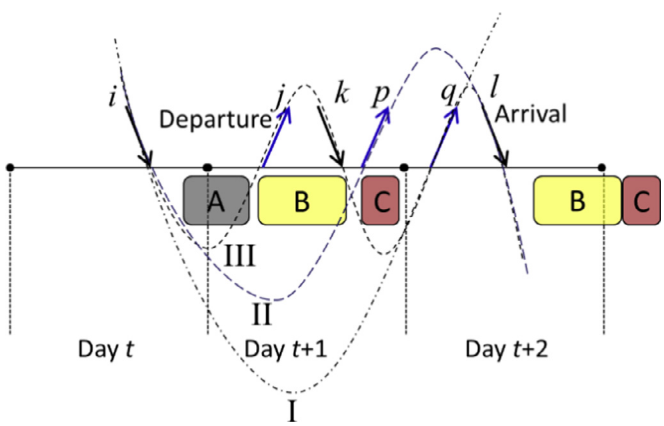

Fig. 2. Possible scenarios for integrated tail rotation and maintenance planning.

sufficient feasible maintenance opportunities (MOs) embedded within the routes to cover the MWD of the whole fleet.

To better illustrate the dependency among the routing and planning decisions, Fig. 2 displays an example of alternatively routing a single aircraft in a single maintenance station with 3 maintenance checks due over a 3-day horizon. The width of each box represents the duration of the corresponding check in terms of man-hours. Task A must be performed at day t while tasks B and C should be performed no later than day $t+3$. Note that if a task will due on day t; the aircraft cannot fly starting day t till the task is completed. The first possible scenario is to consolidate all three checks as a single package and schedule it between arrival flight leg i and departure flight leg q, resulting in maintenance route $i \rightarrow \{A, B, C\} \rightarrow q$ requiring one maintenance visit. The second scenario is to create separate work packages {A, B}, and {C} and schedule them as $i \rightarrow \{A,\ B\} \rightarrow p \ldots \rightarrow l \rightarrow \{C\}$ requiring two maintenance visits. Other possible scenarios are $i \rightarrow \{A,\ C\} \rightarrow p \ldots \rightarrow l \rightarrow \{B\}$, and $i \rightarrow \{A\} \rightarrow j \rightarrow \cdots \rightarrow k \rightarrow \{C\} \rightarrow q \rightarrow \cdots \rightarrow l \rightarrow \{B\}$ with three maintenance visits. The due date of the checks and, thus, the size and pattern of MWD may be changed by altering the routes, resulting in a new set of maintenance scenarios. Clearly, there is a mutual dependency between the created routes and MWD, which raises the need for interaction between aircraft rotation and maintenance planning decisions; something not yet considered in the literature. The problem is that the optimal routes may differ entirely from one period to another; therefore, a cyclic rotation may be not an optimal policy.

1.2. Current practice shortfalls

The consideration of the full range of maintenance requirements requires the integration of tail rotation (TR) and maintenance planning (MP) decisions. The main deficiency of existing practices and policies is the lack of such integration. That is, a master flight schedule is first imposed as a hard constraint, and then the fleet maintenance activities are projected according to the created routes. The above integration theoretically ensures the existence of sufficient maintenance opportunities *at the right place, at the right time for the right aircraft*. In current practices, as the due dates of some maintenance tasks approach, aircraft are rerouted to a maintenance base. Such one-way policies incur many opportunity costs for the airlines, including increased premature maintenance, inefficient usage of maintenance opportunities (MOs), unnecessary grounding of aircraft, maintenance demand fluctuation, and imbalanced fleet utilization. Over the long term, these have a negative impact on the maintenance resource planning phase. Briefly stated, low-quality short-term planning at the operational level has an enormously negative effect on long-term planning at the strategic level.

1.3. Chicken or egg dilemma

The ideal approach would be to simultaneously create the route of each aircraft and to track the route concurrently for various maintenance tasks using various flight attributes (e.g., flight hours, flight cycles, time–calendar, etc.). This methodology guarantees sufficient, feasible MO at the right times within the route to satisfy the projected MWD of each aircraft. However, this integrated methodology is practically impossible due to its sheer complexity. To do so, we need to solve a complicated non-linear optimization problem. We could, for example, use a sequential methodology which first projects the MWD using initial assumptions, e.g., equalized fleet utilization, and then feed the MWD to the routing module as capacity constraints, so as to create the routes and associated MOs. But this one-way methodology does not guarantee that the created routes are feasible for the projected MWD. Thus, we have a "chicken or egg" dilemma: *Should we estimate the MWD first and then create the routes or* vice versa?

1.4. Contribution

We propose a novel decision approach to solve the dilemma. The framework of the proposed approach is schematically illustrated in Fig. 3 in comparison with the classical decision process. The proposed approach simulates an optimal interaction between aircraft rotation and maintenance planning decisions. That is, given a weekly horizon, our approach iteratively creates the week-length route per individual aircraft and projects the corresponding MWD to reduce the *misalignment* between the MOs and MWD of each individual aircraft. The misalignment occurs because, in practice, there is not always a feasible routing that satisfies all due maintenance requirements of the fleet. The approach is terminated whenever no improvement on maintenance misalignment is possible. In practice, the maintenance tasks are generally categorized as line (low interval) tasks and heavy (high interval) tasks. The line tasks are usually projected in terms of the average usage of fleet on daily basis; while, the heavy tasks are projected based on the long-term planning. In the most approach, all tasks are introduced to the aircraft rotation module as hard constraints. However, our approach accurately projects the line tasks not based on the average usage of fleet but the actual usage of individual aircraft. This strategy will result in significant reduction in misalignment.

It is worth mentioning that the sequencing and timetabling of the individual tasks within MWD is beyond the scope of routing

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