Optimization of Aircraft Maintenance Routing Using Uninformed and Informed Search Algorithms

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***Abstract*—Airline sector runs on very high operational costs, strict protocols and complex scheduling process. One of the critical aspect influencing these factors is aircraft maintenance routing. In order to get maintenance at regular intervals as per the FAA regulations, an aircraft is required to be routed towards a feasible maintenance station. Aircraft maintenance routing is one of the major factor that influences the decisions throughout the airline operations. This paper proposes a maintenance feasible route generation technique, based on Breadth first search and Dijkstra's Algorithms. The proposed technique is able to produce the maintenance feasible routes while ensuring that the overall maintenance cost is minimized.**

***Index Terms*—aircraft maintenance routing, aircraft routing, aircraft maintenance, breadth first search, maintenance scheduling, Dijkstra's algorithm**

I. Introduction

The assignment of route to an aircraft while considering its maintenance requirements is called *"Aircraft Maintenance Routing Problem*". Aircraft maintenance routing is one of the challenging and important aspect for an airline for its critical and efficient operations.

As per the rules of Federal Aviation Authority there are four type of checks and maintenances that every airline has to follow. These checks varies in scope, duration and frequency. As discussed by Sriram et al. [1], these checks are categorized as:-

- Type A Check, (after every 65 hours) Duration is almost 8 hours
- Type B Check (after 300-600 hours). Duration is almost 1-3 days
- Type C Check and Type D check (after 1-4 years)

In this research, the main aim remained to provide complete methodology which can find a balanced route for an aircraft that belongs to a particular fleet of an airline. Given a set of flight legs for a specific aircraft type with the specified maintenance locations and known remaining flying hours a search based routing model is proposed which optimizes the aircraft maintenance routes. The objective of this research is to minimize the maintenance cost while keeping in view the maintenance requirements such as availability of man hours, slot availability and turn-around time of aircraft.

Manuscript received May 12, 2018; revised December 5, 2018.

II. Literature Review

A lot of research has been done in the field of aircraft maintenance and its routing. During the last two decades aircraft maintenance routing problem has attained significant attention in the literature. However, initially aircraft maintenance routing was taken as tactical requirement and multiple type of tactical models were proposed in this regard. Like, Kabbani and Patty [2] proposed a set portioning model for route identification of a maintenance feasible aircraft. In their research if the aircraft was grounded overnight in a maintenance station every three days then the aircraft route is maintenance feasible. Similarly, in 1997, Clark et al [3] proposed that the tail number assignment of an aircraft can gain a benefit of thorough value, whereas, penalty for undesired connections can also be imposed on a route.

Talluri et al. [4] presented an algorithm based on polynomial-time solution for the four-day aircraft maintenance routing which ensures that an aircraft should visit a maintenance station and remain grounded for some duration every four days. He shows that the problem is NP-complete. Sriram and Haghani [1] proposed the scheduling problem for a domestic flight schedule based on one-week planning horizon. Afsar et al. [5] proposed a two-step heuristic approach that maximizes the aircraft utilization. In their approach, they used a ten weeks rolling-horizon framework, with one week sliding window.

Keeping foregone in view, the available literature for operational model is relatively insufficient. Sarac et al. in 2006 [6] studied the problem as a daily operation problem rather than addressing it in long-term planning. They presented mathematical formulation for minimizing the unused legal flying hours while adjusting resource availability constraints. Orhan et al. (2012) [7] developed an integer linear goal-programming model with the objective to minimize the legal flying hours of the aircraft before they undergo maintenance. Basdere and Bilge (2014) [8] studied the operational aircraft maintenance routing problem. They considered both the un-capacitated

doi: 10.18178/ijmerr.8.1.141-145

and the capacitated variants. They proposed a multi-commodity flow model that aims to minimize the total unutilized legal flying time of the critical aircraft. In their model, they modified the connection network to be able to track the accumulated flying time of each aircraft. Sarhani et al. [9] extended the model proposed by Sarac et al. [6] for the Aircraft maintenance problem and added the case of aircraft on the ground (AOG) situation which is caused by the unscheduled maintenance events. The one day aircraft routing model along with the side constraints of maintenance is the prime focus of the paper and has been used as basis of our research.

III. Problem Formulation

A. Set Partitioning Method for Aircraft Maintenance Routing

While keeping in view the objective of reducing the aircraft maintenance cost, we have used the set portioning method, given by Sarac et al. [6]. This has been selected because of multiple reasons. First one is that this method can easily combine constraints that are based on availability of routes and it emphases on assignment of realistic routes to the aircraft. While reviewing the general vehicle routing problems we can identify that this type of formulation has been very effective, as proposed by Barnhart et al. [10], Desrosiers et al.1984 [11] and Dumas et al. 1991 [12].

The proposed objective function will be:-

$$\min \sum_{k\epsilon K} \sum_{j\epsilon Rk} c_j^k \, y_j^k \tag{1}$$

Subject to:-

$$y_j^k \in \{0,1\} \; \forall \, k \in K \; and \; j \in R_k \tag{2}$$

$$\sum_{k\in K} \sum_{j\in Rk} \gamma_{ji}^k \, y_j^k = 1 \qquad \forall \, i \in N \tag{3}$$

$$\sum_{k\in K} \sum_{j\in Rk} a_m^k \, d_{js}^k \, y_j^k \; \le \; L_{ms} \quad \forall \, m \in M \; and \; s \in S_m \tag{4}$$

$$\sum_{k\in K} \sum_{j\in Rk} b_m^k \, d_{js}^k \; y_j^k \; \le Z_{ms} \quad \forall \, m \in M \; and \; s \in S_m \tag{5}$$

The notations used in the given equations and their descriptions are as follows:-

i	:	index for flight legs
j	:	route index
m	:	maintenance station number
k	:	Aircraft number
s	:	index of overnight stations
R_k	:	Routes generated for aircraft 'k'
N	:	Set of flight legs
S_m	:	Overnight stations where maintenance can be performed
K	:	List of aircrafts
c_j^k	:	Cost of selecting route 'j' for aircraft 'k'
τ_k	:	Remaining flying hours of an aircraft
a_m^k	:	Randomly assigned Man-hours needed to perform maintenance for selected aircraft 'k'.
b_m^k	:	If aircraft needs maintenance type 'm' it is '1', else '0'
d_{js}^k	:	It is '1' if route 'j' of aircraft 'k' end at overnight station 's', else '0'
L_{ms}	:	availability of man hours for maintenance 'm'
Z_{ms}	:	Defines number of available slots for maintenance
y_j^k	:	Decision variable is set as '1' if the route 'j' of aircraft 'k' is selected, else it is '0'

The objective function given at (1) minimizes the aircraft maintenance routing (AMR) cost while ensuring the constraints of aircraft count (2), flight leg coverage (3), maintenance feasibility for man-hours (4) and maintenance feasibility for available slots (5) [6].

B. Network Structure

Published schedules of any airline are conventionally represented as networks of flight legs. In these type of flight network the nodes are identified as cities and the arcs between those nodes / cities are identified as flight legs that connect those cities. In order to track the arrival and departure time, a connection network was formed, in which nodes represented the flight legs whereas, arcs represented the suitable connections among the flight legs. In our case the selected connection network is cyclic. A feasible solution for the cyclic connection network was generated in such a manner that is ensures the high time aircraft (aircraft due for maintenance) are routed to a feasible maintenance station on the given day and the maintenance is achieved overnight at the maintenance station.

Data set for processing and calculation was obtained from the website of American Bureau of Transportation Statistics [13], and sample flight data was taken from the flight connection network of United Airlines for the month of March, 2017. The data set used after pre-processing was having 743 flights for 150 cities. After pre-processing the flight data network, aircraft related data was randomly generated. First we created the aircraft with maintenance requirements which includes remaining flying hours for that aircraft, requirements for maintenance man hours, than a list of maintenance station was randomly generated with available man hours and number of slots.

C. Flight Network Generation

Operational requirement of an aircraft limits the route generation process because each aircraft has its own set of requirements. Therefore, as mentioned earlier the cost of maintenance and route generation has to be optimized for each aircraft in such a manner that the overall cost of all maintenance feasible routes is minimized. In this study we developed the objective function using Matlab. Initially a list of all 150 nodes were made, then the list of flight schedules was created for 743 flights. Then multiple instance were generated containing aircraft specific data. However, the turnaround time for each aircraft was kept constant at 50 minutes.

IV. Proposed Algorithm For Optimal Route Generation

For initial route generation we used uniformed search method that is Breadth first search, then we applied Dijkstra's algorithm to get the optimal routes. Breadth first search (BFS) was applied to find all the possible cyclic routes for a node, then Dijkstra's algorithm was applied to find the feasible routes from origin to destination. The proposed algorithm is depicted in figure 1 below.

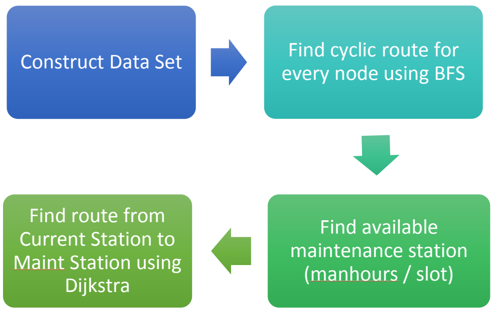

Figure 1. Proposed methodology

A. Breadth First Search (BFS)

BFS was used to find the feasible routes from origin to destination. As compared to depth first search technique which was used by Sriram et al. [1], breadth first search is always able to find all the available routes and produces the solution if it is available.

Randomly a node is chosen from the list of available nodes. To find all the possible cyclic routes of the current node exhaustive breadth first search is performed, if the number of outgoing arcs for that node is greater than or equal to 1. Once the links for cyclic schedule are found then the selected arc is subtracted from the outgoing and incoming arcs of each node. Selected routes are then saved as another list. Again breadth first search is performed to find the cyclic schedules for a randomly selected different node. This procedure was repeated until all the cyclic schedules for all the nodes are found. Otherwise, if all nodes are not covered then the list of nodes is perturbed and then BFS is applied again from the beginning and repeated until all the cyclic routes for each nodes are found.

B. Dijkstra's Algorithm

After finding all the possible routes from origin to destination, another subset of flights legs have been obtained. These flight legs are then used to obtain the most feasible route for an aircraft from its current airport to the maintenance station. However, before assigning a maintenance station S_m to a particular aircraft, capacity limitations of an airport are to be found. Violating the capacity limitations can increase the maintenance cost by applying penalty factors on the cost calculations. The maintenance capacity of an airport / maintenance station have some restrictions. These restrictions could be:-

- Availability of slots for maintenance so that multiple aircrafts can simultaneously undergo maintenance at that particular airport.
- Availability of man hours for that particular maintenance type that an aircraft requires to undergo at that maintenance station.

Once capacity restrictions are calculated, list of suitable maintenance stations are obtained. Now Dijkstra's algorithm is used to find the optimal path of an aircraft from its current station to all the suitable maintenance stations while keeping in view remaining flying hour constraint. Dijkstra's algorithm is an informed search method used to find the shortest path between two nodes. In our case it is used to find the shortest path from the origin airport to the destination that is a maintenance station. Following method was used to generate the maintenance feasible routes:-

- Check for the remaining flying hours of all the aircrafts.
- Use Dijkstra's algorithm to find the shortest route from current station to selected maintenance station
- Check if remaining flying hours are equal to zero
- If zero, then remove the arc form the list of arcs and save as selected route.
- Otherwise, remove the route and save as feasible route
- Keep on finding the route from current node to maintenance station, until the most optimal route is found.

V. Experiments

To solve the problem with uninformed and informed search methods we used Matlab software. In order to evaluate the efficiency of our proposed techniques we used multiple test cases. The result obtained from BFS for one of our test case is depicted in Fig. 2.

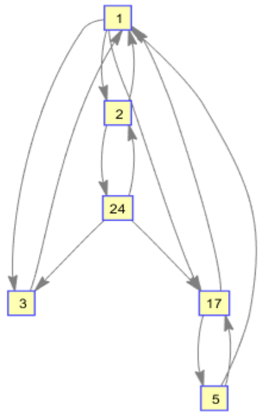

Figure 2. Cyclic schedule obtained using BFS

A. Parameters and Results

The test cases as given in Table I, consist of number of aircrafts, flight leg and stations. For each of the test case we randomly generated the remaining flying hours for all critical aircrafts and then performed 5 runs. Results obtained were then compared for, the minimum value and the maximum value.

TABLE I. TEST PARAMETERS

Case No	Flights	Critical Aircraft	Remaining Flying Time (min)
1	743	1	360
2	743	3	360
3	743	5	300
4	743	10	520
5	743	15	520

Based on the given test cases along with the turnaround time of 50 minutes, the results obtained are displayed in Table II and Table III.

TABLE II. HEURISTIC RESULTS WITH TURNAROUND TIME

Case No	Min (h)	Max (h)	CPU Time (s)
1	0.83333	1.4	0.434
2	2.6667	3.4167	1.445
3	4.450	5.5667	2.847
4	9.2667	10.7167	4.039
5	14.3	16.83	6.229

TABLE III. HEURISTIC RESULTS WITHOUT TURNAROUND TIME

Case No	Min (min)	Max (min)	CPU Time (s)
1	0	0.5667	0.434
2	9.96	55.00	1.445
3	16.98	84	2.847
4	55.98	142.98	4.039
5	108	259.8	6.229

B. Discussion

We can see from the results of the previous section that the hybrid approach using BFS and Dijkstra's algorithm produced the most optimal routes. Whereas, the execution time for each instance was maximum up to 6.3 seconds, which is very promising if this technique is applied on a more complex network.

VI. CONCLUSION

In this paper we presented the mathematical formulation / objective function for the airline maintenance routing problem. Exact methods were not used to solve it, we proposed the combination of breadth first search and Dijkstra's algorithm in order to generate the most optimal maintenance feasible routes.

Future research should attempt to evaluate the approach using the bio inspired optimization algorithms. Furthermore, a complex formulation can also be taken into account which may solve the aircraft maintenance routing problem integrated with crew scheduling problem.

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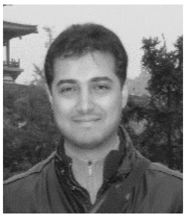

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