Transportation Research Part C 72 (2016) 29–44

Contents lists available at ScienceDirect

Transportation Research Part C

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

A model and optimization-based heuristic for the operational aircraft maintenance routing problem

Nayla Ahmad Al-Thani, Mohamed Ben Ahmed, Mohamed Haouari *

Department of Mechanical and Industrial Engineering, College of Engineering, Qatar University, Qatar

A R T I C L E   I N F O

Article history:
Received 18 June 2016
Received in revised form 8 September 2016
Accepted 8 September 2016

Keywords:
OR in airlines
Aircraft routing problem
Compact formulations
Very large-scale neighborhood search

A B S T R A C T

This paper investigates the Operational Aircraft Maintenance Routing Problem (*OAMRP*). Given a set of flights for a specific homogeneous fleet type, this short-term planning problem requires building feasible aircraft routes that cover each flight exactly once and that satisfy maintenance requirements. Basically, these requirements enforce an aircraft to undergo a planned maintenance at a specified station before accumulating a maximum number of flying hours. This stage is significant to airline companies as it directly impacts the fleet availability, safety, and profitability. The contribution of this paper is twofold. First, we elucidate the complexity status of the *OAMRP* and we propose an exact mixed-integer programming model that includes a polynomial number of variables and constraints. Furthermore, we propose a graph reduction procedure and valid inequalities that aim at improving the model solvability. Second, we propose a very large-scale neighborhood search algorithm along with a procedure for computing tight lower bounds. We present the results of extensive computational experiments that were carried out on real-world flight networks and attest to the efficacy of the proposed exact and heuristic approaches. In particular, we provide evidence that the exact model delivers optimal solutions for instances with up to 354 flights and 8 aircraft, and that the heuristic approach consistently delivers high-quality solutions while requiring short CPU times.

1. Introduction

On December 17, 1903, Orville and Wilbur Wright achieved for the first time a successful flight of an aircraft that they designed and built themselves. Much more than being just an outstanding technological exploit, this pioneering flight marked the birth of modern aviation industry and definitely shaped the twentieth century and the world where we live today. In particular, during the last few decades the airline industry has witnessed one of the most enthralling economic developments in history and is nowadays considered as one of the main pillars of global economy. Actually, data compiled by the Air Transport Action Group (ATAG) yields an insight on the overwhelming importance of the airline industry.[1] Indeed, in 2015 the aviation industry contributed to the global economic with $2400 million that translates to about 3.4% of the global

* Corresponding author.
E-mail address: mohamed.haouari@qu.edu.qa (M. Haouari).

[1] Air Transport Action Group. http://www.atag.org/.

http://dx.doi.org/10.1016/j.trc.2016.09.004
0968-090X/

GDP. Furthermore, the number of air passengers has been steadily increasing by an average of 5.3% between 2012 and 2016 and is expected to reach 3.6 billion passengers by the end of 2016. Actually, the aviation industry contributes to the world GDP more than any other sectors/industries such as the pharmaceuticals, automotive and the textiles industries. As a matter of fact, the development of commercial aviation was, to a large extent, made possible by the development of "what is probably the most complex transportation system and possibly the most *complex man-made system in the world*" (Ball et al., 2007).

In this regard, operations research analysts have played a major role in consistently helping airlines developing optimization models and algorithms that support the efficient management of their complex business. Indeed, since the early 1960s a rich body of literature, namely thousands of papers, dealing with various airline operations problems has been published (Barnhart et al., 2003). The vast majority of these papers focus on the following problems:

(1) Schedule planning: Based on the corporate strategic plan and marketing studies, the airline company determines which cities to fly to, at which frequency, and at what times. The resulting schedule constitutes the basis of the airlines operations.
(2) Fleet assignment problem: This planning process deals with assigning aircraft types, each having a different number of seats, maximum total range, and operating costs, to the scheduled flights. An airlines fleeting decision highly impacts its revenues, and thus constitutes an essential component of its overall scheduling process.
(3) Aircraft routing problem: This planning process involves the determination of the sequence of flight legs to be flown by each individual aircraft so as to cover each flight exactly once.
(4) Crew pairing problem: This planning process requires constructing a minimum-cost set of crew duties and pairings (that is, sequences of duties spanning consecutive days and starting and ending at the crew base) so that every flight is assigned a qualified crew and certain rules and collective agreements are satisfied.

A glaring fact is that all these latter processes involve *tactical* decisions with planning horizons typically ranging from one month (crew scheduling) to one year (schedule planning). By contrast, short-term airline operations problems received (relatively) scant attention. Because of the complexity of the foregoing airline planning processes, and despite the considerable effort that has been devoted during the last decade to develop integrated models (see Shao et al. (in press), Gürkan et al. (2016) and the references therein), most airlines solve these problems separately: the optimal solution of one problem becomes the input for the following problem. However, by solving these problems sequentially, a solution for one process may prove infeasible input to the subsequent decisions. Furthermore, since these problems are solved well ahead of the planned flights (typically, from several weeks, for the crew pairing problem, up to one year for the schedule planning problem), they often need to be updated as the flight departure dates become closer and thereby the demand forecasts become accurate. In particular, the planned aircraft routes require to be frequently revised to accommodate refleeting decisions (that are made to better match demand fluctuations), aircraft breakdowns, and rerouting decisions that are made to repair disrupted plans (see Aloulou et al. (2013) and Samà et al. (2014), among many others).

Consequently, airlines strive to continuously revise aircraft routes through periodically solving the so-called *Operational Aircraft Maintenance Routing Problem (OAMRP)*. This *short-term* planning problem requires building aircraft routes that satisfy maintenance requirements. These latter are imposed, for obvious safety considerations, by the aircraft manufacturers, the aviation administrations, and by airlines. Basically, these requirements enforce an aircraft to undergo a planned maintenance after accumulating a specified number of flying hours. Actually, airlines utilize a planned preventive maintenance program that includes checks having different levels of detail, frequencies, and durations. The most frequent of these checks are often referred to as the A-checks. The periodicity of these checks depends on the aircraft type and airlines' internal rules. For instance, at Qatar Airways the A-check are carried out every 250 flying hours. In addition, rules prevailing at some airlines require that each aircraft should undergo an A-check before accumulating a specified maximum number of landings or accumulating a specified maximum number of days since the last inspection. Depending on the aircraft type, the duration of an A-check typically ranges between 6 and 8 h. On the other hand, the so-called D-checks are extremely comprehensive and are planned only three to six times during the lifetime of an aircraft.

In this paper, we only consider the most frequent preventive maintenance checks, i.e., the type A check, for each aircraft. Other types of checks that are much spaced, and require keeping the aircraft idle for much longer time, are usually planned at a higher decision level. More precisely, we investigate the following problem. We are given a set L of flight legs that are scheduled to be flown during a one-week planning horizon. Each flight $j \in L$ is characterized by a departure time t_j, a flight duration d_j, an origin station O_j and a destination station D_j. These flights should be assigned to a set K of m identical aircraft. Let F denote a parameter that represents the maximum flying time before undergoing a maintenance check, and S be the set of maintenance stations (i.e. stations where maintenance checks can be appropriately carried out). Assume that an aircraft k that has accumulated u_k flying hours (with $u_k \leqslant F$) undergoes a planned maintenance check at the landing station (given that this station is indeed a maintenance station), then the difference $(F - u_k)$ is defined as the *legal remaining time* of k. Each aircraft $k \in K$, is characterized by: (i) a parameter f_k that represents the initial accumulated number of flying hours since the last maintenance check (that is, u_k is initialized at f_k, for each aircraft k), (ii) an origin station, and (iii) a turn-time that represents the minimum preparation time that should elapse between a landing time and the next take-off time. The *OAMRP* requires building exactly one route for each individual aircraft while considering the following constraints: