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Incorporating aircraft efficiency measures into the tail assignment problem

Marcial Lapp [a,*], Florian Wikenhauser [b]

[a] Industrial and Operations Engineering, University of Michigan, 1205 Beal Ave, Ann Arbor, MI 48109, USA
[b] Deutsche Lufthansa AG, Lufthansa Aviation Center, D-60546 Frankfurt/Main, Germany

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A B S T R A C T

We present an optimization framework that minimizes aircraft fuel consumption and emissions through a redesigned tail assignment process. In this fleet specific aircraft assignment, we reallocate aircraft such that fuel efficiency is matched with the fuel productivity of a line-of-flight. We demonstrate substantial fuel cost-savings using a multi-commodity flow network formulation. Realizing that a post aircraft routing, fuel-based aircraft assignment has the potential to alter the pre-existing flight plan, we reformulate the problem within the context of a Pareto-efficiency frontier. Within this framework, we explore the trade-off between fuel savings and three other variables: the number of line-of-flight changes, the number of schedule changes and the combined aircraft utilization. The resulting Pareto-efficiency curves serve as a decision management tool to allow operations managers to determine the most desirable level of fuel savings, while choosing either an acceptable number of changes to a pre-existing schedule or setting a minimum aircraft utilization level.

1. Introduction

The cost of jet-fuel constitutes a major portion of an airline's operational expense. According to the US Bureau of Transportation in 2010 jet-fuel cost $24,791 million to serve the domestic US market. In 2010, fuel costs accounted for 30% of the operating costs for Delta Airlines, which is equivalent to $0.038 per available seat-mile (ASM). While fuel costs are generally of interest to airlines, aircraft efficiency also has environmental impacts. It has been argued that roughly 70% of aircraft exhaust is in the form of CO_2, as well as other environmentally harmful gases. Thus attempting to maximize aircraft efficiency has additional environmental benefits, especially as air-travel is predicted to grow by as much as 50% by 2025 (Economist, 2009). Here we reformulate the tail assignment problem to capture assorted aircraft fuel-efficiencies and thus reduce overall fuel consumption of a flight plan.

2. Fuel efficiency in airline plans

We explore the implementation of a modified planning process to harness differing fuel-efficiencies among aircraft and the heterogeneity, in terms of fuel requirements, that exists between flights. This modification to the planning process resides within the tail assignment, which is typically solved within a week of the day-of-operation (Talluri, 1998). During the process, airlines decide which aircraft (tail) is assigned to a specific line-of-flight (LOF), a daylong sequence of flights that will be flown by a single aircraft. The tail assignment problem is generally solved on a rolling horizon, adding the next planning day during each iteration.

We optimize a flight schedule by minimizing the amount of fuel required for execution and solve the tail assignment problem for a specific fleet based on the results of a fleet assignment process completed earlier in the planning process (Fig. 1). Depending on the airline, further restrictions and maintenance events are generally added, which can further complicate this problem (Gopalan and Talluri, 1998). We assume that these restrictions have already been included during a prior planning phase.

The size of the impact of a fuel-based tail assignment is determined by two properties that are inherent to an airline's operation: the heterogeneity of aircraft in terms of fuel efficiency within the same fleet family, and the degree to which flights differ in terms of requirements.

Fuel efficiency is a gained by changing the composition of aircraft within a fleet; e.g. an airline may have a fleet of Airbus A-321 aircraft that have different properties affecting fuel consumption including (Babikian et al., 2002):

- Engine Properties – The make and model of an aircraft engine feature different fuel consumption ratings.
- Engine Maintenance – Engine washes and general maintenance have been shown to improve overall fuel efficiency by up to 5% as demonstrated through internal studies at our partner airline.

* Corresponding author. Tel.: +1 2483799858.
E-mail address: mlapp@umich.edu (M. Lapp).

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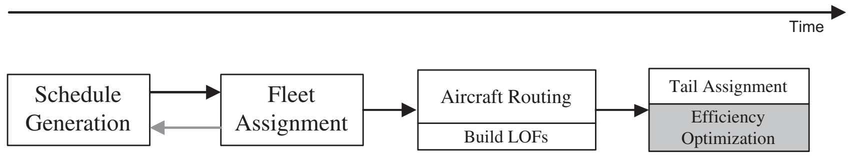

Fig. 1. Airline Planning Process Overview.

- Aircraft Modifications – The addition of wing-tips (Daude, 1982) has significant effects on fuel efficiency. Furthermore, recent aircraft painting can add additional weight, and thus reduce the overall fuel efficiency.
- Aircraft Age – The age of the aircraft is a surrogate for the wear and tear on the airframe, in which small deformations can lead to increased drag and reduced efficiency over time.

Although aircraft are heterogeneous in terms of their fuel efficiencies, we assume that such aircraft are completely interchangeable and, as such, we only consider a single fleet of a common type for our analysis.

Furthermore, a fuel-based tail assignment is only effective if lines-of-flight vary in their fuel requirements. For example, a flight plan may contain short- and long-haul flights, each of which require a different amount of fuel during the take-off and cruise stages. We focus on this difference to gain fuel consumption advantages when performing tail assignments.

Fig. 2 illustrates the approach of the optimization model for two LOFs for a given day. The first LOF requires 24,000 kg of fuel, while the second requires 34,000 kg. Given two aircraft with efficiency ratings of 1.0 and 1.05, it would be advantageous to have the first aircraft fly LOF #2, while the second is assigned to LOF #1; this minimizes the fuel consumption of the flight schedule.

To harness additional fuel savings through the improved assignment process, we recombine the LOFs in Fig. 3. The two LOFs are split when both aircraft are on the ground at FRA. This recombination attributes 14,000 kg of fuel to the newly-created LOF #1, while LOF #2 now requires 44,000 kg. With the same aircraft it is advantageous to assign the aircraft with the efficiency factor of 1.0 to the recombined LOF #2 and the second aircraft to LOF #1.

3. Model framework

To incorporate fuel efficiency measures into the planning process, we examine two mathematical optimization models. The first, flight-based, model performs a fuel-based tail assignment including recombined lines-of-flight. In the second, more restrictive approach, we allow only an entire day's line-of-flight to be assigned; this provides for smaller fuel savings, but does not disrupt an airline's operational process.

The flight-based tail assignment follows a traditional multi-commodity-flow formulation (Grönkvist, 2005). We allow the solution to selectively stitch together flights to form a LOF and subsequently assign such a line to a particular tail (Gopalan and Talluri, 1998). This takes advantage of both factors that affect the fuel consumption of a flight plan: heterogeneity of aircraft efficiency and LOF fuel productivity.

Sets

F: The set of all flights (only for a single fleet type).
T: The set of all tails (only for a single fleet type).
U^i: The set of all possible upstream flights for a given flight $i, \forall i \in F$.
D^i: The set of all possible downstream flights for a given flight $i, \forall i \in F$.

Parameters

p_t: The performance factor (multiplier) of a particular tail, $\forall t \in T$.
r_i: The mean amount of fuel required to fly flight $i, \forall i \in F$.

Decision variables

x_{ijt}: A binary variable that is 1 if flight i is followed by flight j performed by aircraft t and is 0 otherwise.
y_{it}: A binary variable that is 1 if flight i is the first flight performed by aircraft t and is 0 otherwise.
z_{it}: A binary variable that is 1 if flight i is the last flight performed by aircraft t and is 0 otherwise.

Objective:

$$\min \sum_{t \in T} p_t \left(\sum_{i \in F} \left(\sum_{j \in F} x_{ijt} + z_{it} \right) \right) \tag{1}$$

Subject to:

$$\sum_{j \in U^i} x_{jit} + y_{it} - \sum_{j \in D^i} x_{ijt} - z_{it} = 0 \quad \forall i \in F, \forall t \in T \tag{2}$$

$$\sum_{i \in F} y_{it} \leq 1 \quad \forall t \in T \tag{3}$$

$$\sum_{t \in T} \left(y_{it} + \sum_{j \in U^i} x_{jit} \right) = 1 \quad \forall i \in F \tag{4}$$

$$x_{ijt} \in \{0, 1\} \quad \forall i \in F, \forall j \in F, \forall t \in T \tag{5}$$

$$y_{it} \in \{0, 1\} \quad \forall i \in I, \forall t \in T \tag{6}$$

The objective function Eqn. (1), assumes a linear relationship for computing the expected amount of fuel required for a flight leg; i.e. we multiply the performance factor of an aircraft by the expected fuel required for the flight. Furthermore, when determining the possible upstream and downstream set of flights (U^i, D^i), we not only include time and space restrictions, but also assume that the minimum turn-time required for each flight is 30 min.[1]

Eqn. (2) requires each tail to maintain a sequence of events; if a tail performs flight i, then this tail must have performed another activity that ended in i with respect to a particular station and time. This is a type of sequencing constraint for all the activities in the system. Eqn. (3) ensures that each activity is assigned to at most one tail. In addition, Eqn. (4) ensures that each flight is covered by exactly one tail. Finally, we require that both x_{ijt} and y_{it} are binary variables, which, by implication, forces variable z_{it} to be binary, without an explicit restriction.

The model allows for complete freedom to form LOFs to minimize the expected amount of fuel required for a particular flight

[1] In practice an airline may consider additional robustness measures before connecting flights to ensure adequate slack between them.