Scenario-based Stochastic Framework for Operational Aircraft Maintenance Routing Problem

Abdelrahman E.E. Eltoukhy, Felix T. S. Chan, S. H. Chung and T. Qu

Abstract—The operational aircraft maintenance routing problem with flight delay consideration (OAMRPFD) determines the route to be flown by each aircraft in real aspect life. It is observed that OAMRPFD related studies was formulated based on the expected value of the non-propagated delay, which is any delay caused by non-routing issues such as bad weather, technical problems, passengers delays, etc. However, a drawback of this formulation is that the expected value approach may not adequately reflect the final realization of non-propagated delay, as it is characterized by high level of uncertainty. This would result in facilitating the propagation of the delay and increasing its related cost paid by the airline companies. In this paper, we study OAMRPFD with an objective of developing an OAMRPFD that reflects appropriately the final realization of non-propagated delay. For this purpose, a new scenario-based stochastic framework for OAMRPFD (SOAMRPFD) is proposed. In order to solve the proposed model, an Ant Colony Optimization (ACO) algorithm is proposed. A case study of major airline company located in the Middle East is presented to demonstrate the potential of the proposed model.

Key words— **Air transportation, Aircraft routing problem, Ant Colony Optimization, Delay propagation.**

I. Introduction

AIRCRAFT maintenance routing problem (AMRP) has been well recognized as an effective mean for airline companies to build maintenance feasible routes for their aircraft [1]. In the last decade, this task has seen strong challenge, due to the increase of the flight delay minutes, which results in prohibiting the generated routes to be operated as planned, leading to an increase in the operating cost of the airline companies. For example, in 2011, it was estimated that U.S. airline industry experienced a total of 103 million minutes of delay, resulting in a $7.7 billion as an increase in the operating cost, as reported by Liang, et al. [2]. With the expected radical growth for the air traffic, the flight delay minutes will be consequently increased, causing severe losses on the airline industry. Therefore, airline companies shift their focus from maximizing the profit to minimizing the expected cost of the flight delays.

AMRP is one of the most studied problems in the literature with three focuses: tactical (TAMRP), operational (OAMRP), and operational with flight delay consideration (OAMRPFD) [3, 4]. The TAMRP studies aim to generate generic rotations for each aircraft, while neglecting some of the operational maintenance constraints [5, 6]. The generated rotations are repeated by each aircraft in the fleet. Using single rotation for each aircraft is not applicable due to lack of considering operational maintenance constraints, thus, the researchers shifted their focus from TAMRP to OAMRP, in order to generate routes consistent with the operational constraints [1, 7]. However, the drawback of OAMRP is the ignorance of flight delay that is frequently happened in reality, resulting in generation of routes that are easily to be disrupted by the delays. For this reason, the researchers consider OAMRPFD, to produce routes that better withstand disruption and can be easily implemented in reality [2, 8]. It is observed that OAMRPFD studies was formulated based on the expected value of the non-propagated delay, which is any delay caused by non-routing issues such as bad weather, technical problems, passengers delays, etc.

The focus of this paper is OAMRPFD and the contribution of this work is as follow. As mentioned above, it is observed that OAMRPFD was formulated based on the expected value of the non-propagated delay. However, a drawback of this formulation is that the expected value approach may not adequately reflect the final realization of the non-propagated delay, as it is characterized by high level of uncertainty [9]. This would result in facilitating the delay propagation and increasing its related cost, leading to difficult use of the generated routes in reality. This situation motivates us to find better representation for the non-propagated delay. Hence, in this paper, in contrast to expected value approach, we propose considering several potential scenarios for the non-propagated delay so that we have an appropriate look-ahead feature. This scenario based concept leads naturally to a scenario-based stochastic framework for OAMRPFD (SOAMRPFD), as it has been proven one of the most successful ways to handle parameters with high uncertainty [10-12]. In addition to this contribution, we propose an Ant Colony Optimization (ACO) algorithm to solve the proposed model. Furthermore, in order to demonstrate the potential of

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ISBN: 978-988-14048-4-8
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

the proposed model, a case study of major airline company located in the Middle East is presented.

The rest of the paper is organized as follow. In section 2, we describe the model formulation of SOAMRPFD. The ACO algorithm is proposed in section 3. In section 4, the case study is presented. We conclude in the final section of this paper.

II. THE MODEL FORMULATION

SOAMRPFD aims to generate maintenance feasible routes for the aircraft, with an objective of minimizing the total expected propagated delay cost. The SOAMRPFD is formulated based on the connection network, which is one of the commonly used network for AMRP [1, 6]. To formalize the representation of the proposed SOAMRPFD, we first define the notations that are frequently used throughout this paper, before giving the detailed formulation.

First, we start by listing the sets and their associated indices.

$i, j \in NF$: Set of flight legs.

$k \in K$: Set of aircraft.

$m \in MT$: Set of maintenance stations.

$a \in A$: Set of airports.

$v \in \{1,2,\dots,V\}$: Number of maintenance operations that at least should be performed by each aircraft.

$\xi \in \Xi$: Set of disruption scenarios.

$\{o, t\}$: Dummy source and sink nodes of the network.

Next, the parameters are defined as follow.

DT_i: Departure time of flight leg i.

AT_i: Arrival time of flight leg i.

TRT: Turn-around time.

O_{ia}: Origin binary indicator of flight leg i such that $O_{ia} = 1$ if the origin of flight leg i and the airport a are the same, and 0 otherwise.

D_{ia}: Destination binary indicator of flight leg i such that $D_{ia} = 1$ if the destination of flight leg i and the airport a are the same, and 0 otherwise.

FT_i: Flight duration of flight leg i.

T_{max}: Maximum flying time between two successive maintenance operations.

C_{max}: Maximum number of take-offs between two successive maintenance operations.

NPD_{ik}^{ξ}: Non-propagated delay realization of flight leg i covered by aircraft k, under scenario ξ.

Mb_{ma}: Maintenance binary indicator of maintenance station m such that $Mb_{ma} = 1$ if the maintenance station m located at airport a, and 0 otherwise.

MAT: Time required performing the maintenance operation.

KT: Total number of aircraft used to cover the flight legs.

V: The number of maintenance visits to be performed by each aircraft, which is calculated by using the following rule; $V = \sum_{i \in NF} DT_i / T_{max}\, KT$.

M: A considerable big number.

p^{ξ}: Probability for realization of scenario ξ.

C_{pD}: Per minute propagated delay cost.

PD_{ijkv}^{ξ}: Propagated delay caused when aircraft k already covered flight leg i and will potentially cover flight leg j, before performing maintenance operation number v, under scenario ξ.

PD_{ikv}^{ξ}: Total propagated delay of the route covered by aircraft k, caused from the beginning of coverage until covering flight leg i, before performing maintenance operation number v, under scenario ξ.

The decision variables are:

$x_{ijkv}^{\xi} \in \{0,1\}$, it equals 1 if flights legs i and j are covered by aircraft k, before performing maintenance operation number v, under scenario ξ, and 0 otherwise.

$y_{imkv}^{\xi} \in \{0,1\}$, it equals 1 if aircraft k covers flight leg i then perform maintenance operation number v, at maintenance station m, under scenario ξ, and 0 otherwise.

$z_{mjkv}^{\xi} \in \{0,1\}$, it equals 1 if aircraft k covers flight leg j, after performing maintenance operation number v, at maintenance station m, under scenario ξ, and 0 otherwise.

$RTAM_{kv}^{*\xi} > 0$, it is the ready time for aircraft k to continue covering another flight legs after performing the maintenance operation number v, under scenario ξ.

Based on the above notations, the model formulation of SOAMRPFD can be written as follow:

$$\text{Min } Z = \sum_{\xi \in \Xi} p^{\xi} \left(\sum_{v \in V} C_{pD} \left(\sum_{k \in K} \sum_{i \in NF} \sum_{j \in NF} PD_{ijkv}^{\xi}\, x_{ijkv}^{\xi} \right) \right) \quad (1)$$

Subject to

$$PD_{ijkv}^{\xi} = PD_{ikv}^{\xi} + (NPD_{ik}^{\xi} - (DT_j - AT_i - TRT))^{+} \quad \forall i \in NF, \forall j \in NF, \forall k \in k, \forall v \in V, \forall \xi \in \Xi \quad (2)$$

$$\sum_{k \in k} \left(\sum_{j \in NF \cup \{t\}} \sum_{v \in V} x_{ijkv}^{\xi} + \sum_{m \in MT} \sum_{v \in V} y_{imkv}^{\xi} \right) = 1 \quad \forall i \in NF, \forall \xi \in \Xi \quad (3)$$

$$\sum_{j \in NF} x_{ojkv}^{\xi} + \sum_{m \in MT} y_{omkv}^{\xi} = 1 \quad \forall k \in k, \forall v \in V, \forall \xi \in \Xi \quad (4)$$

$$\sum_{i \in NF} x_{itkv}^{\xi} + \sum_{m \in MT} z_{mtkv}^{\xi} = 1 \quad \forall k \in k, \forall v \in V, \forall \xi \in \Xi \quad (5)$$

$$\sum_{j \in NF \cup \{o\}} x_{ijkv}^{\xi} + \sum_{m \in MT} z_{mikv}^{\xi} = \sum_{j \in NF \cup \{t\}} x_{ijkv}^{\xi} + \sum_{m \in MT} y_{imkv}^{\xi} \quad \forall i \in NF, \forall k \in k, \forall v \in V, \forall \xi \in \Xi \quad (6)$$

$$\sum_{j \in NF} \sum_{v \in V} y_{jmkv}^{\xi} = \sum_{j \in NF \cup \{t\}} \sum_{v \in V} z_{mjkv}^{\xi} \quad \forall m \in MT, \forall k \in k, \forall \xi \in \Xi \quad (7)$$

$$AT_i + TRT - DT_j \le M(1 - x_{ijkv}^{\xi}) \quad \forall i \in NF, \forall j \in NF, \forall k \in k, \forall v \in V, \forall \xi \in \Xi \quad (8)$$

$$\sum_{k \in k} x_{ijkv}^{\xi} \le \sum_{a \in A} D_{ia} O_{ja} \quad \forall i \in NF, \forall j \in NF, \forall v \in V, \forall \xi \in \Xi \quad (9)$$

$$\sum_{k \in k} y_{imkv}^{\xi} \le \sum_{a \in A} D_{ia} Mb_{ma} \quad \forall i \in NF, \forall m \in MT, \forall v \in V, \forall \xi \in \Xi \quad (10)$$

$$\sum_{k \in k} z_{mjkv}^{\xi} \le \sum_{a \in A} Mb_{ma}\, O_{ja} \quad \forall m \in MT, \forall j \in NF, \forall v \in V, \forall \xi \in \Xi \quad (11)$$

$$RTAM_{kv}^{*\xi} - DT_j \le M\left(1 - z_{mjkv}^{\xi}\right) \quad \forall m \in MT, \forall j \in NF, \forall k \in k, \forall v \in V, \forall \xi \in \Xi \quad (12)$$

$$RTAM_{kv}^{*\xi} = \sum_{i \in NF \cup \{o\}} \sum_{m \in MT} (AT_i + MAT) z_{mjkv}^{\xi} \quad \forall k \in k, \forall v \in V, \forall \xi \in \Xi \quad (13)$$

$$\sum_{i \in NF \cup \{o\}} \sum_{j \in NF} x_{ijkv}^{\xi} \le C_{max} \quad \forall k \in k, \forall v \in V, \forall \xi \in \Xi \quad (14)$$

$$\sum_{i \in NF \cup \{o\}} \sum_{j \in NF} FT_j\; x_{ijkv}^{\xi} \le T_{max} \quad \forall k \in k, \forall v = 1, \forall \xi \in \Xi \quad (15)$$

$$\sum_{i \in NF} \sum_{j \in NF} FT_j\, x_{ijkv}^{\xi} +$$

ISBN: 978-988-14048-4-8
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

$\sum_{m\in MT}\sum_{j\in NF} FT_j\, z_{mjkv}^{\xi} \leq T_{max} \qquad \forall k \in k, \forall v \in V/\{1\}, \forall \xi \in \Xi \qquad (16)$

$\sum_{i\in NF}\sum_{m\in MT}\sum_{v\in V} y_{imkv}^{\xi} = V \qquad \forall k \in k, \forall \xi \in \Xi \qquad (17)$

$V \geq 1 \qquad (18)$

$x_{ijkv}^{\xi} \in \{0,1\} \qquad \forall\, i \in NF, \forall j \in NF, \forall k \in k, \forall v \in V, \forall \xi \in \Xi \qquad (19)$

$y_{imkv}^{\xi} \in \{0,1\} \qquad \forall\, i \in NF, \forall m \in MT, \forall k \in k, \forall v \in V, \forall \xi \in \Xi \qquad (20)$

$z_{mjkv}^{\xi} \in \{0,1\} \qquad \forall\, m \in MT, \forall\, j \in NF, \forall k \in k, \forall v \in V, \forall \xi \in \Xi \qquad (21)$

$RTAM_{kv}^{*\xi} > 0 \qquad \forall k \in k, \forall \in V, \forall \xi \in \Xi \qquad (22)$

The objective function (1) is the minimization of the total expected cost of propagated delay. Constraints (2) describe the calculation of the propagated delay. In order to ensure covering all the flight legs, constraints (3), (4), and (5) are cast. Constraints (3) indicate that each flight leg must be covered exactly by one aircraft. The constraints in (4) ensure that each aircraft starts its route, whereas constraints (5) guarantee the route completion. In order to keep the circulation of the aircraft throughout the network, the balance constraints (6) and (7) are formulated. To connect two flight legs by using same aircraft, that connection should be feasible in terms of time and place considerations, as described by constraints (8) and (9), respectively. On the other hand, to prepare a maintenance visit for the aircraft, we formulate constraints (10) that consider the locations of the maintenance stations. After finishing the maintenance operation, the aircraft should resume covering its route. For this reason, constraints (11) - (13) are cast.

It must be noted that the coverage and balance constraints do not enforce the aircraft that needs maintenance to undergo maintenance operation. Therefore, the operational restrictive constraints (14) - (18) are cast.

Finally, the constraints (19) - (22) define the domain of the decision variables.

The scope of the proposed SOAMRPFD is described as follow:

- The planning horizon is 4 days.
- The model only considers the existing maintenance stations and there is no recommendation for constructing new stations.
- The maintenance stations are located in the hub airports.
- All the maintenance operations discussed in this paper are Type A maintenance checks, which are commonly considered one in the literature.

III. Solution method

Since SOAMRPFD is formulated based on network representation, for which ACO has proven to be advantageous for large and complex network based problems [13, 14]. This observation motivate us to propose an ACO algorithm, in order to solve the proposed model.

The steps of the algorithm are explained as follow:

Step 0: Set the initial value for the ACO parameters that include; pheromone trial importance (α), heuristic function importance (β), exploration threshold (q_0), evaporation rate (ρ), control factor for pheromone laying (Q), and maximum number of iteration. Then, determine the number of maintenance operations (V) to be performed by each aircraft, generate the disruption scenarios, and put them in a list called (Ξ).

Step 1: Initialize the number of iterations=1.

Step 2: Check the status of Ξ list. If it is not empty, then go to Step 3, otherwise go to step 9.

Step 3: Pick one disruption scenario ξ from Ξ list.

Step 4: Prepare a list that includes the aircraft (K) in which each aircraft is represented by an ant, and make another list to represent the flight leg nodes (NF).

Step 5: Start the routes construction by using the following sub-steps:

Step a: Check the status of K list. If it is empty, then go to Step 6, otherwise go to Step b.

Step b: Pick ant or aircraft k from K list, and assign it to cover the flight leg i from NF list, by considering constraints described by Eq. (4).

Step c: Check whether the NF list is empty or not, by considering coverage constraints described by Eq. (3). If it is not empty, then go to Step d. On contrary, if it is empty go to Step 6.

Step d: Determine a list of potential flight legs to be covered from NF list by using place and time constraints described by Eqs. (8) and (9). If the potential list is empty, then go to Step j, otherwise go to Step e.

Step e: Determine the next flight leg to be covered from the potential list by applying the following state transition equation:

$$j = \begin{cases} \arg\_max_{l\in N_i^k}\left\{\left[\tau_{ij}{}^{\xi}\right]^{\alpha}\left[\eta_{ij}{}^{\xi}\right]^{\beta}\right\} & if\ q \leq q_0 \\ J & if\ q > q_0 \end{cases} \qquad (23)$$

Where $N_i^k$is the set of potential flight legs that can be selected after flight leg i, by the ant k.The terms $\tau_{ij}{}^{\xi}$ and $\eta_{ij}{}^{\xi}$ are the pheromone trial and the heuristic function of the arc (i, j), while solving the disruption scenario ξ, respectively. Since $\eta_{ij}{}^{\xi} = 1/(C_{pD} * PD_{ijkv}^{\xi})$, the constraints described by Eqs. (2) should be considered. q_0 is the exploration threshold parameter $(0 \leq q_0 \leq 1)$ and q is a uniformly distributed random number [0~1]. Typically, the ant selects the next flight leg based on the value q. If $q \leq q_0$, then selects the flight leg j in which its arc (i, j) has the best $\tau_{ij}{}^{\xi}$ and $\eta_{ij}{}^{\xi}$. On the other side, if $q > q_0$, the ant picks the flight leg j according to the following probability rule:

$$P_{ij}^k = \frac{\left[\tau_{ij}{}^{\xi}\right]^{\alpha}\left[\eta_{ij}{}^{\xi}\right]^{\beta}}{\sum_{l\in N_i^k}\left[\tau_{ij}{}^{\xi}\right]^{\alpha}\left[\eta_{ij}{}^{\xi}\right]^{\beta}} \qquad if\ j \in N_i^k \qquad (24)$$

Step f: After selecting the flight leg j, check whether the operational maintenance constraints are violated or not, by considering the constraints described by Eqs. (14) - (18). If these constraints are violated, then go to Step g, otherwise go to Step i.

Step g: Prepare a maintenance visit for the aircraft

ISBN: 978-988-14048-4-8
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

by considering the constraints described by Eq. (10).

Step h: After finishing the maintenance operation, resume covering the flight legs by considering constraints described by Eqs. (6), (7), and (11) - (13).

Step i: Remove the chosen flight leg j from the NF list, add this flight leg to the constructed route, and go to step d.

Step j: Put the end to the current route by considering the constraints described by Eq. (5), remove aircraft k from the K list and go to step a.

Step 6: Update the pheromone trails by using the following rule:

$$\tau_{ij,new}^{\xi} = (1-\rho)\tau_{ij,old}^{\xi} + \Delta\,\tau_{ij}{}^{\xi} \tag{25}$$

Where ρ is the evaporation rate parameter $(0 < \rho < 1)$. The first term $(1-\rho)\tau_{ij,old}^{\xi}$ is used each iteration, so that a uniform reduction of the phermones can be achieved. This would help the ants to forget the bad routes and scoute for better routes in the next iterations. The second term $\Delta\,\tau_{ij}{}^{\xi}$ represents the phermone quantity on the edge (i,j), under disruption scenario ξ. This term is used only to update all the edges included in the best so far solution. Using such update will direct the ants to the most promising routes in the next iterations. To calculate $\Delta\,\tau_{ij}{}^{\xi}$, we use the following rule:

$$\Delta\,\tau_{ij}{}^{\xi} = Q/cost\left(A_{best}^{\xi}\right) \qquad if\{i,j\} \subseteq A_{best}^{\xi} \tag{26}$$

Where Q is the control factor of laying the pheromone, in which its value determines whether to converge to the local optimal or to search randomly. The $cost\left(A_{best}^{\xi}\right)$ is the lowest propagated delay cost from the beginning until now, while handling disruption scenario ξ.

Step 7: Evaluate the solution of the scenario ξ for the current iteration (Z_{iter}^{ξ}), and update the best solution for scenario ξ (Z_{best}^{ξ}) if needed.

Step 8: Store the best solution of the current scenario Z_{best}^{ξ}, remove the disruption scenario ξ from the Ξ list, and go to Step 2.

Step 9: Evaluate the solution of the current iteration by augmenting the best solution obtained from each scenario ($Z_{iter} = \sum_{\xi\in\Xi} Z_{best}^{\xi} * p^{\xi}$).

Step 10: Check whether the stopping criteria is satisfied or not. If it is satisfied, then terminate the algorithm, otherwise, update the Ξ list by using the same list generated in Step 0, increase the number of iterations, and go to Step 2.

IV. Case study

To demonstrate the potential of the proposed model, we present a case study based on data acquired from major airline company located in the Middle East. As described before, the SOAMRPFD's objective is to minimize the expected propagated delay cost for all aircraft flown by the airline company. To test the SOAMRPFD performance in minimizing the propagated delay, we select the fleet with the highest number of delayed flights and collect its related data, as shown in Table 1.

TABLE 1: DATA COLLECTED FROM AIRLINE COMPANY

Airline company	
Number of flight legs	240
Fleet size	30
Maximum number of take-offs (C_{max})	10
Number of airports	8
Number of maintenance stations	4
Turn-around time (TRT)	45 minutes
Maximum flying time (T_{max})	40 hours
Time required to perform maintenance (MAT)	8 hours
Per minute propagated delay cost (C_{pD}).	CpD equals 75 if the propagated delay is less than or equal 15 minutes, or it equals 125 for longer propagated delays.

The experiments of this case study were carried out on an Intel i7 2.50 GHz laptop with 8 GB of RAM memory running on Windows 10 operating system. The proposed algorithm in this study was coded in Matlab R2014a.

A. Results of SOAMRPFD

The solution of the proposed SOAMRPFD can be achieved by implementing the developed ACO algorithm. For computational efficiency and meaningful problem context, the number of disruption scenarios is capped at as 100 equally likely scenarios. The ACO algorithm adopts pheromone trail importance of 1, heuristic function importance of 2, exploration threshold of 0.95, evaporation rate of 0.05, and control factor for pheromone laying of 0.01. Regarding the ant size, the ACO algorithm adopts the size that equals the number of aircraft. Finally, the stopping criteria is set to be happened when the solution improvement is capped for successive 100 iterations, or when the number of iterations exceeds the maximum number of iterations (i.e. maximum number of iterations is set to be 500 iterations).

The result obtained from the experiment shows that after 350 iterations, the ACO algorithm converges and returns its best result to be 1804.25.

B. Performance analysis

In the previous section, we present the performance of the proposed model of SOAMRPFD. Presenting SOAMRPFD performance is not enough to demonstrate its advantage over the existing model. For this purpose, we conduct computational experiment in order to compare SOAMRPFD performance with another traditional model that is formulated based on the expected value of the non-propagated delay (EVNPD). As mentioned before, EVNPD treats the non-propagated delays according to their expected value.

The results obtained from the experiments show that EVNPD underestimate the expected propagated delay cost by 12.3% if compared with the result obtained from the SOAMRPFD (1606.63 vs. 1804.25). This means that using the proposed SOAMRPFD is a potential tool to reflect the propagated delay in reality, thanks to the scenarios that provide appropriate look-ahead feature.

V. Conclusion

In this paper, we present a new scenario-based stochastic framework for operational aircraft maintenance routing problem. Our motivation to present this model stems from the fact that the related models were formulated based on the

ISBN: 978-988-14048-4-8
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

expected value for the non-propagated delay, which have a drawback of non-reflection of real realization of the non-propagated delay. In a consequence, the delay will be propagated and its related cost will be increased. In order to solve the proposed model, an ACO algorithm was proposed. The case study of major airline company located in the Middle East verifies the potential of the proposed model.

ACKNOWLEDGMENT

The work described in this paper was supported by grants from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. PolyU 15201414); The Natural Science Foundation of China (Grant No. 71471158); The Research Committee of Hong Kong Polytechnic University (Project Numbers G-UB03; G-YBFD; G-UA4F; G-YBN1) and under student account code RTYN.

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