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A new approach to fleet assignment and aircraft routing problems

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Abstract

In this study, a new mathematical formulation is developed for fleet scheduling problems (i.e., the combination of fleet assignment and aircraft routing problems) in single hub & spoke systems. The proposed model aims to minimize the total cost of allocating aircraft to flights while observing the sequence of flights to be subject to seat capacity, passenger demand, aircraft availability, and overlapping flights. Since the classical fleet scheduling problem is NP-hard, a couple of complexity reduction techniques are developed. Thus, the size of the problem is decreased significantly. To evaluate the model's performance, it is implemented to an airline carrier with 170 aircraft and 1290 (645 round trip) flights. As a result, the proposed method ended up with an improvement of 36.7% for a 2-day planning horizon.

Keywords: fleet scheduling; fleet assignment; aircraft routing; linear programming

1. Introduction

The increasing number of annual passenger figures triggers the growth of the civil aviation industry, which is a highly competitive market. Aircraft and aircrew are expensive resources to be efficiently utilized. Therefore, the airline companies' pricing policies, operational costs, and service quality should be managed effectively and in a

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coordinated manner (Sevkli et al., 2012). Airlines use complex methods of operation research to deal with the planning and logistics activities for maximizing the total revenue to be standing in the market.

Many commercial airlines decompose the planning and scheduling processes into sequential sub-problems with less complexity (e.g., flight scheduling, fleet assignment, aircraft routing, and crew assignment), as seen in Figure 1. Even though all these problems are strongly dependent on each other, consolidation and optimization cannot be achieved in a reasonable time due to the high complexity and large-scale nature of the problem. For that reason, all these sub-problems have to be considered independently (Papakostas et al., 2010).

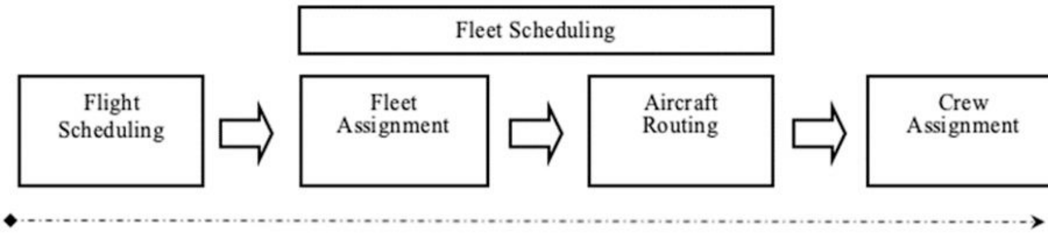

Fig. 1. The general process flow of airline logistic operations

Fleet assignment problem (FAP) covers assigning aircraft with different capacities, to the scheduled flights, according to their equipment capabilities and availabilities, by minimizing the operational costs or maximizing the potential revenues (Bae, 2010; Sherali et al., 2006). Thus, flights are matched to aircraft types to reduce the expected number of aircraft-route pairs that form the basis of the aircraft routing problem.

The aircraft routing problem (ARP) involves assigning tail numbers of aircraft to a specific set of flights or pre-generated feasible routes subject to flight coverage, aircraft maintenance, and utilization constraints (Sarac et al., 2006).

Fleet assignment and aircraft routing problems have been traditionally solved separately because of their complexity. However, with the help of advances in computer hardware and heuristic search optimization, integrated approaches are getting popular in recent years (Mercier, 2008).

In this study, a new framework and a mixed-integer linear mathematical programming (MILP) model are developed to optimize the total cost of fleet assignment and aircraft routing problems for a single hub & spoke system. Thus, the model finds unique rotations that will be repeated by each aircraft in the fleet subject to seat capacity, passenger demand, aircraft availability, and overlapping flights.

The novelty of the model is based on reducing the complexity of the problem. In hub & spoke systems, the hub refers to the single centralized operation center. The nodes are the delivery points, while the spokes are the communication routes between the nodes and the hub. Therefore, there are no direct point-to-point flights between the nodes, all the traffic is recognized between the nodes and the hub. This condition is converted to an advantage to reduce the size of the problem by considering the flight as a round trip manner.

The second reduction is obtained by generating two new binary matrices. The first one represents which airplane can be utilized in which flights with respect to sector constraints, capacities, availability, etc. The second one demonstrates which flights are overlapped. Using these matrices, the constraints that ensure airplane capability for a specific flight and prevent assigning an airplane to overlap flights are reduced to a single type of constraint structure. With the help of the problem size reduction techniques, it is shown that the solution for the fleet scheduling problem can be achieved in a reasonable time interval.

In order to demonstrate the validity and performance of the proposed model, it is implemented to a 2-day flight schedule of an airline carrier with 710 flights and 170 airplanes. To solve this real case, the model is coded in "Xpress Optimization Suite" software and run in a 128GB-RAM & 16-Core Intel Xeon Workstation 2.4GHz. As a result, the proposed model generated 36% better solutions than the current method used by the company.

2. Literature Review

Airline fleet assignment problems are covered mostly in the airline logistics literature. The problem is mainly based on the flight schedules that specify the covered flight legs and their respective departure times.

A fleet assignment model introduced by Abara (1989) uses a connection-based network structure that encompasses coverage and flow balance constraints and considers the number of available aircrafts. A large-scale integer program that uses a time-space network structure for the fleet assignment was developed by Hane et al. (1995). Since this method eliminates the use of connection decision variables, it becomes a widely accepted and adopted approach utilized for the fleet assignment problem formulation. Another mathematical model that focuses on the aircraft rotation problem is presented by Clarke et al. (1996). In this study, a Lagrangian relaxation approach is used, and sub-tour elimination and maintenance constraints are added to the original model when violated. Another interesting model and a novel solution approach is introduced by Barnhart et al. (1998) as a simultaneous solution for the fleet assignment and aircraft routing problems. They consider aircraft connection costs and complex constraints like maintenance requirements. Sherali, Bae and Haouari (2013, 2010) proposed some efficient Benders decomposition algorithms for the integrated flight scheduling and fleet assignment problem that acknowledges optional legs, multiple fare categories, and itinerary-based demands.

Salazar-Gonzales (2014) worked on the integrated aircraft routing, fleet assignment, and crew pairing problem. They developed a heuristic algorithm, taking an integer programming model as a base. Cadarso and Marin (2013) proposed a robust model for the integrated fleet assignment and flight scheduling problem to minimize the number of misconnected passengers. Lin and Zhang (2017) considered the congestion problem at the hubs and they worked on the economic impact of altering the flight frequency, runway capacity, and some other factors on a hub-and-spoke network. Dozic and Kalic (2015) proposed a robust model for the fleet planning of the airlines, considering the fleet size and some composition problems that utilize different approaches like fuzzy logic, heuristic/analytic methods, and MCDM techniques. Dong et al. (1996) also proposed a heuristic model for the integrated fleet assignment and flight scheduling problems. Shao et al.(2015) introduced a decomposition method for the integrated aircraft routing, fleet assignment, and crew pairing problem. A considerable effort has been expended to optimize the airline operations by (Lee et al., 2016). Desaulniers et al. (2008) and Rexing et al. (2003) tackled another version of FAP where some deviations on the flight departure times is allowed. They determined some “time windows” that represent the allowable ranges for the departure times. This flexibility enables new feasible options for the flight connections and may lead to fleet assignments with more profitable/less costly outcomes.

On the other hand, ARP, first presented by Daskin and Panayotopoulos (1989), is modeled as mixed-integer linear mathematical programming (MILP) that maximizes profits in a single hub & spoke network. The model developed by Feo and Bard (1989) was tested in American Airlines to determine the locations of the maintenance stations. Their proposed model fulfills the recursive demand for A-checks by enabling better flight schedules. Other approaches to ARP include feasible route selection model (Kabani and Patty, 1993), a mathematical formulation inspired from the asymmetric traveling salesman problem (Clarke et al., 1997), network flow and polynomial-time swapping algorithm (Gopalan and Talluri, 1998), a heuristic approach to mixed-integer ARP (Sriram and Haghani, 2003), and a MILP model based on the multi-commodity network flows (Basdere and Bilge, 2014).

Haouari et al. (2011) describe some models with exact solutions for an integrated aircraft routing and fleeting problem for Tunis Air. In addition, they investigated some methods exploiting Branch-and-Price and Benders decomposition approaches for this problem.

Various studies have been presented in the literature regarding the integration of crew scheduling and fleet scheduling and aircraft routing problems (Klabjan et al., 2002; Papadakos, 2009; Sandhu and Klabjan, 2007; Weide et al., 2008).

In this paper, the fleet scheduling problem (FSP), which integrates the FAP and ARP, is considered under the single hub and spoke system. The primary purpose of the FSP is to minimize the total cost or maximize the total revenue acquired from aircraft-route assignments during the planning time-horizon (e.g., 3-7 days). AP assigns aircraft types to the scheduled flights concerning seat capacity, passenger demand, equipment capabilities, aircraft availabilities, and operational costs. For instance, some aircraft cannot fly long distances since fuel tanks are not adequate or the gate structure of the destination airport may not be suitable for the corresponding aircraft. Besides, for short-range flights, large-scale airplanes are not preferred since the operating cost of these airplanes is higher than the operation cost of small aircraft. Therefore, instead of using big aircraft, flight frequencies of small aircraft are increased to meet the passenger demands. For that reason, FAP is essential for the overall scheduling process of an airline and highly affects airline revenues.

3. The proposed model

In this study, fleet assignment, route generation, and aircraft routing problems for single hub&spoke systems are integrated and formulated in a single mathematical optimization model. Since this integration also increased the complexity, we performed constraint reduction techniques.

In a "point-to-point system", generally, there are flights from every city to other cities in its neighborhood. However, in hub&spoke systems, all flights are operated between hub and cities. Due to this fact, problem complexity of FSP in hub&spoke systems can be reduced by altering the classical one-directional flight concept in Figure 2 to a round-trip one depicted in Figure 3. Thus, the number of flights in the flight schedule during the planning time-horizon (i.e., problem size) was reduced at the rate of 0.50 by the proposed technique.

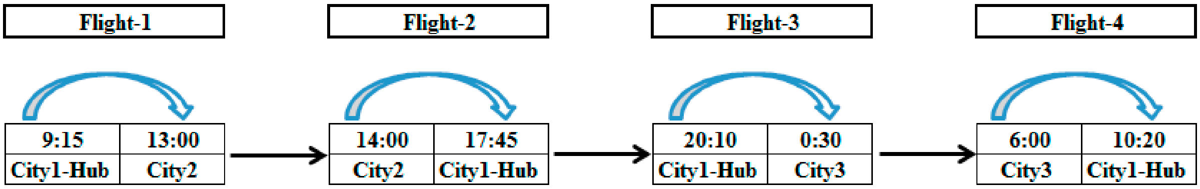

Fig. 2. Flight concept in the airlines; (City1 is the hub-airport)

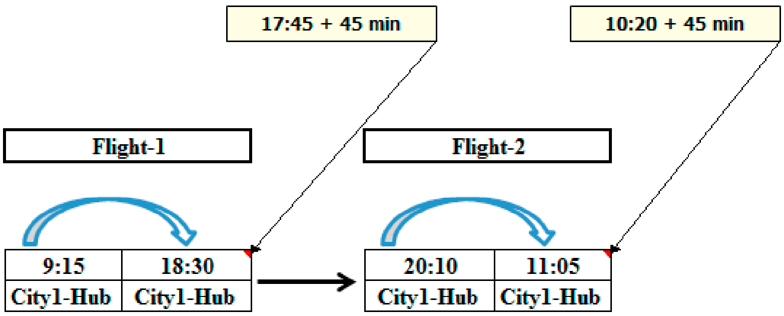

Fig. 3. The proposed flight concept in the airlines

The second complexity reduction is achieved by excluding maintenance scheduling out of ARP or route generation process. Although this does not affect the applicability of the proposed model, it brings a different systematic approach to fleet scheduling. Note that, in hub&spoke systems, all the air traffic is between nodes and hubs; that is, there are no direct point-to-point flights between the nodes. Therefore, on two consecutive flights, the aircraft must visit the hub for once. For that reason, each aircraft already visits the hub more than once during the planning time horizon. Thus, most of the time, sufficient maintenance opportunities will be available for the aircraft.

3.1. Problem Formulation

This section explains how fleet assignment and aircraft routing problems for single hub&spoke systems are consolidated and formulated as a MILP model. In order to integrate these two problems, the objectives and corresponding constraints discussed in previous sections are harmonized.

Let us remind that, to remove complexity in traditional fleet scheduling, feasible routes are generated according to predefined rules before the aircraft routing problem is tackled. However, on the contrary, routes are generated as an output of the optimization process in our proposed model. That is, specific routes are obtained while the model minimizes the total cost of the aircraft-to-flight assignment subject to flight coverage, network flow, overlapping flights, seat capacity, and aircraft availability constraints. Thus, the general mathematical formulation of FSP can be represented as follows:

Parameters:

$\boldsymbol{F}$	$= Number\ of\ Flights$ *(Flights are defined as hub to hub –round trip travel)*	
$\boldsymbol{N}$	$= Number\ of\ Aircrafts(tails)$	
$\boldsymbol{Cost_{i,j}}$	$= Cost\ of\ aircraft\ j\ in\ Flight_i$	$: set(F \times N)$
$\boldsymbol{AT_i}$	$= Arrival\ time\ of\ Flight_i$	$: set(F)$
$\boldsymbol{DT_i}$	$= Departure\ time\ of\ Flight_i$	$: set(F)$
$\boldsymbol{CCC_j}$	$= Comfort\ class\ seat\ capacity\ of\ Aircraft_j$	$: set(N)$
$\boldsymbol{CBC_j}$	$= Business\ class\ seat\ capacity\ of\ Aircraft_j$	$: set(N)$
$\boldsymbol{CEC_j}$	$= Economy\ class\ seat\ capacity\ of\ Aircraft_j$	$: set(N)$
$\boldsymbol{BCC_i}$	$= Number\ of\ booked\ passengers\ on\ comfort\ class\ of\ Flight_i$	$: set(F)$
$\boldsymbol{BBC_i}$	$= Number\ of\ booked\ passengers\ on\ business\ class\ of\ Flight_i$	$: set(F)$
$\boldsymbol{BEC_i}$	$= Number\ of\ booked\ passengers\ on\ economy\ class\ of\ Flight_i$	$: set(F)$
$\boldsymbol{BCR}$	$= Booking\ Cancellation\ Rate$: $If\ Overbooking\ Passenger\ Rate\ is\ assumed\ as$ 0.1 Booking Cancellation Rate: 0.9	
$\boldsymbol{R_j}$	$= Ready\ (available)\ time\ of\ aircrafts\ for\ their\ first\ departure$	$: set(N)$
M	$= Sufficiently\ large\ number$	

Decision variables:

$$X_{i,j} = \begin{cases} If\ Flight_i\ is\ assigned\ to Aircraft_j & 1 \\ Otherwise & 0 \end{cases} \qquad \left. \forall i = 1, \dots, F \wedge \forall j = 1, \dots, N \right\}$$

$$y_{ijk} = \begin{cases} If\ Flight_i\ and\ Flight_j\ is\ assigned\ to\ Aircraft_k \\ \quad Otherwise \quad 0 \end{cases} \qquad \left. \forall i, k = 1, \dots, F \wedge \forall j = 1, \dots, N \right\}$$

Objective Function

$$Min \quad \sum_{i=1}^{F} \sum_{j=1}^{N} Cost_{ij} * X_{ij} \tag{1}$$

S.t.

$$\sum_{j=1}^{N} X_{i,j} = 1 \qquad \forall\ i = 1, \dots, F \tag{2}$$

$$AT_i * X_{ij} - DT_k \times X_{kj} \leq M * y_{ijk} \qquad \forall\ i, k = 1, \dots, F \quad \wedge \quad \forall\ j = 1, \dots, N \tag{3}$$

$$AT_k \times X_{kj} - DT_i \times X_{ij} \leq M\left(1 - y_{ijk}\right) \qquad \forall\ i, k = 1, \dots, F \quad \wedge \quad \forall\ j = 1, \dots, N \tag{4}$$

$$R_j \times X_{ij} \leq X_{ij} \times DT_i \qquad \forall\ i = 1, \dots, F \quad \wedge \quad \forall\ j = 1, \dots, N \tag{5}$$

$$BCC_i \times BCR \leq CCC_j \times X_{ij} \qquad \forall\ i = 1, \dots, F \quad \wedge \quad \forall\ j = 1, \dots, N \tag{6}$$

$$BBC_i \times BCR \leq CBC_i \times X_{ij} \qquad \forall\ i = 1, \dots, F \quad \wedge \quad \forall\ j = 1, \dots, N \tag{7}$$

$$BEC_i \times BCR \leq CEC_i \times X_{ij} \qquad \forall i = 1, \dots, F \quad \wedge \quad \forall j = 1, \dots, N \tag{8}$$

$$X_{ij} = \{0,1\} \qquad \forall i = 1, \dots, F \quad \wedge \quad \forall j = 1, \dots, N \tag{9}$$

The objective function in Eq.(1) minimizes the total operation cost of the aircraft-flight assignments (e.g., fuel costs, crew salaries, etc.). Eq.(2) is the flight coverage constraint that ensures that an aircraft is assigned to each flight. Eq.(3) and Eq.(4) are either/or constraints providing that overlapping flights cannot be carried out by the same aircraft. Note that, in this model, a round-trip flight (i.e., a flight departing and returning to a hub) will be considered as a one-way flight. Therefore, we don't need to follow the aircraft's flight legs (i.e., airport) since the aircraft will always be on a hub point when it is idle.

When the model is executed, the aircraft may not be available at the hub point (e.g., it can be on air). So that, for the first departure, the ready time (i.e., R_j) of each aircraft on the hub point should be calculated. Eq. (5) guarantees that the departure time of the aircraft's first flight is greater than or equal to the available time of the aircraft.

Especially in the summer seasons, the demand for airline transportation increases excessively. Thus, the load factor of aircraft approaches 100% level in most of the flights. However, cancellation of the booked tickets may lead to revenue losses. For that reason, airlines may sell more tickets than the capacity of the aircraft to cope up with cancellations. Eq. (6-8) are the capacity constraints to ensure that anticipated passengers (i.e., booked passengers – booked cancellation) of business, comfort, and economy class passengers cannot exceed the seating capacity (Utilizing overbooking passenger policy is optional).

To obtain a computational advantage, we simplified the proposed method by decreasing the number of constraints. In the new model, Eq. (3-8) will be represented by two sets of constraints. To achieve that, the following "$O_{i,k}$" and "$G_{i,j}$" matrix will be generated:

$$\boldsymbol{O}_{\mathbf{i,k}} = \begin{Bmatrix} If\ Flight_{\ i}\ and\ Flight_k\ \ is\ overlapped\ 1 \\ Otherwise\ \ 0 \end{Bmatrix} \qquad : set(FxF)$$

$$\boldsymbol{G}_{\mathbf{i,j}} = \begin{Bmatrix} If\ Aircraft_j\ \ can\ be\ assigned\ to\ Flight_i\ \ 1 \\ Otherwise\ \ 0 \end{Bmatrix} \qquad : set(FxN)$$

Note that $O_{i,k}$ is a binary data set that depicts whether two corresponding flights are overlapped or not by checking the arrival and departure times. Additionally, $G_{i,j}$ demonstrates that seat capacity and ready time of $Aircraft_{\ j}$ is appropriate for $Flight_{\ i}$. Thus, the proposed model can be transformed as follows. Here, Eq.(10) and Eq.(11) encapsulate the sets of Eq.(3-4) and Eq.(5-8) in the primal model. The new proposed model is as follows:

Objective Function:

$$Min \ \sum_{i=1}^{F}\sum_{j=1}^{N} Cost_{\ ij} * \ X_{ij} \tag{1}$$

St.

$$\sum_{j=1}^{N} X_{ij} \ = 1 \qquad \forall i = 1, \dots, F \tag{2}$$

$$O_{i,k} + X_{ij} + X_{kj} \leq 2 \qquad \forall i,k = 1, \dots, F \ \wedge \ \forall j = 1, \dots, N \quad | \, i \neq k \tag{10}$$

$$X_{ij} \leq G_{ij} \qquad \forall i = 1, \dots, F \quad \wedge \ \forall j = 1, \dots, N \tag{11}$$

4. Results and discussion

In the current system, the airline carrier uses commercial software that generates feasible solutions for 2-3-4-7 days' fleet scheduling. For unexpected events such as weather conditions, postponed flights, and aircraft failures, etc., the obtained solution can be manually altered by the planning department.

In order to show the efficiency of the new proposed model given in Equations (1-2-10-11), it is applied to the two days-flight-schedule of an airline company, which consists of scheduled "645" round-trip flights (e.g., City1-City2-City1, City1-City3-City1, and so on). The airline carrier has 24 different fleet types with "170" aircraft to carry out these flights. Thus, the proposed model tackles this two-days-assignment problem with 70.615.415 constraints and 109650 variables without applying reduction techniques.

Two days-flight schedule problem of an airline company was carried out on a supercomputer with 128 GB RAM, 16core i-7 processor. Xpress Optimization Suite (XPressMP) is utilized in this study to obtain an optimal solution for the proposed model. XPressMP can solve integer linear programming problems with up to millions of variables and constraints, with no fixed limits on problem size. It uses a branch and bound algorithm combined with cutting planes.

A feasible solution for a 2-day fleet schedule with a cost of €11.725.580 is obtained within 2.5 hours, which can be considered reasonable. The optimality gap for this solution is approximately 30%. Although this is not an optimal solution, the solution quality is about 14% better than the solution obtained by the commercial software company uses. XpressMP software converged the optimal solution of €8.723.063 within 27.5 hours (approx. 100000 sec). This optimal solution is better than the company's solution, with a rate of 36.7%. This improvement can save about five million euros only for a 2-days' planning horizon, as seen in Table 1.

Table 1. Total scheduling cost of current and proposed methods

Airline's Current Method	€13.771.473 (3 hours)	
The proposed method	€11.725.580 (solution obtained within 2.5 hours)	€8.723.063 (solution obtained within 27.5 hours)
Difference	€2.045.893	€5.048.410
Improvement Rate	14.9%	36.7%

An overview of the optimal solution is presented in Table 2.

Table 2. Optimal solution of the proposed model

Aircraft	1st Flight	2nd Flight	3rd Flight	4th Flight	5th Flight	6th Flight	7th Flight
1	39	200	290	348	419		
2	130	307	382	393			
3	80	143	389	414	594		
4	82	160	212	269	357		
5	58	87	89	237	312	460	
6	176	199	240	327	335		
7	83	88	124	204	418	461	
8	72	120	202	252	345		
9	35	133	159	169	433		
10	48	90	95	161	180	209	380
.	.	.	.	.	.	.	.
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170	136	163	213	328	509	619	

5. Conclusion and future work

Fleet scheduling is an important activity for airlines. It aims at finding an acceptable solution for an aircraft-route assignment for a definite planning time horizon. The most used approach in the literature is dividing fleet scheduling problem (FSP) into two independent problems named "fleet assignment" and "aircraft routing" to decrease the complexity of the problem and generate solutions in a reasonable time.

In this study, a new mathematical programming model is developed to solve the complete FSP for single hub & spoke systems by integrating fleet assignment and aircraft routing problems. Thus, the proposed model minimizes total assignment cost subject to the traditional constraints such as seat capacities, overlapping flights, aircraft availability, etc. Although the model does not contain any constraints for the maintenance operations, which can be considered as a limitation of this study, it brings a new systematic approach for short-term maintenance planning (A-

Type) checks.

In order to reduce the complexity of the problem, two novel reduction techniques are developed. Firstly, a round trip (i.e., string base) flight concept is utilized for a hub and spoke system. Secondly, we simplified the proposed method by decreasing the number of constraints.

Thus, the proposed approach is modeled as a mixed-integer linear model that can be solved in a reasonable time. In order to compare the performance of the model, it is applied to an actual 2-days flight schedule of an airline carrier. In terms of the total cost, the model yielded 14.9% and 36.7% improvement of the company fleet schedule with respect to different CPU times of 2.5 and 27.5 hours, respectively.

As future work, the concept of aircraft utilization balancing can be incorporated into the model. In addition, the solution time of the proposed model can be reduced by developing some relaxation, decomposition, and meta-heuristic search techniques.

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