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Decision Support

The Aircraft Maintenance Base Location Problem

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ABSTRACT

Aviation authorities such as the Federal Aviation Administration (FAA) provide stringent guidelines for aircraft maintenance, with violations leading to significant penalties for airlines. Moreover, poorly maintained aircraft can lead to mass cancellation of flights, causing tremendous inconvenience to passengers and resulting in a significant erosion in brand image for the airline in question. Aircraft maintenance operations of a complex and extended nature can only be performed at designated *maintenance bases*. Aircraft maintenance planning literature has focused on developing good tail-number routing plans, while assuming that the locations of the maintenance bases themselves are fixed. This paper considers an *inverse optimization* problem, viz., locating a minimal number of maintenance bases on an Euler tour, while ensuring that all required aircraft maintenance activities can be performed with a stipulated *periodicity*. The Aircraft Maintenance Base Location Problem (**AMBLP**) is shown to be NP-complete and a new lower bound is developed for the problem. The performance of four simple "quick and dirty" heuristics for obtaining feasible solutions to **AMBLP** is analyzed.

1. Introduction

On April 9, 2008 American Airlines was forced to cancel about a thousand flights (more than one-third of its schedule), stranding approximately one hundred thousand passengers (Koenig, Ilnytzky, & Carlton, 2008). A day earlier, the airline cancelled an additional four hundred and sixty flights. Federal inspectors allegedly found problems with aircraft wiring, although American claimed that passenger safety was never jeopardized. Stranded passengers included businesspeople, information technology consultants and even a bishop on his way to a sermon in Atlanta. In addition to flight cancellations, American was also forced to offer compensations for meals, transportation and hotels since this was not a weather-induced aircraft delay. The Federal Aviation Administration (FAA) is egalitarian however when dispensing maintenance-related punitive measures and American Airlines is not by far the only airline to be singled out. In Section 1.1 of the online appendix accompanying this paper, a brief history of problems that airlines have faced, specifically relating to maintenance issues, is provided. Given the mission-critical nature of airline maintenance operations and their cost and complexity, it behooves airlines to carefully study them in order to extract every possible efficiency from this domain. Motivated by this goal, this work develops an analytical framework for optimizing the *number* and *locations* of aircraft maintenance bases.

The contributions of this paper are listed below:

1. We develop a formal and detailed model of the **AMBLP**, and demonstrate its NP-completeness.
2. A new lower bound is developed for the number of bases required to achieve a desired periodicity of maintenance.
3. The lower bound is used to analyze the performance for four simple "quick and dirty" heuristics for the **AMBLP**.
4. Finally, in the online appendix, the paper proposes two categories of extensions to the basic **AMBLP** model, in order to take into consideration robustness of the (maintenance-base) solution with respect to real-world operational disruptions.

We note that the problem description herein, while stated in an airline context, is applicable to a much wider variety of operational situations where maintenance needs to be performed, e.g., Vaidyanathan, Ahuja, and Orlin (2008) describe a railroad routing problem wherein threshold limits are placed on the number of miles that locomotives can travel before being forced to visit either a refueling station, or a maintenance base. The rest of the paper is organized as follows. Section 2 provides further details about the problem context, notation and also reviews relevant literature. Section 3 resolves the complexity of the **AMBLP**. Section 4 devises a new lower bound for this problem. The performance for four heuristics for **AMBLP** is discussed in Section 5. Section 6 provides a short numerical example (in the online appendix). Section 7 (in the online appendix) provides a discussion of *robust* Aircraft

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Maintenance Base Location and extends the basic **AMBLP** model to situations where operational considerations force lines of flights for certain aircraft to be altered. For instance, Heinold (2008) considers aircraft swaps designed to increase maintenance opportunities. Since the location of maintenance bases represents a strategic decision whose consequences cannot be easily reversed, a robust set of maintenance bases must be selected a priori while taking into consideration the potential for such operational disruptions. Finally, the limitations of the current set of models, conclusions and future research directions are presented in Section 8.

2. Literature review, problem definition and notation

Gopalan and Talluri (1998a) provide a comprehensive overview of the airline schedule development process. The first step in the process determines the *schedule* itself, which consists of a series of flight legs, e.g., a flight from Boston to Miami, departing at 3 p.m. Schedule development is followed by *fleet assignment* which determines the equipment *type* to be assigned to a flight leg, e.g., that the Boston to Miami flight at 3 p.m. is to be flown by a MD-80. The principal consideration in fleet assignment is matching plane capacity with passenger demand. Fleet assignment does *not* indicate which one of the aircraft (called tail numbers or nose numbers in the industry) in that fleet actually flies the flight leg (e.g. the airline may own twenty MD-80s, but fleet assignment does not determine which precise tail number will fly from Boston to Miami at 3 p.m.). Fleet assignment is followed by *through-flight selection* and the determination of *aircraft maintenance rotations*. The current paper deals with an *inverse optimization problem* that is closely related to, and complementary to the design of effective aircraft rotations. It considers the location of aircraft maintenance bases in order to ensure that all required forms of maintenance can be performed with a pre-determined *periodicity*.

After fleet assignment and through flight selection have been completed, the aircraft rotation problem can be decomposed by fleet. The Federal Aviation Administration (FAA) requires several different types of aircraft maintenance. The checks, subdivided as *A*, *B*, *C* and *D* type checks, vary in their scope, duration and frequency. Of these, only type *A* checks have to be performed frequently (approximately every 65 flight hours) and are considered routine maintenance. A type *A* check involves a visual inspection of all the major systems. If the check is not performed within the specified period, FAA rules prohibit the aircraft from flying. The remaining checks are of longer duration and are not considered routine maintenance (however, a few of the major airlines split the *C* check into quarter *C*-checks or balance-checks and plan them together with *A* checks (Gopalan & Talluri, 1998a)). Industry maintenance practices are usually more stringent than even FAA requirements. Airlines allow at most 35–40 hours of flying before the plane undergoes what is called a *transit check*. This check involves a visual inspection and a check of the Minimum Equipment List (MEL). The transit check is usually performed whenever a plane visits a maintenance station, regardless of how recently it was last performed. Note that a visit to a maintenance station represents a maintenance opportunity and does not necessarily mean that we actually perform maintenance on that aircraft.

During a typical day, a plane starts off at some station, makes a series of stops at intermediate airports and overnights at some other station, which may or may not be a maintenance base. In this work, we consider the location of maintenance bases to appropriately enable the performance of extended maintenance checks that can only be performed at night. We abbreviate a day's activity for a specific tail number in terms of *lines of flying* (LOFs). A LOF only specifies the origin at the start of the day and the destination at the end of the day for a particular airplane (ignoring intermediate stops made during the day). LOFs are also referred to as *over-the-day routings* (Kabbani & Patty, 1992). The LOFs can be easily constructed from a fleeting by using simple rules such as first-in–first-out (FIFO) or last-in–first-out (LIFO). However, we note that the LOFs so constructed need not satisfy maintenance requirements. In order to meet the requirement for transit checks, we require that every tail number spend a night at a maintenance station after at most k days of flying ($k = 3, 4$) since its last overnight visit to a maintenance station. All aircraft rotations must possess this *periodic structure* and any proposed locations for a set of maintenance bases must ensure that rotations can be developed that periodically pass through a maintenance base after at most k days of flying.

The development of aircraft *rotations* within each fleet is therefore crucial for ensuring periodic maintenance. Two broad solution approaches are usually adopted when developing aircraft rotations: the first approach uses detailed mathematical programming methodology to appropriately insert maintenance opportunities into sequences of flights, referred to as flight strings (Barnhart et al., 1998; Clarke, Hane, Johnson, & Nemhauser, 1996; Clarke, Johnson, Nemhauser, & Zhu, 1997). Desaulniers, Desrosiers, Dumas, Solomon, and Soumis (1997) and Sarac, Batta, and Rump (2006) consider operational aircraft routing and scheduling problems. Cohn and Barnhart (2003) and Cordeau, Stojkovic, Soumis, and Desrosiers (2001) incorporate crew considerations with maintenance and aircraft routing, while more recently, Liang, Chaovalitwongse, Huang, and Johnson (2011) have considered a "rotation-tour" network model for aircraft maintenance.

The second approach, which we adopt in this paper, uses the structure of the underlying lines of flying (LOFs) for the day to devise maintenance heuristics (Gopalan & Talluri, 1998b). After completing fleet assignment, which determines the equipment *type* assigned to each flight leg, the routings of planes amongst airports can be modeled as an Eulerian graph (i.e., a graph where each node is incident to an even number of edges), where each arc (in the Eulerian graph) represents a line-of-flight (LOF) for a specific plane for a day (Fig. 1). In aircraft maintenance, it's common practice to require tail numbers to follow an Euler tour of the graph (i.e., a tour that covers every edge exactly once) in order to ensure uniform wear and tear on all aircraft. The following sub-section provides some background information on Euler tours and their applications in various real-world logistical problems.

2.1. Euler tours and their applications

The Euler tour problem was first conceived by Leonhard Euler in the famous "7 Bridges of Konigsberg" problem. Assad (2007) provides a historical review of Euler and his contributions to graph theory. In an Euler tour, every edge in a graph is covered exactly once: a necessary and sufficient condition for the existence of an Euler tour is that every node be of even degree (Edmonds & Johnson, 1973). This condition is automatically satisfied in any graph $G = (V, E)$ where the edges E represent the lines of flight for aircraft for a day, since the number of aircraft that overnight at a station must equal the number of aircraft originating at the station the next day (this observation excludes red-eye flights). Euler tours also naturally arise in a number of logistical contexts, e.g., salting streets during winter (Eglese & Li, 1992; Muyldermans, Cattrysse, Van Oudheusden, & Lotan, 2002). Edmonds and Johnson (1973) studied a variant of the Euler tour problem known as the Chinese Postman problem wherein each edge must be covered *at least* once in a CPP tour.

2.2. The K-MET and K-AMBLP

We now define a useful concept, the K-MET.