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An exact solution algorithm for maximizing the fleet availability of a unit of aircraft subject to flight and maintenance requirements

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ABSTRACT

We address the Flight and Maintenance Planning (FMP) problem, i.e., the problem of deciding which available aircraft to fly and for how long, and which grounded aircraft to perform maintenance operations on in a group of aircraft that comprise a unit. The aim is to maximize the unit fleet availability over a multi-period planning horizon, while also ensuring that certain flight and maintenance requirements are satisfied. Heuristic approaches that are used in practice to solve the FMP problem often perform poorly, generating solutions that are far from the optimum. On the other hand, the exact optimization models that have been developed to tackle the problem handle small problems effectively, but tend to be computationally inefficient for larger problems, such as the ones that arise in practice. With these in mind, we develop an exact solution algorithm for the FMP problem, which is capable of identifying the optimal solution of considerably large realistic problems in reasonable computational times. The algorithm solves suitable relaxations of the original problem, utilizing valid cuts that guide the search towards the optimal solution. We present extensive experimental results, which demonstrate that the algorithm's performance on realistic problems is superior to that of two popular commercial optimization software packages, whereas the opposite is true for a class of problems with special characteristics that deviate considerably from those of realistic problems. The important conclusion of this research is that the proposed algorithm, complemented by generic optimization software, can handle effectively a large variety of FMP problem instances.

1. Introduction

Flight and Maintenance Planning (FMP) is an important decision making problem arising on the operational level of numerous types of mission fleets, involving military or fire-fighting aircraft, rescue choppers, etc. The objective is to maximize the fleet availability of a unit of mission aircraft over a multi-period planning horizon, while also ensuring that certain flight and maintenance requirements are satisfied. Simple heuristic techniques that are used in practice to solve the FMP problem often perform poorly, generating solutions that are far from the optimum. On the other hand, the exact optimization models that have been developed to tackle the problem handle small problems effectively, but tend to be computationally inefficient for larger problems, such as the ones that arise in practice, forcing researchers to resort to heuristics for solving them.

To overcome these obstacles, in this work we develop an exact solution algorithm for the FMP problem, which is capable of identifying the optimal solution of considerably large realistic problems in very reasonable computational times. Initially, the algorithm obtains a valid upper bound on the optimal fleet availability by solving a simplified relaxation of the original problem. In subsequent iterations, this bound is gradually reduced, until a feasible solution is identified. Solutions encountered along the search procedure that do not qualify for feasibility and therefore cannot be optimal are excluded from further consideration through the addition of suitable valid inequalities (cuts). The algorithm terminates when the first feasible solution that attains the current fleet availability bound is identified, which, naturally, comprises the optimal solution of the problem.

A preliminary version of this paper was presented at an international conference (Gavranis & Kozanidis, 2013). With respect to that work, this paper presents additional theoretical findings, further algorithmic details, and considerably more extensive computational results. Its remainder is structured as follows. In Section 2 we summarize the related literature and we present a mixed integer linear programming (MILP) formulation for the FMP problem in Section 3. In Section 4 we develop the proposed solution algorithm, and in Section 5 we present experimental results evaluating its computational performance. In Section 6 we discuss some interesting model extensions, and in Section 7 we summarize this work and we point to promising directions for future research.

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2. Literature review

Numerous problems dealing with the optimization of aircraft operations have been investigated in the past. In this section, we review the related literature, focusing mostly on works that address military related applications. First, we review works in the general field of military aircraft maintenance. Then, we turn our attention to papers that employ special purpose techniques in order to address the problem of scheduling military aircraft for maintenance inspections and mission assignments. We conclude with a review of the papers which are directly related to the problem that we address.

The increasing importance of effective military aircraft maintenance was recently recognized by the Operations Research and Management Science community (Horner, 2006). The 2006 Franz Edelman INFORMS Award for outstanding operations research and management science practice was bestowed on Warner Robins Air Logistics Center (WR-ALC). WR-ALC, located in Georgia, U.S., is responsible for the repair, modification and overhaul of various mission aircraft of the U.S. Air Force, such as the F-15 Eagle and Strike Eagle, the C-130 Hercules models, the C-5 Galaxy, the C-17 Globemaster III, as well as their respective avionics system components. Working with Realization Technologies and faculty from the University of Tennessee, WR-ALC used an operations research technique called Critical Chain to reduce the number of C-5 aircraft undergoing repair and overhaul in the depot from twelve to seven in just eight months. As a direct consequence, the time required to repair and overhaul the C-5 aircraft was reduced by 33 percent.

Several published works address the problem of assigning a group of available aircraft to missions and repair activities, so as to establish a high level of unit readiness. This is the case with the work of Safaei, Banjevic, and Jardine (2011), who develop a mixed integer optimization model to formulate the problem of workforce-constrained maintenance scheduling for a fleet of military aircraft. The goal is to maximize the aircraft that can be assigned to missions under maintenance scheduling and workforce availability constraints. The model utilizes a network flow structure in order to simulate the flow of aircraft between missions, the hangar and the repair shop, and is solved with generic optimization software. In a recent related work, Bajestani and Beck (2013) address a dynamic repair shop scheduling problem that takes into consideration flight requirements, aircraft failures, as well as maintenance related capacity constraints. The goal is to assign aircraft to flights and schedule repair jobs, so as to maximize the coverage of the unit flight requirements. The authors accommodate the stochasticity that the problem exhibits by decomposing it into smaller static sub-problems, and propose several alternative solution methodologies, including mixed integer programming, constraint programming, logic-based Benders decomposition, and heuristics.

The U.S. Department of the Army has released a Field Manual on Army Aviation Maintenance, which describes a practical “sliding scale scheduling” or “aircraft flowchart” graphical tool for scheduling aircraft for phase/periodic inspection and deciding which aircraft should fly in certain missions (US DoA, 2000). In a relatively recent work, Rosenzweig, Domitrović, and Bubić (2010) develop a MILP to formulate the sliding scale method for deciding the aircraft flight times. This model minimizes the penalty associated with the deviation of the aircraft flight times from their diagonal target values, but does not consider the maintenance requirements and the impact that they can have on the fleet availability of the unit. The authors solve the model with generic optimization software and illustrate its application on a small fleet of training aircraft. Utilizing the aircraft flowchart, Kozanidis, Gavranis, and Kostarelou (2012) develop a mixed integer nonlinear optimization model and a solution algorithm that accommodate a single-period planning horizon for the FMP problem. In contrast, the solution algorithm that we develop in this work accommodates a multi-period framework.

Although FMP is an important decision making problem encountered in several diversified areas, the relevant published research is rather limited. Sgaslik (1994) introduces a decision support system for maintenance planning and mission assignment of a helicopter fleet that partitions the master problem into two sub-problems which are solved separately. The first sub-problem is called the Yearly Planning Model (YPM). The YPM assigns helicopters to inspections and exercises, while also providing their maintenance schedule and their flight hour distribution. The second model is called the Short Term Planning Model (STPM). The STPM takes as input the maintenance schedule produced by the YPM and returns the helicopters’ mission assignments. The author develops two elastic mixed integer programs to formulate these two sub-problems and solves them using standard optimization software. The YPM minimizes the cost associated with the violation of some of the problem’s constraints (e.g., those referring to the required flight time, the maintenance capacity and the flight time of each individual aircraft), while also maintaining a given lower bound on the fleet availability.

Pippin (1998) develops a MILP and a quadratic program for the FMP problem, which try to find a flight hour allocation that ensures a steady-state sequence of aircraft into phase maintenance. Both these models minimize the cost associated with the deviations of the individual aircraft residual flight times from their diagonal line target values, but neither of them incorporates the apparent difficulties introduced by the maintenance aspect of the problem. Kozanidis (2009) proposes a multi-objective MILP model for the FMP problem that maximizes the minimum aircraft and flight time availability of the wing (main unit) and of the squadrons (sub-units) that comprise it. This work was extended by Kozanidis, Liberopoulos, and Pitsilkas (2010) through the development of a single objective optimization model that adopts one out of these objectives and incorporates the remaining ones through suitable constraints. Due to the computational complexity of the aforementioned models, the authors resort to heuristics for solving them (Kozanidis, Gavranis, & Liberopoulos, 2014).

Finally, Cho (2011) develops a MILP to model the FMP problem. The proposed formulation generates a daily flight and maintenance plan that distributes the maintenance workload evenly across the planning horizon. The main difference that this model exhibits with respect to the one that we address in the current work is that it uses different definitions for the objective function and for the flight requirements of the unit. With respect to the former, that model minimizes the maximum number of aircraft in maintenance at any given time in order to smoothen the variability of the maintenance demand over time. With respect to the latter, it translates the original flight load requirements into specific flight assignments, which are successively assigned to the aircraft of the unit. The author also considers a two-stage formulation that disaggregates the problem in order to determine the flight and maintenance decisions separately. All the decisions related to either the flight or the maintenance schedule are made in the first stage, while the remaining ones are determined in the second one. Both the single and the two stage models are solved with generic optimization software, although a discussion that proposes equivalent alternative formulations and potential heuristic solution approaches is also included.

3. FMP model formulation

We consider a fleet (typically, a combat wing), comprised of several aircraft. In order to retain the readiness of the unit at a high level, the unit command issues at the beginning of each planning horizon suitable flight requirements, which determine the total flight time that must be fulfilled by the aircraft of the unit in each associated time period. These requirements are also referred to as *flight load* in the related military literature.