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Robust aircraft maintenance routing problem using a turn-around time reduction approach

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Abstract

This paper discusses the problem of how to efficiently build aircraft routes that better withstand potential disruptions, such as bad weather, technical problems, and passenger delays. This optimization problem is called robust aircraft maintenance routing problem (RAMRP). There are three approaches in the literature to deal with the RAMRP, such as the buffer time allocation approach (BT), the departure retiming approach (DR), and the scenario-based stochastic programming approach (SSP). Most of the previous approaches have some shortcomings in terms of fleet productivity and delay absorption. In addition, the majority of the RAMRP models overlook maintenance regulations, which result in the generation of infeasible routes. In this paper, RAMRP is investigated with two main objectives. First, a novel robustness approach, called the turn-around time reduction approach (TRTR), that avoids the shortcomings of the existing approaches, is incorporated into RAMRP. The main idea of the TRTR is to act towards the disruptions (i.e. propagated delay), whereas the concept of the TRTR is to speed up or reduce the normal turn-around time (TRT) by allocating more ground resources (i.e. workforce and facilities)to ground operations, while observing any accumulated propagated delay. Consequently, the accumulated propagated delay can be mitigated. The proposed RAMRP model considers TRTR by introducing three types of TRT: (1) the normal TRT, which is adopted when the accumulated propagated delay does not occur; (2) the reduced TRT (i.e. 30% reduction of normal TRT); and (3) the extra-reduced TRT (i.e. 50% reduction of normal TRT), which are applied while observing the accumulated propagated delay. The second objective is to develop a RAMRP model that simultaneously considers all maintenance regulations. The effectiveness of the proposed RAMRP model along with the TRTR is demonstrated using real data from a major Middle Eastern airline. The results reveal an improved performance of the TRTR over the BT by about 3.43 – 12.20% and 2.5 – 13.58%, while handling the expected propagated delay costs and fleet productivity, respectively. In addition, the results show that the TRTR is better than the SSP by about 2.07– 18.82%, while minimizing the propagated delay costs. Therefore, the TRTR has a great potential to be implemented in the actual industry.

Keywords: Turn-around time, Airline operations, Aircraft maintenance routing problem, Robustness.

1. Introduction

Over the last few decades, the world has witnessed an enormous economic growth in the aviation industry. This has been demonstrated by a continuous growth in passenger volumes. In year 2017, 4.1 billion passengers were transported by airlines, and this figure is expected to grow annually by around 5%[1]. To handle the expected growth in passenger volumes, the size of the worldwide fleet is expected to increase from 24,597 in 2014 to 29,955 in 2022. Consequently, building aircraft routes before day of operation and implementing these routes practically, while considering the expected growth in the worldwide fleet, are great challenges for airlines. For instance, the Department of Transport in the U.S.A. reports that, due to the traffic growth, American airlines experienced around 5.6 million minutes of delay in one month, March 2018 [1]. This results in significant costs paid by American airlines in order to cover the increased number of working hours, host the passengers during the delay, and other issues. In this vein, solving the aircraft maintenance routing problem (AMRP) is very important for airlines, as it constructs the aircraft routes and prepares aircraft maintenance visits. The AMRP has been addressed in the literature using three different variants: tactical aircraft maintenance routing problem (TAMRP), operational aircraft maintenance routing problem (OAMRP), and robust aircraft maintenance routing problem (RAMRP). Robustness can be defined as the ability of the aircraft routes to mitigate or withstand potential disruptions [2]. In the literature, robustness has been studied in two different aspects: stability and flexibility [3]. Stability means constructing aircraft routes that are insensitive to the potential disruptions. This can be achieved using approaches, such as the buffer time allocation approach (BT) [4], the departure retiming approach (DR) [3] , and the scenario-based stochastic programming approach (SSP) [5]. Flexibility means constructing aircraft routes that are flexible enough so that it can be easily recovered during the disruptions. This can be achieved using some approaches, such as aircraft swap opportunities approach [6], and station purity approach [7]. More details about the approaches that enhance routes flexibility have been covered in a recent survey by Eltoukhy, et al. [8]. There is another concept that could be considered for the AMRP, called resilience. Generally, resilience means the ability of a system to recover its function from an attack, which causes the structural change of the system [9]. The key difference between resilience and robustness (i.e. flexibility)

[1] https://www.iata.org/pressroom/pr/Pages/2018-09-06-01.aspx

is that the robustness maintains the function of a system under disruptions or attaches which have not caused the structural change of the system. It should be noted discussing the robustness from stability point of view is the main focus of this paper. From the above, we can see that the aircraft can take advantage of the AMRP by building the routes to be flown in reality. However, maintenance can benefit from the AMRP by considering the constraints of maintenance regulations, such as allowable flying hours, allowable days, and allowable take-offs since the last maintenance check. In addition, the working times and the capacity of maintenance stations are also considered.

1.1. TAMRP models

TAMRP is solved several months before the day of operation with the aim of producing generic rotations. The model is addressed while overlooking some conditions like initial location of the aircraft and maintenance regulations [10, 11]. The first study on this model, based on set-partitioning formulation and a 3-day planning horizon, is reported by Kabbani and Patty [12]. Solution to the model is formulated from a two-stage solution algorithm, which constructs daily routes or lines of flights (LOF) in the first stage and then connects these routes to generate tours in the second stage. Clarke, et al. [13] present another TAMRP model aimed at maximizing the profit of the generated routes. An extension of the LOF is described by Gopalan and Talluri [10] using TAMRP with multiple days of planning horizon. The authors develop a polynomial time algorithm as a solution method for a 3-day planning horizon TAMRP model, whereas an effective heuristics is adopted to solve the TAMRP model with a 4-day planning horizon [14]. Liang, et al. [11] address the daily TAMRP by developing a new network representation based on the time-space network. The previous studies show that the TAMRP models may be successful in generating aircraft routes. However, these routes may not be viable in real application due to the following reasons. Firstly, these routes overlook maintenance regulations. Secondly, these routes are designed in order to be repeated by aircraft. This repetition is difficult to be implemented by airlines, as this industry is characterized by fluctuating passenger demands. Based on the previous shortcomings, some researchers developed another variant of AMRP, called OAMRP.

1.2. OAMRP models

The OAMRP is solved few days before the day of operation with the aim of producing aircraft routes to be flown in real practice. Maintenance regulations are taken into consideration, including allowable flying hours, allowable days, and allowable take-offs since last maintenance check. In addition, working times and capacity of maintenance stations are considered in order to avoid delays in the maintenance stations. Sriram and Haghani [15] report one of the first investigations on OAMRP that deploys an integer linear programming (ILP) model. ILP considers maintenance regulations to comprise allowable days since the last maintenance check and maintenance capacity. But no solution is found for the model due to its high complexity. Sarac, et al. [16] present another solution to the OAMRP model framed on the set-partitioning formulation by applying the branch-and price method. Similarly, a non-linear formulation for the OAMRP, which considers three main maintenance regulations, is proposed by Haouari, et al. [17]. These regulations are allowable flying hours, allowable days, and allowable take-offs since the last maintenance check. Besides, Başdere and Bilge [18] present an ILP model with a maintenance regulation of allowable flying hours since the last maintenance check. The authors adopt branch and bound (B&B) to solve small-sized test instances, and compressed annealing to handle large-sized test instances. Later on, Al-Thani, et al. [19] extend the scope of the work of Başdere and Bilge [18] by utilizing more maintenance regulations, such as allowable number of take-offs and allowable days since the last maintenance check. A recent study by Eltoukhy, et al. [20] utilize a model that considers allowable flying hours since the last maintenance check and capacity of the maintenance stations as two maintenance regulations. In a follow-up paper by the authors, Eltoukhy, et al. [21] present a model that employs polynomial number of decision variables and constraints. This polynomial formulation not only considers all three main maintenance regulations, but also factors in working times and capacity of the maintenance stations. Although OAMRP models can generate routes that take maintenance regulations into cognizance, the application of these routes is questionable because flight delays that occur frequently are overlooked. This results in the generation of routes that are sensitive to disruptions. Towards the goal of generating routes that better withstand disruptions, flight delays should be considered in addition to maintenance regulations, as in the RAMRP variant.

1.3. RAMRP models

The main aim of the RAMRP is to generate aircraft routes that can better withstand disruptions, such as technical problems, passenger delays, bad weather and others [22]. This has been achieved by using three main approaches: BT, DR, and SSP. With the aim of minimizing expected propagated delay, Lan, et al. [23] use the BT in their model. However, from the operational point of view, the proposed model overlooks all the maintenance regulations. An enhancement to the model of Lan, et al. [23] is provided by Dunbar, et al. [24], where aircraft routing is integrated with crew scheduling in a single model to capture their interdependence. It should be noted that the proposed model also ignores all the maintenance regulations. Furthermore, Liang, et al. [4] present a set-partitioning model for the RAMRP that considers fleet assignment problem with the objective of minimizing the expected propagated delay cost. . It is noteworthy that their model is among the first to incorporate maintenance regulations by taking capacity of the maintenance stations into account. However, the model neglects other regulations. Recently, another application of the BT proposes integrating RAMRP, flight scheduling and fleet assignment, as shown by Jamili [25]. The pitfall of the proposed model lies in ignoring all the maintenance regulations. Although the

BT has received considerable attention in the literature, the drawbacks of the BT are as follows: i) Imposing a large buffer time between flight legs reduces the number of flight legs that can be covered by each aircraft, resulting in a reduction of the fleet productivity, especially when covering a large number of flight legs, and ii) Inserting a small buffer time may not be enough to absorb the expected delays. These two observations motivate researchers to adopt another approach called DR. Lan, et al. [23] pioneer the application of DR by proposing a model that minimizes passenger disruption. Later, Dunbar, et al. [26] incorporate the information of stochastic delay in an algorithm that accurately calculates the propagated delay. . Recently, Ben Ahmed, et al. [3] propose a mixed non-linear programming model that adopts the DR in order to minimize the number of delayed passengers and maximize the on-time performance. Ben Ahmed, et al. [2] also develop a two-stage mixed integer quadratic programming model for RAMRP that adopts the DR. The first stage is aimed at minimizing the penalty cost induced by aircraft connections with short connection times, whereas the second stage is designed to minimize the penalties for passenger connection that violates the connection time. It is noted that all the previous models that are based on DR ignore maintenance regulations, except the work by Ben Ahmed, et al. [3] that consider the allowable days since the last maintenance check. To the best of our knowledge, the study by Eltoukhy, et al. [5] is the only RAMRP study that has attempted to apply the SSP. The authors propose a model, whose objective function is the minimization of the expected propagated delay cost. The model recognizes three maintenance regulations, including allowable flying hours, allowable days, and allowable take-offs since the last maintenance check. Computational results indicate the efficiency of the SSP in reducing the propagated delay costs. However, the SSP has two main disadvantages. Firstly, it requires prior knowledge of the flight delay uncertainty, which requires collecting real data. However, in some cases, the data are not rich enough to accurately represent the delay uncertainty. Secondly, a large number of scenarios needs to be generated in order to represent the delay uncertainty. This results in the introduction of computational burdens and challenges.

The remaining parts of this paper are organized as follows. Section 2 discusses the research gaps and presents the contribution of this study. The model formulation is presented in Section 3. In section 4, the solution method for the RAMRP is presented. Section 5 covers the comparison between the TRTR and existing robustness approaches. In section 6, the computational experiments are provided using a major Middle Eastern airline real data. Finally, Section 7 presents the conclusions of the study.

2. Research gaps and contribution

2.1. Research gaps

One of the glaring facts that is revealed after investigating the literature review is that there is no RAMRP that takes into consideration all the maintenance regulations. This limits the applicability of the proposed models in real practice. Moreover, it is noticed that most of the robustness approaches, like the BT and the SSP, have some drawbacks that affect their efficiency in real practice. These observations constitute the motivation to conduct this study to fill the previous research gaps by developing a RAMRP model, which pays attention to all the maintenance regulations. Furthermore, this research develops a novel robustness approach that avoids the drawbacks of the existing approaches.

2.2. Contributions

First, as mentioned earlier, the BT suffers either from fleet productivity reduction while imposing large buffer times, or from inefficient delay absorption while inserting small buffer times. Moreover, the shortcoming of the SSP lies in its higher computational burden due to the requirement of generating a large number of scenarios. In this paper and in contrast to the previous robustness approaches, we propose a novel robustness approach, called the TRTR. Before explaining the idea of this approach, it is important to define the turn-around time (TRT) as the time taken by the airlines or other service companies to help the aircraft to complete the operations related to the last covered flight legs and finalize the operations related to the next flight legs. These operations are called ground handling operations and include unloading the luggage for the last covered flight leg, loading the luggage for the next flight leg, moving the aircraft between gates, and fueling the aircraft. It should be noted that the TRT is different from the buffer time. As explained earlier, the TRT is the time that should be added between flight legs to finalize the ground handling operations. On the other hand, the buffer time is an additional time that is optionally inserted among flight legs after adding the TRT, in order to absorb flight delays. However, inserting the buffer time has some drawbacks as previously discussed. The main idea of the TRTR is to speed up or reduce the normal TRT by allocating more ground resources (i.e. workforce and facilities), while observing any accumulated propagated delay. Consequently, the accumulated propagated delay can be mitigated, which results in avoiding the delay propagation for the downstream flight legs. This in turn, leads to significant recovery cost savings for the airline. Before designing the TRTR, consultation with experts in a major Middle Eastern airline indicate the viability of this approach. Their response shows that allocating more ground resources can contribute to speeding up some ground operations, especially unloading and loading the luggage, which leads to a 30-50% reduction in the normal TRT. In addition, the potential saving from delay propagation and recovery, caused by reducing the normal TRT, is far greater than the cost of allocating more ground resources. These observations motivate us to select TRT to be the core of our approach.

Secondly, literature survey indicates that most of the RAMRPs overlook maintenance regulations, with the exceptions of the works by Liang, et al. [4] and Ben Ahmed, et al. [3]. However, these studies neglect other regulations, such as allowable flying hours and allowable take-offs since last maintenance check. Ignoring these regulations produces infeasible maintenance routes, which restricts the applicability of the produced routes in real practice. Also, overlooking capacity of the maintenance stations leads to aircraft arriving at the maintenance stations with insufficient capacity, and this delays the aircraft in the maintenance stations. Aircraft delay can also happen if the working times of the maintenance stations are ignored, such that aircraft arrive at times that are different from the working times of the maintenance stations. The aircraft delays in the previous two situations cause delays or cancelations for subsequent flights that should be covered by the aircraft. Therefore, it is important for the proposed RAMRP model to simultaneously consider the three main maintenance regulations, besides considering capacity and working times of the maintenance stations.

Indeed, using such a RAMRP is fruitful for airlines. Firstly, from robustness point of view, the TRTR is helpful, as it improves fleet productivity and enhances the ability to absorb propagated delays. Secondly, from operational point of view, maintenance regulations are important, as they strengthen the applicability of the model in the real industry.

3. The RAMRP model

The RAMRP model presented in this study can be defined as follows. Given a scheduled set of flight legs, the aim of the RAMRP is to construct robust routes by minimizing the propagated delay cost. It is noteworthy that the RAMRP constructs the routes while considering the maintenance regulations mandated by the Federal Aviation Administration. These regulations include the allowable flying hours, the allowable take-offs, and the allowable days since the last maintenance check. Working times and capacity of the maintenance stations are also taken into account.

3.1. Modified connection network

The RAMRP is formulated based on the connection network, as it has been shown to be an efficient application in representing the aircraft routing models [21]. The original connection network consists of two main elements; node sets and arc sets. The node sets include the flight legs set (I) and the maintenance stations set (MT), whereas the arc sets include the coverage arc set (COV), the visiting maintenance arc set (VMA) and the leaving maintenance arc set (LMA). The coverage arc $cov\ (i,j) \in COV$ is used to link between flight legs i and j. The visiting maintenance arc $vma\ (i,m) \in VMA$ is designed to prepare maintenance visits for the aircraft, whereas the leaving maintenance arc $lma\ (m,j) \in LMA$ is incorporated in the network to let the aircraft leave the maintenance stations and resume covering the subsequent flight legs. From the above description, we can notice that the structure of the original connection network is helpful in building aircraft routes that include maintenance visits, but it is not helpful while applying the TRTR, as it consists of three types of TRT: normal TRT, reduced TRT (i.e. 30% reduction of the normal

TRT) and extra-reduced TRT (i.e. 50% reduction of the normal TRT). The first TRT is applied when the accumulated propagated delay does not appear, whereas the rest of the TRTs are applied when accumulated propagated delay appears. Therefore, to apply the TRTR, the model needs to distinguish between different types of TRT. To do so, more arcs for those that connect between flight legs should be added. For this purpose, the structure of the original connection network is slightly modified by replacing the coverage arc set (COV) with three other arc sets: the normal TRT coverage arc set ($COVN$), the reduced TRT coverage arc set ($COVR$), and the extra-reduced TRT coverage set ($COVE$), as shown in Fig. 1. The normal TRT coverage arc $covn(i,j) \in COVN$ is used to link two consecutive flight legs, such that the TRT is normal. In fact, this arc is used when there is no accumulated propagated delay. On the other hand, when the accumulated propagated delay appears in the network, the other two types of arcs, $covr(i,j) \in COVR$ and $cove(i,j) \in COVE$, are used, depending on the severity of the accumulated propagated delay.

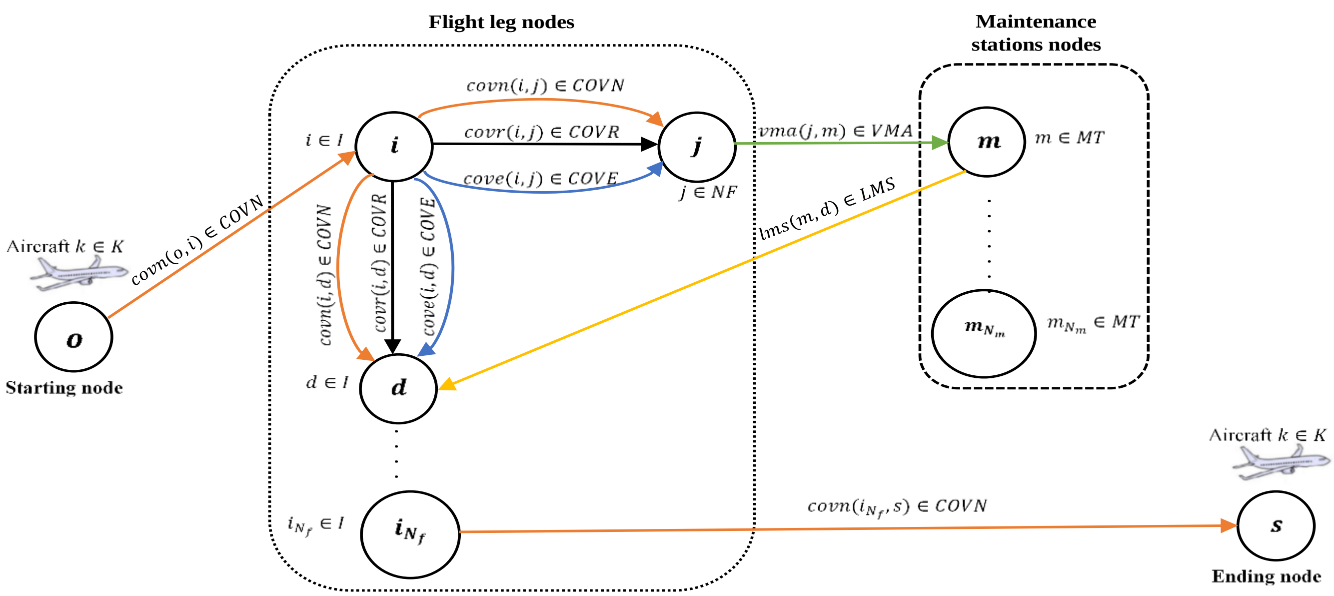

Fig. 1: Representation of the modified connection network.

3.2. Scope of the model and notations

The scope of the proposed RAMRP is described as follows:

- The planning horizon of the RAMRP is 4-day [5, 10, 21].
- The robustness of the RAMRP can be achieved by minimizing the propagated delay [4]. To do so, the TRTR is proposed. This approach includes applying the normal TRT between flight legs when the accumulated propagated delay does not appear. On the other hand, when the accumulated propagated

delay appears, the TRTR applies the reduced TRT (i.e. 30% reduction of normal TRT) and the extra-reduced TRT (i.e. 50% reduction of normal TRT) between the flight legs. The TRTR can be realized by speeding up the TRT through allocating more resources (i.e. workforce and facilities) during the ground operations.

- The maintenance check considered by the RAMRP is Type A, as it is the most frequent one among the others.
- The maintenance checks are performed in the hub airports, as they host the maintenance stations.

The notations used throughout the model can be summarized as follows:

Sets and indices:

A:	Set of airports, indexed by a.
MT:	Set of maintenance stations, indexed by m.
I:	Set of flight legs, indexed by i or j.
K:	Set of aircraft, indexed by k.
$t \in T$:	Turn-around time (TRT) types $\{n, r, e\}$, such that n, r, and e represent normal TRT, reduced TRT, and extra-reduced TRT, respectively.
$v \in \{1,2,\dots,\Psi\}$:	The average number of maintenance checks that each aircraft should receive during the planning horizon.
o:	Starting node of the modified connection network.
s:	Ending node of the modified connection network.

Parameters

DT_i:	Departure time of flight leg i.
O_{ia}:	Binary parameter. It equals 1 when the origin airport of flight leg i is airport a, otherwise it is 0.
AT_i:	Arrival time of flight leg i.
D_{ia}:	Binary parameter. It equals 1 when the destination airport of flight leg i is airport a, else it is 0.
FT_i:	Duration of flight leg i .
TRT^t:	Turn-around time of type t. It is noteworthy that TRT is the time consumed in unloading and loading the luggage, and fueling the aircraft
T_{max}:	Maximum allowable cumulative flying hours for each aircraft since the last maintenance check.
C_{max}:	Maximum allowable take-offs for each aircraft since the last maintenance check.
$E(NPD_i)$:	Expected value of the non-propagated delay of flight leg i.

Mb_{ma}: Binary parameter. It equals1 when the location of maintenance station m is airport a, else it is 0.

MAT: Duration of Type A maintenance check.

WC_m: Capacity of maintenance station m.

OT_m: Opening time of maintenance station m.

ET_m: Closing time of maintenance station m.

FS: Number of aircraft included in the fleet.

Ψ: Maximum average number of maintenance checks that should be received by each aircraft. The value of Ψ can be calculated from the expression $\Psi = \sum_{i \in NF} FT_i / (T_{max}\, FS)$.

M: A big number.

PD_{ijkv}^t: The propagated delay that occurs when flight leg i and j are consecutively flown by aircraft k, while using turn-around time of type t, before completing maintenance check number v.

PD_{ikv} : The accumulated propagated delay that occurs until aircraft k flies flight leg i, before completing maintenance check number v.

SEV: Severity threshold for the accumulated propagated delay, such that going beyond it causes severe delays for the downstream flights.

C_{pD}: Propagated delay cost per minute paid by airline.

Decision variables

$x_{ijkv}^t \in \{0,1\}$: It equals 1 when two consecutive flight legs i and j are flown by aircraft k, using turn-around time of type t, before completing maintenance check number v, otherwise it is 0.

$y_{imkv} \in \{0,1\}$: It equals 1 when flight leg i is flown by aircraft k, then this flight is followed by a maintenance visit at maintenance station m to receive maintenance check number v, otherwise, it is 0.

$z_{mjkv} \in \{0,1\}$: It equals 1 when the maintenance visit at maintenance station m is followed by covering flight leg j by aircraft k, after completing maintenance check number v,otherwise, it is 0.

$RT_{kvm} > 0$: The ready time when aircraft k completes maintenance check number v at maintenance station m, and able to fly the next scheduled flight legs.

3.3. Formulation of the RAMRP

The structure of the modified connection network helps in presenting the RAMRP as a multi-commodity network flow model. In the RAMRP, each commodity is represented by a single aircraft that moves through the connection network. To manage the movement of the aircraft, the RAMRP uses three main decision variables: x^t_{ijkv}, y_{imkv} and Z_{mjkv}. The first variable, x^t_{ijkv} represents the coverage arcs, such that t determines its type. Secondly, y_{imkv} represents the visiting maintenance arcs, whereas Z_{mjkv} represents the leaving maintenance arcs. Moreover, the RAMRP also uses another decision variable, called RT_{kvm}, to determine the suitable times for adopting the leaving maintenance arcs after completing the maintenance checks. The formulation of the RAMRP can be represented as follows:

$$\boldsymbol{min} \sum_{v=1,\dots,\Psi} C_{pD}\left(\sum_{k\in K}\sum_{i\in I}\sum_{j\in I}\ \sum_{t\in T} PD^t_{ijkv}\ x^t_{ijkv}\right) \tag{1}$$

s.t.

$$PD^t_{ijkv} = \left(PD_{ikv} + E(NPD_i) - (DT_j - AT_i - TRT^t)\right)^+ \quad \forall\, i,j \in I, \forall t \in T, \forall\, k \in K, \forall\, v = 1,\dots,\Psi \tag{2}$$

$$\sum_{k\in K}\left(\sum_{j\in I\cup\{s\}}\sum_{t\in T}\sum_{v\in\Psi} x^t_{ijkv} + \sum_{m\in MT}\sum_{v\in\Psi} y_{imkv}\right) = 1 \quad \forall\, i \in I \tag{3}$$

$$\sum_{j\in I}\sum_{t\in T} x^t_{ojkv} + \sum_{m\in MT} y_{omkv} = 1 \quad \forall\, k \in k, \forall\, v = 1 \tag{4}$$

$$\sum_{i\in I}\sum_{t\in T} x^t_{iskv} + \sum_{m\in MT} z_{mskv} = 1 \quad \forall\, k \in K, \forall\, v = \Psi \tag{5}$$

$$\sum_{j\in I\cup\{o\}}\sum_{t\in T} x^t_{jikv} + \sum_{m\in MT} z_{mikv} = \sum_{j\in I\cup\{s\}}\sum_{t\in T} x^t_{ijkv} + \sum_{m\in MT} y_{imkv} \quad \forall\, i \in I, \forall\, k \in K, \forall\, v = 1,\dots,\Psi \tag{6}$$

$$\sum_{j\in I}\sum_{v=1,\dots,\Psi} y_{jmkv} = \sum_{j\in I\cup\{t\}}\sum_{v=1,\dots,\Psi} z_{mjkv} \quad \forall\, m \in MT, \forall\, k \in K \tag{7}$$

$$AT_i + TRT^t - DT_j \le M\left(1 - x^t_{ijkv}\right) \quad \forall\, i,j \in I, \forall\, t \in T, \forall\, k \in K, \forall\, v = 1,\dots,\Psi \tag{8}$$

$$\sum_{k\in K} x^t_{ijkv} \le \sum_{a\in A} D_{ia} O_{ja} \quad \forall\, i,j \in I, \forall\, v = 1,\dots,\Psi \tag{9}$$

$$x^n_{ijkv} + x^r_{ijkv} + x^e_{ijkv} \le 1 \quad \forall\, i,j \in I, \forall\, k \in K, \forall\, v = 1,\dots,\Psi \tag{10}$$

$$1 - PD_{ikv} \le M\left(1 - x^n_{ijkv}\right) \quad \forall\, i,j \in I, \forall\, k \in K, \forall\, v = 1,\dots,\Psi \tag{11}$$

$$PD_{ikv} - SEV \le M\left(1 - x^r_{ijkv}\right) \quad \forall\, i,j \in I, \forall\, k \in K, \forall\, v = 1,\dots,\Psi \tag{12}$$

$$SEV - PD_{ikv} \le M\left(1 - x^e_{ijkv}\right) \quad \forall\, i,j \in I, \forall\, k \in K, \forall\, v = 1,\dots,\Psi \tag{13}$$

$$AT_i + MAT - ET_m \le M(1 - y_{imkv}) \quad \forall\, i \in I, \forall\, m \in MT, \forall\, k \in K, \forall\, v = 1,\dots,\Psi \tag{14}$$

$$OT_m - AT_i \le M(1 - y_{imkv}) \quad \forall\, i \in I \cup \{o\}, \forall\, m \in MT, \forall\, k \in K, \forall\, v = 1,\dots,\Psi \tag{15}$$

$$\sum_{k\in K} y_{imkv} \le \sum_{a\in A} D_{ia} Mb_{ma} \quad \forall\, i \in I, \forall\, m \in MT, \forall\, v = 1,\dots,\Psi \tag{16}$$

$$\sum_{k\in K} z_{mjkv} \le \sum_{a\in A} Mb_{ma}\ O_{ja} \quad \forall\, m \in MT, \forall\, j \in I, \forall\, v = 1,\dots,\Psi \tag{17}$$

$$RT_{kvm} - DT_j \le M\left(1 - z_{mjkv}\right) \quad \forall\, m \in MT, \forall\, j \in I, \forall\, k \in K, \forall v = 1,\dots,\Psi \tag{18}$$

$$RT_{kvm} \ge \sum_{i\in I\cup\{o\}}\sum_{j\in I\cup\{t\}}\sum_{m\in MT}(AT_i + MAT) z_{mjkv} \quad \forall\, k \in K, \forall\, v = 1,\dots,\Psi, \forall\, m \in MT \tag{19}$$

$$\sum_{i\in I\cup\{o\}}\sum_{j\in I}\sum_{t\in T} x^t_{ijkv} \le C_{max} \quad \forall\, k \in K, \forall\, v = 1,\dots,\Psi \tag{20}$$

$$\sum_{i\in I\cup\{o\}}\sum_{j\in I}\sum_{t\in T} FT_j\, x^t_{ijkv} \le T_{max} \quad \forall\, k \in K, \forall\, v = 1 \tag{21}$$

$$\sum_{i\in I}\sum_{j\in I}\sum_{t\in T} FT_j\, x^t_{ijkv} + \sum_{m\in MT}\sum_{j\in I} FT_j z_{mjkv} \le T_{max} \quad \forall\, k \in K, \forall\, v = 2,\dots,\Psi \tag{22}$$

$$\sum_{i \in I \cup \{o\}} \sum_{k \in K} \sum_{v \in \Psi} y_{imkv} \geq 1 \qquad \forall\, m \in MT \qquad (23)$$

$$\sum_{i \in I \cup \{o\}} \sum_{k \in K} \sum_{v \in \Psi} y_{imkv} \leq WC_m \qquad \forall\, m \in MT \qquad (24)$$

$$x_{ijkv}^{t} \in \{0,1\} \qquad \forall\, i, j \in I, \forall\, t \in T, \forall\, k \in K, \forall\, v = 1, \dots, \Psi \qquad (25)$$

$$y_{imkv} \in \{0,1\} \qquad \forall\, i \in I, \forall\, m \in MT, \forall\, k \in K, \forall\, v = 1, \dots, \Psi \qquad (26)$$

$$z_{mjkv} \in \{0,1\} \qquad \forall\, m \in MT, \forall\, j \in I, \forall\, k \in K, \forall\, v = 1, \dots, \Psi \qquad (27)$$

$$RT_{kvm} > 0 \qquad \forall k \in K, \forall\, v = 1, \dots, \Psi, \forall\, m \in MT \qquad (28)$$

The objective function stated in (1) is to minimize the expected propagated delay cost. Constraints (2) express the propagated delay calculation. Towards the goal of building feasible aircraft routes, all flight legs should be flown by the aircraft. For this reason, the coverage constraints (3) – (5) are cast. Constraints (3) ensure that only one aircraft covers each flight leg. Constraints (4) guarantee initiation of the aircraft route, whereas constraints (5) confirm the completion of aircraft route. While constructing the aircraft routes, it is necessary to keep the aircraft circulating through the network. To do so, the balance constraints (6) and (7) are formed. Constraints (6) retain the balance for the flight leg nodes, whereas constraints (7) retain the balance for the maintenance stations nodes. To use the same aircraft to connect two consecutive flight legs via any type of the coverage arcs, time and location issues are expected to be satisfied. Therefore, constraints (8) and (9) are formulated. The time constraints (8) state that the two consecutive flight legs can be flown using the same aircraft, if the sum of the arrival time of the first flight plus the selected TRT is earlier than the departure time of the second flight leg. Similarly, the location constraints (9) indicate that two consecutive flight legs can be flown using the same aircraft, when the destination airport of the first flight leg and the origin airport of the second flight leg are identical. As mentioned earlier, one of the distinctive features of the proposed model is using the TRTR as a robustness approach. For this purpose, constraints (10) – (13) are designed. Indeed, the TRTR includes three types of TRT, the normal TRT, the reduced TRT, and the extra-reduced TRT, while connecting two consecutive flight legs. However, all these TRT cannot be used at the same time. For this purpose, constraints (10) are formulated to guarantee the usage of a single type of TRT. To select among the three types of TRT, constraints (11) - (13) are formed. Constraints (11) describe the situation when the normal TRT is used, such that it can be used only when the accumulated propagated delay is zero. On the contrary, when the aircraft suffers from an accumulated propagated delay, the role of either the reduced TRT or the extra-reduced TRT appears, as described in constraints (12) and (13). Before discussing these constraints, it is important to note that the invocation of reduced TRT needs more ground resources, whereas using extra-reduced TRT requires excessive ground resources. Frequent usage of reduced TRT may not be enough to absorb severe accumulated propagated delay. In addition, frequent usage of extra-reduced TRT may not be suitable during normal accumulated propagated delay due to the excessive usage of ground resources. This may violate the manpower capacity restrictions and slightly increase the operational costs of the airline. Therefore, it is necessary to introduce a threshold- severity threshold, that helps to select either the reduced TRT or the extra-reduced TRT. This severity threshold distinguishes between normal and severe accumulated propagated delays. Normal accumulated propagated delay occurs when the accumulated propagated delay is less than the severity threshold. This implies that it is suitable to use the reduced TRT, as shown in constraints (12). However, severe accumulated propagated delay arises if the accumulated propagated delay crosses the severity threshold, hence, the extra-reduced TRT is adopted, as shown in constraints (13). In summary, the threshold helps to improve the performance of the TRTR. The applicability of the constructed routes is ensured by including some maintenance visits. This is done by considering the time and location issues for the potential maintenance stations and the last flown flight leg. Therefore, constraints (14) – (16) are designed. Constraints (14) and (15) represent the time issue, as they indicate the working times of the maintenance station. The location issue is described by constraints (16) and they ensure that the maintenance station can only be visited by the aircraft, when the location of the maintenance station and the destination of the last flown flight leg are identical. After completing the maintenance check, the aircraft are required to depart the maintenance station and start flying the subsequent flight legs. To do so, location and time issues for the maintenance stations and potential flight legs for coverage should be taken into consideration, which are denoted by constraints (17) – (19). Constraints (17) constitute the location issue and they guarantee that a potential flight leg can be flown by an aircraft after completing the maintenance check, when the origin airport of the potential flight leg is the same as the location of the maintenance station. The time issue is represented by constraints (18), which ensure that a potential flight leg can be flown by an aircraft after completing the maintenance check, when the ready time for the aircraft, RT_{kvm} is earlier than the departure time of the potential flight leg. It should be noted that the ready time is calculated according to constraints (19). All the previous constraints help in building aircraft routes that include some maintenance visits. However, these constraints fail in forcing the aircraft to undergo maintenance. Therefore, the maintenance regulations, contained in constraints (20) – (23), are formulated. Constraints (20) guarantee the non-violation of the maximum allowable take-offs for each aircraft. Similarly, (21) and (22) represent the restriction towards the accumulated flying hours. Constraints (23) are cast to keep at least a single maintenance visit for each aircraft. It is important to note that the proposed RAMRP has a 4-day planning horizon. Based on this observation and the purpose of constraints (23), we can say that the model complies with the 4-day regulation as the allowable days since the last maintenance check. Before assigning a maintenance visit to an aircraft, it is necessary to check the capacity of the maintenance stations. This issue is described in constraints (24), which guarantee that the number of aircraft visiting the maintenance station is within the capacity of the maintenance station. Finally, constraints (25) – (28) represent the status of the decision variables.

4. Solution method

Before describing the solution algorithm used, it is important to note here that it has been proven that the AMRP is an NP-hard problem [19, 21]. In addition, the model of this study is proposed with the target of handling large-sized test instances that contain up to 4000 flight legs. Therefore, it is reasonable to adopt an algorithm-based meta-heuristics as a solution method, because they have shown successful applications while handling various problems, including vehicle routing problem [27, 28], crew scheduling problem [29], location management [30], aircrew rostering problem [31], control of wireless network [32], and robotics [33]. As mentioned earlier, the RAMRP model is formulated as a network-based problem, in which its large and complex forms are efficiently solved using the ant colony optimization (ACO) [5, 34-38]. This observation motivates us to adopt the ACO based-algorithm that is proposed by Eltoukhy, et al. [5] to solve the proposed RAMRP model, while considering three main modifications.

The differences between this work and the solution method in Eltoukhy, et al. [5] are summarized as follows:

1. The proposed solution method ignores disruption scenarios that are generated to represent the non-propagated delay.
2. The expected value of the non-propagated delay for each flight is calculated by applying the neural network-based algorithm proposed by Chung, et al. [39] and Eltoukhy, et al. [40], as it shows an accurate prediction for non-propagated delays. It is noteworthy that, when calculating the non-propagated delays, historical data for the delays that have occurred during a complete year (i.e. 2017) are considered. Besides, some external factors, including bad weather, seasons, and congestion of maintenance stations, are considered because they affect the expected propagated delay.
3. And finally, the proposed solution method incorporates all the different types of the TRT in the ACO-based algorithm.

In this study, the stopping criteria for the algorithm is set to either convergence (i.e. after reaching 200 successive iterations without solution improvement), or when the number of iterations reaches the maximum number of iterations that is set at 1000 iterations, whichever comes first.

5. Comparison between the TRTR and existing robustness approaches

To demonstrate the advantage of the TRTR over the existing robustness approaches, a comparison between the TRTR and other approaches, called the BT and the SSP, is made. These two approaches are selected for this comparison because they have shown good performance in absorbing propagated delays, as reported by Liang, et al. [4] and Eltoukhy, et al. [5]. To conduct this comparison, the proposed TRTR is replaced with the BT and the SSP. For this purpose, the RAMRP proposed in section 4 is modified.

To replace the TRTR with the BT, the proposed RAMRP should be modified to get a so-called RAMRP-BT. This can be achieved by using the whole RAMRP presented in section 4, except adopting the following steps. First, all the constraints and notations related to the TRTR are ignored. Second, all the notations of the TRT types, t, are replaced with a single TRT, called normal TRT. Since the main idea of the BT is to insert the optimal buffer time after finishing a specific aircraft take-off [4], the last modification is to introduce the following set, parameters and decision variable, which are related to the aircraft take-off.

Sets and indices:

$c \in \{1, \ldots, C_{max}\}$: Set of take-offs that can be flown by each aircraft.

Parameters:

bt_c: Optimal buffer time for insertion after finishing the take-off number c. It is noteworthy that these optimal buffer times are determined using the same procedure applied in the study by Liang, et al. [4].

PD_{ijkv}^{c}: The propagated delay value that occurs when flight legs i and j are consecutively flown by aircraft k, such that the flight leg i is counted as a take-off number c, before completing the maintenance check number v.

TRT: Normal turn-around time.

Decision variable

$x_{ijkv}^{c} \in \{0,1\}$: It equals 1 when flight legs i and j are consecutively flown by aircraft k, such that the flight leg i is counted as a take-off number c, before completing the maintenance check number v, and 0 otherwise.

The optimal buffer time should be incorporated in the RAMRP-BT. Thus, the following modifications are formulated:

- Constraints in Eq. (8) are modified as follows:

$$AT_i + TRT + bt_c - DT_j \leq M\left(1 - x_{ijkv}^{c}\right) \quad \forall\, i, j \in I, \forall\, c \in \{1, \ldots, C_{max}\}, \forall\, k \in K, \forall\, v = 1, \ldots, \Psi \quad (29)$$

  The previous constraints ensure that, in order to connect two consecutive flight legs using the same aircraft, the optimal buffer time bt_c should be allocated between the arrival time of the first flight and the departure time of the second flight.

- The decision variable, x_{ijkv}^{t}, used in the RAMRP presented in section 4, is replaced with the above-mentioned decision variable, x_{ijkv}^{c}.

By applying all the previous modifications, the RAMRP-BT is fully developed, which follows the same idea as presented in the model by Liang, et al. [4]. To solve the RAMRP-BT, the ACO-based algorithm is used, while the steps that represent the TRTR are ignored.

To replace the TRTR with the SSP to obtain a so-called RAMRP-SSP model, the first two modifications presented in RAMRP-BT are called up. Besides, a third modification is incorporated by introducing the following set, parameters and decision variable:

Sets and indices:

$\xi \in \Xi$: Set of flight delay scenarios. It should be noted that these scenarios are generated using the same procedures proposed in the study by Eltoukhy, et al. [5].

Parameters:

NPD_i^{ξ}: The flight leg i delay realization under scenario ξ.

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

PD_{ijkv}^{ξ}: Propagated delay occurs when flight legs i and j are consecutively flown by aircraft k, before completing the maintenance check number v, under scenario ξ.

PD_{ikv}^{ξ}: The accumulated propagated delay that occurs till flying flight leg i by aircraft k, before completing the maintenance check number v, under scenario ξ.

TRT: Normal turn-around time.

Decision variables

The decision variables used in the RAMRP presented in section 4 are utilized, but for different scenarios. So the decision variables become x_{ijkv}^{ξ}, y_{imkv}^{ξ}, z_{mjkv}^{ξ}, and RT_{kvm}^{ξ}.

Since the flight delay scenarios with their related probability should be incorporated in the RAMRP-SSP, the following modifications are utilized:

- The objective function stated in Eq. (1) is re-written as:

$$min \sum_{\xi \in \Xi} p^{\xi} \left(\sum_{v \in V} C_{pD} \left(\sum_{k \in K} \sum_{i \in NF} \sum_{j \in NF} PD_{ijkv}^{\xi} \, x_{ijkv}^{\xi} \right) \right) \quad (30)$$

  This objective function calculates the cost of expected propagated delay for all flight delay scenarios.

- The constraints presented in Eq. (2) are modified as:

$$PD_{ijkv}^{\xi} = \left(PD_{ikv}^{\xi} + NPD_i^{\xi} - \left(DT_j - AT_i - TRT \right) \right)^{+} \quad \forall\, i \in NF, \forall j \in NF, \forall k \in k, \forall v \in V, \forall \xi \in \Xi \quad (31)$$

  These constraints indicate that the flight delay related to each scenario are considered while calculating the flight delay propagation.

- All the constraints relating to multiple flight delay scenarios are redesigned by incorporating $\forall \xi \in \Xi$ for each constraint.

By implementing all the previous modifications, the RAMRP-SSP is formulated, which follows the same idea proposed in the model by Eltoukhy, et al. [5]. To solve the RAMRP-SSP, the ACO-based algorithm presented in the work by Eltoukhy, et al. [5] can be used directly.

6. Computational experiments

We conduct computational experiments based on the real data obtained from a major Middle Eastern airline. In this section, we report results obtained while using the RAMRP. In addition, we present the results of the comparison between the RAMRP and the existing models in the literature.

6.1. Test cases

The experiments of this study are conducted based on fifteen test cases. These test cases are divided into real and generated cases. The first ten cases are real cases obtained from a major Middle Eastern airline, whereas the remaining five cases are generated based on combinations of the first ten cases. For real cases, they are constructed by using ten real flight schedules flown by different fleets. To generate larger test cases for testing purposes, SIM01, SIM02, SIM03, SIM04, and SIM05 are constructed by merging the flight schedules of multiple fleets in different ways. For example, SIM01 is built by merging the flight schedules of cases 7 and 9, whereas SIM02 is built by merging the flight schedules of cases 9 and 10. Another way for constructing large test cases, is repeating the flight schedule of some cases by adjusting the arrival and departure times of the flight schedule using a specific period. In such a way, SIM03 is created by repeating the flight schedule of SIM02 twice through adjusting the arrival and departure times of the flight schedule by 15 minutes. Similarly, SIM04 is generated by repeating the flight schedule of SIM01 four times through adjusting the arrival and departure times of the flight schedule by 15, 30, 45, and 60 minutes, for each time of repetition. Finally, SIM05 is formed by repeating the flight schedule of SIM04 twice through adjusting the arrival and departure times of the flight schedule by 5 hours. It is interesting to mention that SIM05 is even larger than the size of the largest fleet in the world, operated by Southwest Airlines, with a Boeing 737-700 fleet that include 350 aircraft to cover 3469 flight legs in 4 days [4]. Table 1 presents the complete features for the test instances. The airline recommends that the turn-around time TRT should take a value of 90 minutes, T_{max} should take a value of 40 hours, and the time taken to complete Type A maintenance check should be within 8 hours. Lastly, severity threshold is set at 1 hour.

It is commonly known that the runs of any solution method should be replicated several times to evaluate the performance of the algorithm. Therefore, we replicate the runs of the ACO-based algorithm thirty times for all test cases. We decide on thirty runs because additional runs did not demonstrate better results. Note that these experiments have been performed on a Windows 10 laptop, which features Intel i7 CPU, 2.52 GHz, and 8 GB RAM. The models and algorithms presented in this study are coded in MATLAB R2014a.

Table 1: Features of the collected test cases.

Test cases	No. of flight legs	Fleet size	Max. no. of take-offs	No. of airports	Maintenance Stations
Case 1	40	9	10	4	4
Case 2	48	10	7	5	4
Case 3	64	12	7	7	4
Case 4	96	21	10	13	6
Case 5	120	21	10	8	6
Case 6	160	23	15	10	6
Case 7	210	30	10	9	9
Case 8	240	42	15	19	9
Case 9	300	53	15	26	15
Case 10	400	65	15	28	18
SIM01	510	83	15	35	24
SIM02	700	118	15	54	33
SIM03	1400	236	15	54	33
SIM04	2040	332	15	35	24
SIM05	4080	664	15	35	24

6.2. The RAMRP results

In this section, we report the computational results of the RAMRP model while handling all test cases, using the ACO-based algorithm. To get these results and for computational convenience, values for the parameters of the ACO-based algorithm are set as α=1, β=2, q_0=0.95, ρ=0.05, Q=0.01, and number of ants=fleet size. Before using the neural network-based algorithm to predict the expected value of the non-propagated delay, parameter tuning process should be conducted. For this purpose, Taguchi method is adopted as it is a powerful tool to define the best parameter settings [41]. The To apply Taguchi method, the most effective parameter and their levels are selected [42], as shown in Table 2. Applying L_9 as an orthogonal array and S/N ratio as a performance indicator, results of the best parameter settings as shown in bold-face figures in Table 2.

Table 2:Parameter levels for the neural network- based algorithm.

Parameter	Level 1	Level 2	Level 3
Learning rate	0.01	**0.1**	0.3
Momentum	0.1	0.3	**0.5**
Number of neurons in the first hidden layer	15	30	**45**

Number of neurons in the second hidden layer	0	**15**	30

The results of the RAMRP are summarized in Table 3. The columns of Z_{best}, $\bar{Z}$, and σ_z represent the best solution, the average solution and the standard deviation of the algorithm replications, respectively. The last two columns, $\overline{CPU(s)}$ and *Iterations of stopping*, are used to record the average computational time and the number of iterations taken by the algorithm till reaching the convergence point, respectively. It should be noted that $\overline{CPU(s)}$ is recorded by using the internal calculation function of MATLAB. In addition, $\overline{CPU(s)}$ does not reflect the average time to obtain the best solution, as the best solution is obtained after finishing all the replications.

Table 3:Result of the RAMRP for all test cases

Test cases	Z_{best}	$\bar{Z}$	σ_z	$\overline{CPU(s)}$	*Iterations of stopping*
Case 1	0	0	0	1.23	1
Case 2	0	0	0	1.47	1
Case 3	237	237	0	4.34	4
Case 4	321	322	3.78	4.27	2
Case 5	336	338	4.56	17.17	229
Case 6	1,294	1,301	6.09	37.46	338
Case 7	493	495	3.36	39.40	346
Case 8	2,693	2,715	8.23	48.18	417
Case 9	2,688	2,705	8.46	67.22	342
Case 10	6,240	6,325	55.36	122.54	405
SIM01	3,925	3,970	26.23	166.79	427
SIM02	8,097	8,265	93.85	222,31	377
SIM03	15,543	15,865	126.78	716.32	325
SIM04	46,899	47,754	289.23	867.12	201
SIM05	132,040	135,652	731.23	2013.61	152

From the obtained results, it is noted that RAMRP can efficiently handle all the test cases. For the first few cases, case 1 up to case 3, the best solution and the average solution are the same. When the case complexity increases, meaning that the number of flight legs and aircraft increase, the average solutions slightly deviate from the best solutions, as shown in case 4 up to SIM05. However, the standard deviations for all cases are not significant, which means that the solution variability is not significant. This point reflects the stability and reliability of the proposed ACO-based algorithm.

By observing the average computational time and the iterations till stopping, it can be observed that the solutions are obtained within reasonable computational time and number of iterations. This point is apparent in the largest case, SIM05, in which the solution is obtained within 2013.62 seconds ≅ 33.5 minutes. Indeed, solving test case SIM05, whose size is larger than the largest fleet size in the world, within half an hour is acceptable practically.

6.3. Importance of the TRTR approach

So far, the solutions of the RAMRP are presented for different test cases. Indeed, this may not be sufficient to show the importance of the proposed TRTR. To further demonstrate the importance of the TRTR, two other models are compared with it: the RAMRP and the non-robust AMRP (NRAMRP). The RAMRP is already described in section 4. The NRAMRP can be captured by Eqs. (1) – (28), with two main modifications. Firstly, Eqs. (10) – (13) that represent the TRTR are ignored. Secondly, only the normal TRT, as a type of the TRT, t, is considered. The NRAMRP can be solved using the ACO-based algorithm that is used to solve the RAMRP, while ignoring the steps that represent the TRTR. Remarkably, the NRAMRP with the previous formulation, represents some studies in the literature, including the study by Eltoukhy, et al. [21] and Başdere and Bilge [18]. The performances of the RAMRP and NRAMRP are shown in Table 4, which presents the same statistics as Table 3.

Table 4: Performance characteristics of RAMRP and NRAMRP.

Test cases	RAMRP				NRAMRP				Outperformance (%)
	Z_{best}	$\bar{Z}$	$\overline{CPU(s)}$	*stopping*	Z_{best}	$\bar{Z}$	$\overline{CPU(s)}$	*stopping*	
Case 1	0	0	1.23	1	0	0	1.27	1	0
Case 2	0	0	1.47	1	0	0	1.48	1	0
Case 3	237	237	4.34	4	493	497	4.63	6	52.31
Case 4	321	322	4.27	2	539	546	4.60	3	41.03
Case 5	336	338	17.17	229	602	620	19.22	243	45.48
Case 6	1,294	1,301	37.46	338	2,312	2354	34.49	340	44.73
Case 7	493	495	39.40	346	845	850	42.87	393	41.76
Case 8	2,693	2,715	48.18	417	6,318	6,453	86.91	460	57.93
Case 9	2,688	2,705	67.22	342	5,126	5,254	68.88	353	48.52
Case 10	6,240	6,325	122.54	405	11,082	11,528	123.32	540	45.13
SIM01	3,925	3,970	166.79	427	7,245	7,493	162.35	427	47.02
SIM02	8,097	8,265	222.31	377	16,023	16,330	215,02	359	49.38
SIM03	15,543	15,865	716.32	325	59,145	59,852	798.37	342	73.49
SIM04	46,899	47,754	867.12	201	183,987	185,894	850.23	192	74.31
SIM05	132,040	135,652	2,013.61	152	773,584	785,232	2,007.87	148	82.72

Note: Outperformance (%) $= (\bar{Z}_{NRAMRP} - \bar{Z}_{RAMRP}) * \frac{100}{\bar{Z}_{NRAMRP}}$

It can be seen from Table 4 that the RAMRP outperforms the NRAMRP by 41.03 – 82.72%, in minimizing the expected propagated delay costs. The main reason for this outperformance is due to the TRTR, which reduces the TRT by allocating more ground resources (i.e. workforce and facilities), while observing any accumulated propagated delay. Consequently, the accumulated propagated delay can be mitigated, resulting in a significant minimization of the expected propagated delay cost, as in the RAMRP. In contrast to the RAMRP, the NRAMRP does not include any robustness approach, so that no action is taken when observing the accumulated propagated delay. As a result, the delays can be easily propagated, leading finally to increase in the propagated delay costs. To summarize, the RAMRP, which includes the TRTR, is beneficial to airlines. This is because it helps to mitigate the propagated delay, thus the airline realizes significant savings in the expected propagated delay costs.

6.4. Performance analysis

In the previous two sections, the performance of the RAMRP, that includes the TRTR, is presented, while solving different test cases. Indeed, presenting such performance may not be sufficient to demonstrate the superiority of the proposed TRTR over the existing robustness approaches. For this purpose, our experiments are extended to compare the performance of the TRTR with traditional approaches in the literature, called the BT and the SSP. It should be noted that these approaches are selected for comparison purposes because of their efficient performance in absorbing propagated delays, as reported by Liang, et al. [4] and Eltoukhy, et al. [5]. To ease this comparison, we have modified the proposed RAMRP by replacing its TRTR with the BT and the SSP. More details on the above-mentioned modifications are presented in section 5. Modifications to the RAMRP-BT and the RAMRP-SSP are implemented to conform with the concepts of the models proposed by Liang, et al. [4] and Eltoukhy, et al. [5], respectively. The performance of the three robustness approaches are shown in Table 5 and Table 6, including the same statistics presented in the previous sections. In addition, we record the fleet productivity of each approach, which means the number of covered flight legs, while using the robustness approach.

Table 5: Performance characteristics of the three robustness approaches.

Test cases	No. of flight legs	BT approach			SSP approach			TRTR approach		
		$\overline{Z}$	FP	$\overline{CPU(min)}$	$\overline{Z}$	FP	$\overline{CPU(min)}$	$\overline{Z}$	FP	$\overline{CPU(min)}$
Case 1	40	0	40	0.028	0	40	2.125	0	40	0.020
Case 2	48	0	48	0.033	0	48	5.785	0	48	0.025
Case 3	64	237	64	0.088	242	64	13.258	237	64	0.072
Case 4	96	322	96	0.085	332	96	18.578	322	96	0.071
Case 5	120	350	117	0.320	351	120	25.085	338	120	0.286
Case 6	160	1361	153	0.655	1,386	160	38.258	1,301	160	0.624
Case 7	210	518	198	0.700	523	210	52.278	495	210	0.657
Case 8	240	2,856	223	0.902	2,924	240	70.578	2,715	240	0.803
Case 9	300	2,887	274	1.320	2,916	300	85.782	2,705	300	1.120
Case 10	400	6849	365	2.452	7,004	400	125.358	6,325	400	2.042
SIM01	510	4,274	464	3.250	4,352	510	193.237	3,970	510	2.780
SIM02	700	9,122	631	4.157	9,250	700	302.578	8,265	700	3.705

SIM03	1400	17,633	1249	12.339	18,110	1400	732.578	15,865	1400	11.939
SIM04	2040	53,308	1802	15.152	56,201	2040	1258.232	47,754	2040	14.452
SIM05	4080	154,501	3526	37.256	167,100	4080	2878.987	135,652	4080	33.560

Table 6: Outperformance characteristics of the TRTR over the BT and the SSP.

Test cases	$\boldsymbol{OUT}\%(\bar{\boldsymbol{Z}})_{\boldsymbol{BT}}$	$\boldsymbol{OUT}\%(\mathbf{FP})_{\boldsymbol{BT}}$	$\boldsymbol{OUT}\%(\bar{\boldsymbol{Z}})_{\boldsymbol{SSP}}$	$\boldsymbol{OUT}\%(\mathbf{FP})_{\boldsymbol{SSP}}$
Case 1	0	0	0	0
Case 2	0	0	0	0
Case 3	0	0	2.07	0
Case 4	0	0	3.01	0
Case 5	3.43	2.5	3.70	0
Case 6	4.41	4.38	6.13	0
Case 7	4.44	5.71	5.35	0
Case 8	4.94	7.08	7.15	0
Case 9	6.30	8.67	7.24	0
Case 10	7.65	8.75	9.69	0
SIM01	7.11	9.02	8.78	0
SIM02	9.39	9.86	10.65	0
SIM03	10.03	10.79	12.40	0
SIM04	10.42	11.67	15.03	0
SIM05	12.20	13.58	18.82	0

Note: $OUT\%(\bar{Z})_{BT} = \left((\bar{Z}_{BT} - \bar{Z}_{TRTR}) * \frac{100}{\bar{Z}_{BT}}\right)$; $OUT\%(\mathrm{FP})_{BT} = ((FP_{TRTR} - FP_{BT}) * 100/FP_{TRTR})$; $OUT\%(\bar{Z})_{ssp} = \left((\bar{Z}_{ssp} - \bar{Z}_{TRTR}) * \frac{100}{\bar{Z}_{ssp}}\right)$; $OUT\%(\mathrm{FP})_{SSP} = ((FP_{TRTR} - FP_{SSP}) * 100/FP_{TRTR})$.

Regarding the comparison between the TRTR and the BT, the results in Tables 5 and 6 show that the TRTR outperforms the BT by about 3.43 – 12.20% and 2.5 – 13.58%, respectively, while handling the propagated delay costs and fleet productivity. The main reason for this outperformance, in terms of the propagated delay costs, is due to the structure of the TRTR. As mentioned earlier, the TRTR includes reducing the TRT times by allocating more ground resources when the propagated delay appears. This results in absorbing the propagated delay, which finally leads to significant savings in the propagated delay costs. In contrast to the TRTR, the BT sometimes inserts small buffer times, which may not be enough to absorb the propagated delays, resulting in an increase in the propagated delay costs. Moving to the reason for the outperformance in terms of the fleet productivity, the BT sometimes imposes large buffer time among the flight legs, which reduces the number of flight legs that should be covered by each aircraft. Consequently, the BT suffers from a reduction in the fleet productivity, especially when covering a large number of flight legs. In contrast to the BT, the TRTR does not include this large time insertion, so that the fleet productivity reduction can be easily avoided.

For the comparison between the TRTR and the SSP, the results demonstrate that the TRTR is better than the SSP by about 2.07 – 18.82%, while minimizing the propagated delay costs. In terms of fleet productivity, the performance of both approaches is identical. The rationale behind the outperformance, in terms of propagated delay costs, is as follows. In fact, the SSP only includes arranging the flight legs in a formation, in which suitable times between the flight legs exist, so that the propagated delays can be absorbed. Occasionally, the times between the flight legs are insufficient to absorb the propagated delays, resulting in an increase in the propagated delay costs. In contrast to the SSP, the TRTR has an efficient structure, as mentioned earlier, which can significantly absorb the propagated delays, resulting in a significant saving in the propagated delay costs. By looking at the results in Table 5, a striking observation is that the TRTR is much faster than the SSP. For instance, the TRTR takes around half an hour to handle SIM05, whereas the SSP takes around 2878.987 minutes ≅ 48 hours to handle the same test case. The main reason for this time difference is that applying the SSP necessitates solving the model several times, as the model includes several scenarios, but, applying the TRTR includes only solving the model once.

Therefore, the results of this section demonstrate that the proposed TRTR significantly improves the results obtained by the existing robustness approaches, such as the BT and the SSP. This echoes the superiority and importance of the TRTR when implemented by airlines in real practice.

6.5. Discussion

In this study, a novel robustness approach, called the TRTR, is proposed. The results of this approach in comparison with the models that do not include any robustness approaches, show an improved performance in terms of propagated delay absorption. So, airlines can shift their focus from using the non-robustness models to the robustness models. Furthermore, to help airline to select either the proposed robustness model or existing models, a comparison between both approaches is conducted, including the BT and the SSP. The results show that the TRTR and the BT are equivalent in terms of computational time, but the TRTR is better than the BT in terms of propagated delay absorption and fleet productivity. Moreover, the results show that the TRTR and the SSP offer the same performance in terms of fleet productivity. However, the TRTR shows better propagated delay absorption and computational time performance compared to the SSP. To summarize, this study shows the viability and the superiority of the TRTR approach. Therefore, airlines may benefit significantly by implementing this approach in real practice.

This paper presents a RAMRP model with a novel robustness approach. However, there are some limitations in the proposed model. Firstly, the RAMRP is limited to a 4-day planning horizon. Secondly, the RAMRP assumes a deterministic maintenance capacity. Nonetheless, these limitations suggest some future research avenues. First, we suggest solving the RAMRP that considers all the maintenance regulations, while adopting a longer planning horizon (i.e. weekly planning horizon). This planning horizon means a larger number of flight legs and aircraft are involved and thus, solving this formulation is challenging. Therefore, developing an efficient algorithm for solving the previously suggested model can be a second research topic. Our proposed model assumes, for simplicity, that the maintenance capacity is deterministic. Therefore, a third research direction may consider solving the RAMRP while considering the uncertainty of the maintenance capacity.

7. Conclusions

In this study, we investigate the RAMRP with two main objectives. Firstly, to propose a novel robustness approach, called the TRTR. Secondly, to develop a RAMRP model, in which all the maintenance regulations are simultaneously considered. These regulations include the allowable flying hours, the allowable days, and the allowable take-offs since the last maintenance check. In addition, the working times and the capacity of maintenance stations are also considered in the model. An ACO-based algorithm is adopted as a solution algorithm for the proposed model. The effectiveness of the proposed RAMRP, along with the TRTR approach, is demonstrated through computational experiments using real data from a major Middle Eastern airline. In our computational experiments, a solution to the proposed RAMRP using the ACO-based algorithm is first obtained. In order to demonstrate the importance of the TRTR, which is included in the RAMRP, we make a comparison with the NRAMRP. The results show that the RAMRP outperforms the NRAMRP by 41.03 – 82.72%, in minimizing the expected propagated delay costs. In a trial to show the advantage of the TRTR over the existing robustness approaches, we extend our experiments to compare with the traditional approaches in the literature, including the BT and the SSP. The results reveal an outperformance of the TRTR over the BT by about 3.43 – 12.20% and 2.5 – 13.58%, while handling the propagated delay costs and fleet productivity, respectively. In addition, the results show that the TRTR is better than the SSP by about 2.07 – 18.82%, while minimizing the propagated delay costs. The results of this study indicate that the novel TRTR has great potential for implementation in the real industry.

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