Computational Experiments on Maintenance Scheduling in Airline Companies

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Abstract. Essential for complying with the strict safety regulations in the aviation industry and with the increasing passengers demand, aircraft maintenance planning has become a factor of the upmost importance for operational efficiency and cost optimization, which is crucial for the airlines to face fierce global competition. An effective method to optimize aircraft maintenance operations is to minimize the associated costs, by reducing the amount of maintenance activities, and consequently, increasing aircraft availability. Thus, a mixed-integer linear programming model and a heuristic approach are presented, which minimizes aircraft maintenance costs. This mathematical optimization model creates a maintenance schedule, including light maintenance checks (A-type) and heavy maintenance checks (C-type), during a specified planning horizon. Firstly, the model is verified by applying it to an illustrative example, showing the applicability of both the branch-and-bound and the heuristic approaches. Then, both approaches are applied to a case study of the "narrow-body" aircraft fleet of the Portuguese airline, TAP Air Portugal, for a two-year planning horizon. The results show that with the heuristic approach the computational time can be reduced to 48 minutes, while providing equal or lower maintenance costs than the branch-and-bound approach that showed non-zero optimality gaps. Finally, some sensitivity analysis associated with threshold values, the COVID-19 pandemic situation and the hangar capacity availability, are studied. Overall, this work provides a decision framework that can support aircraft maintenance planning, while reducing the planning time and providing near-optimal feasible solutions.

Keywords: Maintenance, Maintenance Scheduling, Aircraft Maintenance, Mixed-Integer-Linear Programming, Heuristic

1. Introduction

Airlines are obligated to follow the strict safety measures to be able to fly in European Union (EU) airspace. Not complying with the safety regulations can bring penalties or suspension of certificates on certificate holders throughout all the Member States of the EU (EC, 2021), which means that being efficient on safety procedures and measures is crucial for the airlines to remain competitive. It is projected that European air traffic will increase 50% by 2035 (EC 2021). This increase in air traffic will make operational efficiency one of the most important aspects that European airline companies need to worry about, making fleet availability and maintenance operations key factors for companies to succeed, in the face of the growing number of challenges and fierce global competition.

Maintenance of aircrafts is one of the most important factors for air safety, mainly because it ensures the airworthiness of the aircrafts, but also because it has a direct impact on air traffic management, since it affects aircraft's availability, as maintenance require to remove aircrafts out of service. This unavailability has an indirect impact on the revenues of the airline company, emphasizing the importance of properly optimizing the scheduling of the maintenance activities in order to reduce costs and minimize unavailability of the airline fleet. The different types of aircraft maintenance checks are divided into 4 categories and each one is identified by a letter: the A-check, the B-check, the C-check and the D-check. Moreover, each type of check is usually divided into groups of tasks that are numbered, for example the A-check has 4 groups of tasks (A1, A2, A3 and A4) and the C-check has 12 groups of tasks (C1, …, C12). In line with these ideas, the current research work aims to solve aircraft maintenance scheduling problem for the case study of a Portuguese airline company in Lisbon, TAP Air Portugal. The research problem consists of scheduling the maintenance checks that need to be performed, in a way that it minimizes the overall cost of the maintenance procedure, and it reduces maintenance activities and increases aircraft availability in the process, but without compromising its feasibility. The main objective of this work is to develop a decision model that schedules all the aircraft maintenance checks that need to be performed and apply it to the case study of the TAP Air Portugal's fleet. The decision model should be able to find an optimized maintenance schedule for a given planning horizon. This work follows the efforts from previous dissertations (Martinho (2018) and Fernandes (2019)), which served as a starting point to the development of the model and the heuristic for the aircraft maintenance scheduling problem.

The present paper is structured in the following order. A brief introduction was provided in this first section. In section 2, a literature review is presented. In section 3, the mixed-integer linear programming model and the heuristic approach are explored. The TAP Air Portugal's case study is discussed in section

4 and the results are analysed in section 5. Finally, in section 6, conclusions and future research are stated.

2. Related Literature

The problem of maintenance planning in aircrafts and other means of transportation has received a lot of contributions. Siriam and Haghani (2003) addresses the problem of cost minimization on scheduling aircraft maintenance activities, using a MILP formulation and a heuristic approach to solve the problem approximately in a reasonable computational time, and thus, without compromising its feasibility for larger instances. From a given flight schedule, the main objective is to schedule aircraft maintenance of types A and B, during flight inactivity (late evening/early morning), while taking into account, not only constraints such as fleet characteristics or the maintenance facilities in different locations, but also the cost penalties on the re-assignment of aircrafts from the flight schedule.
Saltoğlu *et al.* (2016) studies the problem of aircraft maintenance and the inherent direct and indirect costs. Contrary to previous articles, which only consider direct maintenance costs (e.g. workforce, material), they propose an innovative model that calculates the indirect maintenance cost of aircraft downtime during the time that maintenance actions are performed, considering the influence of different seasons. It serves as a decision support system for operators to determine the best time to schedule maintenance and reduce maintenance operating costs. They not only described the different types of maintenance checks (the Line, A, B, C, and D types), but also the different threshold values of maintenance checks intervals for each type of maintenance, and for each type of aircraft.
Martinho (2018) deals with the minimization of the total costs associated with aircraft preventive maintenance applied to a Portuguese airline company, which is the same company explored in this dissertation (TAP Air Portugal). A MILP formulation was developed to optimize the costs associated with maintenance checks and associated with aircraft downtime. The checks studied are grouped in different check types A (short-term) and check types C (long-term), because of airline company inputs for the research. The model considers constraints on threshold values for flight hours, flight cycles and days for maintenance checks to occur and constraints regarding hangar capacity availability throughout the planning horizon. Finally, the model outputs a maintenance schedule for the airline company fleet of 45 aircrafts during a 6-month period, which showed promising results in comparison to the original maintenance schedule.
Fernandes (2019) deals with the minimization of bus preventive maintenance total costs applied to a Portuguese bus operating company. To achieve this, the following three different methods are applied: an extension and improvement of a mixed integer linear programming (MILP) model from a previous work (Martins 2018); a parallel solving approach; and a heuristic approach. All the models output a technical planning schedule for the bus maintenance operations. The heuristic approach, even though it solves the problem approximately and thus the optimal solution cannot be guaranteed, it achieves a excellent result for the cost minimization and for the computational time. In fact, the heuristic approach followed by Fernandes (2019) serves as a basis for the heuristic algorithm developed in the present work. Martins *et al.* (2021) focuses on the problem of scheduling maintenance tasks and crew in a bus operating company. They used an integer linear programming (ILP) model that minimizes the costs related to the maintenance actions and bus unavailability, followed by a heuristic approach that solves a sub-problem sequentially for each bus, reducing the computational time. The model takes into consideration constraints of maintenance resources capacity, such as the depot space availability and the number of maintenance workers. The model is applied to a case study of a Portuguese bus operating company and outputs an optimized maintenance schedule that includes which type of maintenance worker is assigned to each bus and at what day and time.
The previous work carried out by Martinho (2018) schedules the maintenance checks required by TAP M&E, but it is only able to do that for a 6-month planning horizon, which is considered too short for the aviation industry planning horizon. Moreover, it does not take into account the influence of different seasons on the demand and overall business. Besides, the model does not guarantee finding an optimal solution, achieving a feasible solution with an optimality gap of approximately 9% in 24 hours of computational time, which might be considered still high for this scheduling problem.

3. Mixed-integer linear programming model and heuristic approach to schedule aircraft maintenance

The present mathematical model is an improvement of the one developed by Martinho (2018). For the aircraft maintenance planning, the time horizon of just 6 months was considered too short to provide a reasonable plan for the maintenance activities as it can lose medium-term effects in certain maintenance tasks. Therefore, the model was extended to include a time horizon of 2 years, and it changes the time step, from 1 day to 1 week, aiming to reduce the computational time, which otherwise would be too long if the 2 years would be scheduled day by day. Besides, the previous model did not consider penalties on checks done during high season and that for check C the aircraft has an unavailability of two weeks. Furthermore, to reduce computational time, without compromising the solution feasibility and optimization, a heuristic approach is implemented. This heuristic approach is done mainly because in the previous model by Martinho (2018), even though it achieved a good solution in terms of optimization values, the computational time was still too high for a problem of this complexity. In order to implement a heuristic procedure, a heuristic algorithm was adapted from Fernandes (2019) and Martins *et al.* (2021), which showed promising results on the heuristic procedure, not only for the computational time, but also for the optimization results. Figure 1 gives an overview of the relation with the previous works.

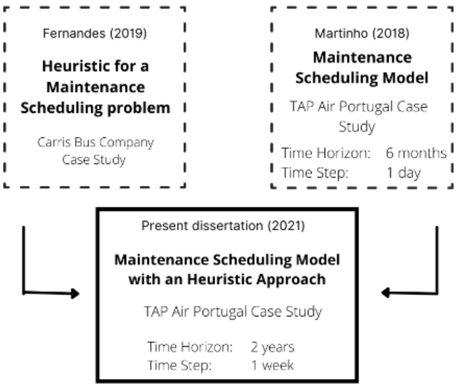


Figure 1 – Relation of the present dissertation with previous works

3.1 Indexes

$\boldsymbol{p}$	plane
$\boldsymbol{c}$	type of maintenance check
$\boldsymbol{t}$	time period (week)
$\boldsymbol{k}$	number of maintenance check

3.2 Constants

$\boldsymbol{Np}$	number of planes
$\boldsymbol{Nc}$	number of different types of maintenance checks (Two check types: A-type and C-type, $Nc = 2$)
$\boldsymbol{Nw}$	number of weeks in the planning horizon
$\boldsymbol{Nk_c}$	number of maintenance checks of type c
$\boldsymbol{M}$	large number
$\boldsymbol{\varepsilon}$	small number

3.3 Sets

$\boldsymbol{P}$	set of planes, p
$\boldsymbol{C}$	set of types of maintenance checks, c
$\boldsymbol{T}$	set of time periods (week), t
$\boldsymbol{T^{HS}}$	set of time periods (week) of High Season, t
$\boldsymbol{K_c}$	set of number of maintenance checks k of type c

3.3. Parameters

$\boldsymbol{S_t}$	available hangar maintenance slots, in week t
$\boldsymbol{L_{c,p}}$	last maintenance check number of type c, for plane p
$\boldsymbol{FH^0_{c,p}}$	accumulated Flight Hours (FH), since last maintenance check of type c, for plane p, in week $t = 0$ (i.e., at the beginning of the planning horizon)
$\boldsymbol{FC^0_{c,p}}$	accumulated Flight Cycles (FC), since last maintenance check of type c, for plane p, in week $t = 0$ (i.e., at the beginning of the planning horizon)
$\boldsymbol{W^0_{c,p}}$	accumulated Weeks (W), since last maintenance check of type c, for plane p, in week $t = 0$ (i.e., at the beginning of the planning horizon)
$\boldsymbol{FHw_{c,p}}$	estimated weekly Flight Hours (FH), for plane p, in week t
$\boldsymbol{FCw_{c,p}}$	estimated weekly Flight Cycles (FC), for plane p, in week t
$\boldsymbol{FH^{max}_c}$	threshold value for maximum Flight Hours (FH), between two consecutive maintenance checks of type c
$\boldsymbol{FC^{max}_c}$	threshold value for maximum Flight Cycles (FC), between two consecutive maintenance checks of type c
$\boldsymbol{W^{max}_c}$	threshold value for maximum Weeks (W), between two consecutive maintenance checks of type c
$\boldsymbol{\gamma_1}, \boldsymbol{\gamma_2}$	decision weights for the objective function
$\boldsymbol{c_{un}}$	unavailability cost
$\boldsymbol{c_c}$	cost of maintenance check of type c

3.4. Decision variables

$\boldsymbol{x_{p,c,k,t}}$	binary variable set to 1 if maintenance activity type c, number k, is performed on plane p, in week t
$\boldsymbol{y_{p,t}}$	binary variable set to 1 if plane p, is in hangar, in week t
$\boldsymbol{FH_{p,c,t}}$	accumulated flight hours, for plane p, since last type check c, in week t
$\boldsymbol{FC_{p,c,t}}$	accumulated flight cycles, for plane p, since last type check c, in week t
$\boldsymbol{W_{p,c,t}}$	accumulated weeks, for plane p, since last type check c, in week t

Note: A-type checks corresponds to $c = 1$, and C-type checks correspond to $c = 2$.

3.5. Objective function

$$\text{Minimize: } \sum_{p \in P} \sum_{t \in T} c_{un} \times y_{p,t} + \left(\sum_{p \in P} \sum_{t \in T} \sum_{k \in K_c} c_1 \times x_{p,1,k,t} + c_2 \times x_{p,2,k,t} \right) + \gamma 1 \times \left(\sum_{p \in P} \sum_{c \in C} \sum_{t \in T} t \times FH_{p,c,t} \right) + \gamma 2 \times \left(\sum_{p \in P} \sum_{k \in K_c} \sum_{t \in T^{HS}} c_2 \times x_{p,2,k,t} \right)$$

Subject to:

$x_{p,c,k,t} \in \{0,1\}$	$\forall\, p \in P, c \in C, k \in K_c, t \in T$	(1)
$y_{p,t} \in \{0,1\}$	$\forall\, p \in P, t \in T$	(2)
$FH_{p,c,t} \leq FH_c^{max}$	$\forall\, p \in P, c \in C, t \in T$	(3)
$FC_{p,c,t} \leq FC_c^{max}$	$\forall\, p \in P, c \in C, t \in T$	(4)
$W_{p,c,t} \leq W_c^{max}$	$\forall\, p \in P, c \in C, t \in T$	(5)
$FH_{p,c,t} = FH_{c,p}^{0}$	$\forall\, p \in P, c \in C, t \in \{1\}$	(6)
$FH_{p,c,t} \geq FH_{p,c,t-1} + FHw_{p,t} \times \left(1 - \sum_{k \in K_c} x_{p,c,k,t}\right) - FH_c^{max} \times \sum_{k \in K_c} x_{p,c,k,t}$	$\forall\, p \in P, c \in C, t \in \{2, \dots, Nw\}$	(7)
$FH_{p,c,t} \geq \varepsilon \times \sum_{k \in K_c} x_{p,c,k,t}$	$\forall\, p \in P, c \in C, t \in \{2, \dots, Nw\}$	(8)
$FC_{p,c,t} = FC_{c,p}^{0}$	$\forall\, p \in P, c \in C, t \in \{1\}$	(9)
$FC_{p,c,t} \geq FC_{p,c,t-1} + FCw_{p,t} \times \left(1 - \sum_{k \in K_c} x_{p,c,k,t}\right) - FC_c^{max} \times \sum_{k \in K_c} x_{p,c,k,t}$	$\forall\, p \in P, c \in C, t \in \{2, \dots, Nw\}$	(10)
$FC_{p,c,t} \geq \varepsilon \times \sum_{k \in K_c} x_{p,c,k,t}$	$\forall\, p \in P, c \in C, t \in \{2, \dots, Nw\}$	(11)
$W_{p,c,t} = W_{c,p}^{0}$	$\forall\, p \in P, c \in C, t \in \{1\}$	(12)
$W_{p,c,t} \geq W_{p,c,t-1} + 1 \times \left(1 - \sum_{k \in K_c} x_{p,c,k,t}\right) - W_c^{max} \times \sum_{k \in K_c} x_{p,c,k,t}$	$\forall\, p \in P, c \in C, t \in \{2, \dots, Nw\}$	(13)
$W_{p,c,t} \geq \varepsilon \times \sum_{k \in K_c} x_{p,c,k,t}$	$\forall\, p \in P, c \in C, t \in \{2, \dots, Nw\}$	(14)
$\sum_{c \in C} \sum_{k \in K_c} x_{p,c,k,t} \leq M \times y_{p,t}$	$\forall\, p \in P, t \in T$	(15)
$\sum_{k \in K_c} x_{p,c,k,t} \leq y_{p,t+1}$	$\forall\, p \in P, c \in \{2\}, t \in \{1, \dots, 104\}$	(16)
$\sum_{k \in K_c} x_{p,c,k,t} + \sum_{k \in K_c} x_{p,c,k,t+1} \leq 1$	$\forall\, p \in P, c \in \{1\}, t \in \{1, \dots, 104\}$	(17)
$\sum_{p \in P} y_{p,t} \leq s_t$	$\forall\, t \in T$	(18)

$$\sum_{k \in K_c} x_{p,c,k,t} \leq 1 \qquad \forall\, p \in P, c \in \{1\}, t \in T \tag{19}$$

$$\sum_{k \in K_c} x_{p,c,k,t} \leq 1 \qquad \forall\, p \in P, c \in \{2\}, t \in T \tag{20}$$

$$\sum_{t \in T} \sum_{k \in \{2,\ldots,4\} | k=n+1} x_{p,c,k,t} \geq 1 \qquad \forall\, p \in P, c \in \{1\}, n \in \{1,2,3\} |\, L_{c,p} = n \tag{21}$$

$$\sum_{t \in T} x_{p,c,1,t} \geq 1 \qquad \forall\, p \in P, c \in \{1\} |\; L_{c,p} = 4 \tag{22}$$

$$\sum_{t \in T} \sum_{k \in \{2,\ldots,12\} | k=n+1} x_{p,c,k,t} \geq 1 \qquad \forall\, p \in P, c \in \{2\}, n \in \{1,\ldots,11\} |\, L_{c,p} = n \tag{23}$$

$$\sum_{t \in T} x_{p,c,1,t} \geq 1 \qquad \forall\, p \in P, c \in \{2\} |\; L_{c,p} = 12 \tag{24}$$

$$\sum_{t' \in T | t' \leq t} x_{p,c,k+1,t'} \leq \delta_{k,\mathrm{L_{c,p}}} + \sum_{t'' \in T | t'' \leq t} x_{p,c,k,t''} \qquad \forall\, p \in P, c \in C, k \in K_c/\{Nk_c\}, t \in T/\{1\} \tag{25}$$

$$\sum_{t' \in T | t' \leq t} x_{p,c,1,t'} \leq \delta_{Nk_c,\mathrm{L_{c,p}}} + \sum_{t'' \in T | t'' \leq t} x_{p,c,Nk_c,t''} \qquad \forall\, p \in P, c \in C, t \in T/\{1\} \tag{26}$$

The objective function has four components. The first and second components are the main objectives and are responsible for the real overall cost value of the maintenance activities. The first component considers the unavailability cost whenever an aircraft is in the hangar for a maintenance activity, while the second component considers the costs of the actual maintenance checks, both A and C, each time one is scheduled to be done. The third component is responsible to ensure that the maintenance activities are done as close to the threshold values as possible in the start of the scheduling horizon, when there are less factors that could interfere with the normal realization of the schedule activities, such as delays on the maintenance procedures. Then, at the end of the schedule, the maintenance activities are done earlier than the threshold values, so there is time for any changes in schedule that may need to be done, due to previous delays. The fourth term is responsible to provide an extra penalty cost for when maintenance check type C is done on the high season. Note that the value for best solution will be the overall value of the objective function, but the real cost value of the scheduled maintenance checks is defined just by the sum of the first and second components.

Constraints (1) and (2) define as binary variables, the decision variables $x_{p,c,k,t}$ and $y_{p,t}$, respectively. Constraints (3)-(5) are responsible to guarantee that the threshold values between A-types and C-types maintenance checks are not exceeded for any plane p at any time t. Constraint (3) is for the thresholds associated with flight hours, (4) is associated with the flight cycles and (5) is associated with the weeks for each type of maintenance check.

Before continuing the constraints explanation, consider that for the set K_1, which represents the set for the A-type maintenance checks, the values are $\{1,2,3,4\}$; while for the set K_2, which represents the set for the C-type maintenance checks, the values are $\{1, \ldots, 12\}$. This means that there are four different numbers of A-type checks, while there are twelve different numbers of C-type checks.

Constraints (6)-(14) are responsible to ensure that a maintenance check occurs when the accumulation of flight hours, flight cycles or weeks reaches the threshold values and that in each week, the weekly values of these parameters are added. These constraints can be divided into three groups of three to be better explained. The first group (6)-(8) of constraints regards to flight hours for the maintenance check type c. Constraint (6) sets the value of the decision variable $FH_{p,c,t}$ equal to the value of the parameter $FH^0_{c,p}$, which is the value of accumulated flight hours for aircraft p at the beginning of the time horizon $(t = 1)$, since last maintenance check type c was done. Constraint (7) ensures the continuous accumulation of flight hours $FH_{p,c,t}$ throughout the time horizon, by adding the weekly flight hours $FHw_{p,t}$ to the previous week value $FH_{p,c,t-1}$, while checking if the value of $FH_{p,c,t}$ remains under the threshold value of flight hours FH^{max}_c for maintenance check type c. If for a certain week t, the value of $FH_{p,c,t}$ is going to be higher than the FH^{max}_c, then a maintenance check type c needs to occur in that week t and the decision variable $x_{p,c,k,t}$ must be equal to one. Constraint (8) guarantees that if a maintenance check type c needs to occur in a certain week t, then the value of $FH_{p,c,t}$

is set to zero for that same week t. For the remaining two groups of three, the formulation has the same purpose and similarity, but for different types of counters. Constraints (9)-(11) are for flight cycles for maintenance checks type c, while constraints (12)-(14) are for weeks for maintenance checks type c.
Constraint (15) ensures that whenever a plane p needs to undergo a maintenance check at a certain week t, defined by the decision variable $x_{p,c,k,t}$, then the aircraft must go to the hangar at the same week t, defined by the decision variable $y_{p,t}$. Constraint (16) defines that for C-type maintenance checks, the aircraft needs to stay at the hangar one more week, adding up to two weeks of downtime, while constraint (17) states that two different A-type maintenance checks cannot be done in two sequential weeks, to avoid assigning two consecutive A-type maintenance checks to be done only because the aircraft is already at the hangar for the C-type maintenance check. Constraint (18) guarantees that the sum of the aircrafts at the hangar at a certain week t, does not surpass the hangar capacity of maintenance slots available s_t, for that week t.
Constraints (19) and (20) state that a plane p cannot have two A-type maintenance checks or two C-type maintenance checks, respectively, in the same week t. Constraints (21)-(26) ensure that the cycle order of the different numbers of A-type and C-type maintenance checks are respected. Constraints (21)-(24) guarantee that for a certain number of last maintenance check before the start of the planning horizon $L_{c,p}$, the next number of maintenance check that needs to occur follows the cycle order previously showed. Constraints (21) and (22) refer to A-type maintenance checks, while constraints (23) and (24) refer to C-type maintenance checks. Constraints (25) and (26) ensure that the cycle order is respected throughout the entire planning horizon. In both equations, the δ represents a Kronecker delta, i.e., for $\delta_{k,L_{c,p}}$, δ is only equal to 1 if $k = L_{c,p}$, or else the δ is equal to zero.

3.6. Heuristic approach

The main objective of using the heuristic approach is to reduce computational time. To achieve this reduction, instead of solving the entire MILP problem at once, the heuristic approach solves the problem sequentially, one aircraft at a time, saving and gathering the results one aircraft after the other. To implement the heuristic, some changes need to be done on the model formulation. First, it is necessary to create a new parameter called Gp_p, that is responsible for defining in which order the aircrafts will be solved, i.e., Gp_1 will be the first plane to be solved and so on. This way, the first plane to be solved does not mean that it is the aircraft number 1 of the input data order, represented on the set $\boldsymbol{P}$, since, for example, the value of Gp_1 could be equal to 9, which results in aircraft number 9 of the input data order being the first aircraft to be solved. The criteria for deciding the order will be stated on subsection 5.2. For the heuristic process, a loop is created, in which a new variable $NPlane$ is created with the value of zero and increased by one in each iteration. The variable $NPlane$ is then used on the parameter Gp_{NPlane}, to add a new plane to the new set $P1$, which will be the set of planes in the order defined by the criteria previously decided. At the end of each procedure, the achieved solution is saved on the parameter $Prop\_x_{p,c,k,t}$.
To ensure that the solution achieved of each previous plane is considered for each next one, constraint (27) is added to the model formulation.

$$x_{p,c,k,t} = Prop\_x_{p,c,k,t} \qquad \forall\, p \in P1 \setminus \{Gp_{NPlane}\}, c \in C, k \in K_c, t \in T \qquad (27)$$

This constraint (27) guarantees that if an aircraft has a solution to undergo maintenance activities at certain times t, then the procedure for the next aircraft will take into account that those maintenance checks already scheduled, and thus, “locking” the time and hangar availability slots. Figure 2 shows the heuristic algorithm flowchart.

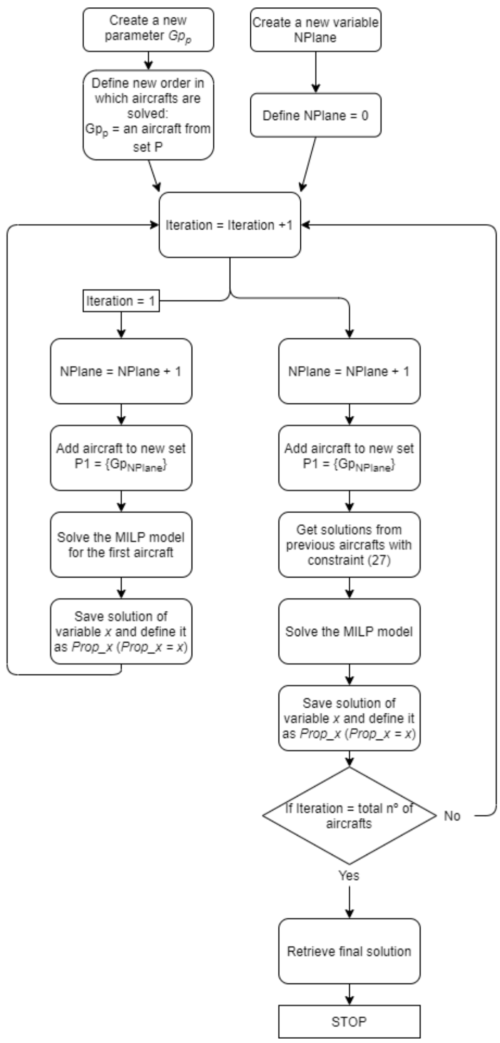


Figure 2 - Heuristic algorithm flowchart

4. Case study of TAP Air Portugal

Section 4 explores the case study under analysis in the present research, in which the mathematical model is applied to the TAP Air Portugal case study.

4.1. TAP Air Portugal problem specifications

The airline company that is under analysis is TAP Air Portugal, but since this is a problem related to maintenance operations, almost all data came from TAP Maintenance & Engineering (TAP M&E), which is the aircraft maintenance and engineering unit of TAP Air Portugal. For this case study, the data used is from 2018, which means that the aircraft fleet and time estimations are from that year. The data corresponds to the same used in Martinho (2018). Unfortunately, more recent data and information could not be acquired. The data was only for a 6-month period, so symmetric assumptions were used to extrapolate for a 2-year planning horizon. The hangar facilities in Humberto Delgado Airport (Lisbon, Portugal) includes 3 hangars that can simultaneously hold 3 WB (wide-body aircraft) and 5 NB (narrow-body aircraft), and this was also taken into account for the assumed value of hangar availability. Variations on the hangar capacity throughout the planning horizon are not considered, since further information on this could not be obtained and variations in the availability of human resources is also not considered in the present model. Although TAP Air Portugal aircraft fleet includes *narrow-body* and *wide-body*, this case study only studies and schedules the *narrow-body* part of the fleet, which means that only the Airbus aircrafts A319, A320 and A321 are considered.

In short, the main objective of TAP Air Portugal is to schedule the maintenance checks of A-type and C-type of their *narrow-body* fleet of 45 aircrafts, in a 2-year planning horizon (105 weeks), by using their hangar facilities on the Lisbon Airport, while minimizing maintenance and unavailability costs, and avoiding C-type maintenance checks during the High Season. The values of the constants M and ε are 100,000 and 0.001, respectively.

4.2. Parameters for the case study

For the case study, the hangar availability is constant throughout the planning horizon and has the value of $s_t = 6$. The decision weights parameters are set for the values of $\gamma_1 = 0.000001$ and $\gamma_2 = 0.001$. The purpose of these values is to provide a different preference on the different components of the objective function, which impact the final optimization value. The cost values defined are 20 k€ for the unavailability cost, 30 k€ for the A-type maintenance check cost, and 600 k€ for the C-type maintenance check cost. The threshold values to trigger each type of maintenance are: 750 flight hours and 750 flight cycles for the A-type check; and 7500 flight hours and 5000 flight cycles for the C-type check. The flight hours are the elapsed time between wheel lift off and touchdown, while each flight cycle considers a complete take-off and landing sequence. The threshold value of time between checks is 4 months (17 weeks) for the A-type check and 24 months (105 weeks) for the C-type check. Some input data for this case study is shown in the following tables and figures. Table 1 sets the high season time periods for certain weeks t, which includes summertime and Christmas and new year´s season. Figure 2 shows a scheme on how the planning horizon is divided into 3 different time groups. This split represents approximately the Summertime (Time 3), the Fall / Spring times (Time 2) and the Wintertime (Time 1). Tables 2 and 3 sets the parameters for the weekly estimated flight hours and flight cycles, respectively, for each aircraft type.

Table 1 – High Season set values

Set	Time			
	18th June 2018 – 16th September 2018	*17th December 2018 – 6th January 2019*	*17th June 2019 – 15th September 2019*	*16th December 2019 – 5th January 2020*
T^{HS}	$20 \leq t \leq 32$	$46 \leq t \leq 48$	$72 \leq t \leq 84$	$98 \leq t \leq 100$

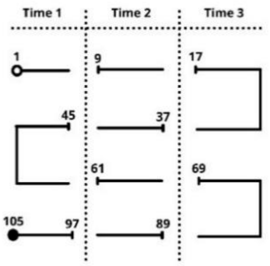


Figure 3 - Partition of the time periods into 3 time groups

Table 2 – Weekly flight hours for each aircraft type

Plane type	Parameter		
	$FHw_{p,t}$		
	Time group 1	Time group 2	Time group 3
A319	66.8	70.0	73.5
A320	77.3	80.5	84.0
A321	74.1	80.5	80.5

Table 3 – Weekly flight cycles for each aircraft type

Plane type	Parameter		
	$FCw_{p,t}$		
	Time group 1	Time group 2	Time group 3
A319	37.1	38.9	40.7
A320	31.0	32.3	33.6
A321	31.0	32.3	33.6

The rest of the input data regarding the aircraft fleet is available in the dissertation document and the associated appendixes.

5. Results

In this fifth section, the results for the TAP Air Portugal case study are presented and discussed. The results from both approaches (the exact method using the branch-and-bound approach and the heuristic approach) are shown. Then, the results are analysed and compared in order to take conclusions.

5.1. Branch-and-Bound approach (exact method)

In this subsection the results of the exact method (branch-and-bound approach) are presented and analysed. For the exact method, the model was executed for 199,662.3 seconds, which is approximately 55 hours and 28 minutes. The exact method could not find any feasible solution during this period, which is considered too long for this type of problem, and thus, no more results are discussed in this subsection.

5.2. Heuristic approach

In this subsection, the results for the heuristic approach applied to the case study are presented and analysed. For the case study, the criteria chosen for the order in which the aircrafts were executed, was the amount of weekly flight hours $FHw_{p,t}$, i.e., for the case study, the first aircrafts to be executed are the A320´s from aircraft number 22 to number 41, which are the ones with higher weekly flight hours throughout the planning horizon, then the A321´s from aircraft number 42 to number 45, and finally the A319´s from aircraft number 1 to number 21, knowing the $FHw_{p,t}$ parameter values for each plane, present in Table 2.

On the heuristic approach, the model converged to an optimal solution with a minimum solution value of 53,130.3, which results in a real minimum cost of 52,290 k€, since only the first and second term of the objective function are considered for the actual costs of the scheduled maintenance activities. The total time elapsed since the beginning of the program computation until the end was 2,886.4 seconds, which represents a competitive time of approximately 48 minutes. All the previous aircrafts reached an optimal solution in their MIP search, in order for the programme to move to the next aircraft and so on. Even though the total MIP search time was 675 seconds, the problem needs to import increasing data due to the write and rewrite of arrays from previous solutions, each time it moves to the next aircraft, which justifies a larger overall computational time throughout the number of aircrafts. This can be verified in Figure 4, which shows the total computational solving time for each aircraft, since the end of the previous aircraft until it finds an optimal solution, increases along with the number of aircrafts already solved.

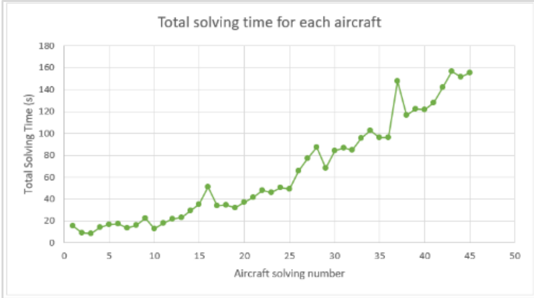
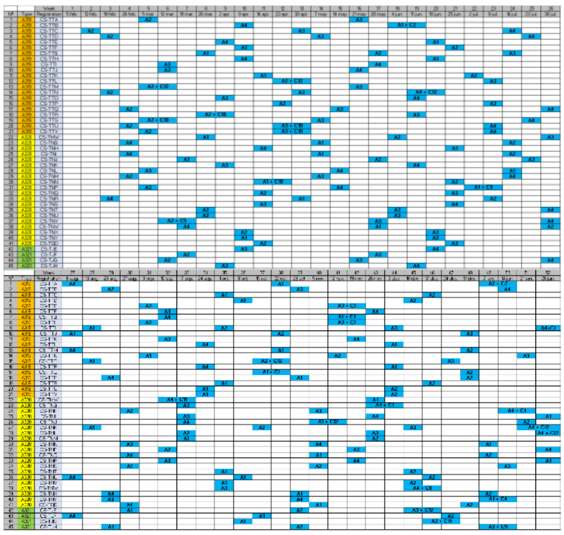


Figure 4 – Total solving time for each aircraft for the heuristic approach

The results are verified to check for any inaccuracies that could make the solution unfeasible. Firstly, the decision variables $x_{p,c,k,t}$ and $y_{p,t}$, which refer to when a maintenance activity needs to be performed and the aircraft stays at the hangar, respectively, are analysed and it is confirmed that whenever a maintenance check occurs, the aircraft goes to the hangar to perform the activity. It is also confirmed that for the maintenance C-type, the aircraft stays at the hangar two weeks in a row and that the model also utilizes the unavailability of the aircrafts to also perform an A-type maintenance check at the same time as a C-type. Moreover, to ensure that the model is feasible, for each of the forty-five aircrafts in the case study, none exceeds the threshold values of flight hours, flight cycles or time between two sequential same type checks, at any given time throughout the planning horizon. Once this is confirmed, the model can be considered verified, which results in the maintenance operations schedule for all the 45 aircrafts fleet, throughout the planning horizon of 2-years, presented in Figure 5.



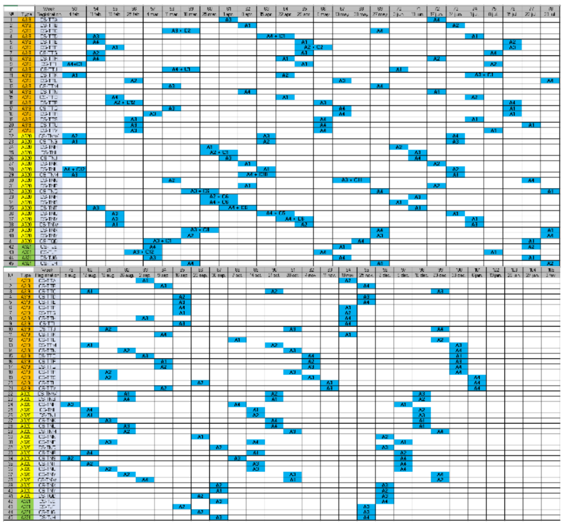


Figure 5 - Maintenance schedule solution of the heuristic approach.

For all the times an aircraft is unavailable due to C-type maintenance checks (summing a total of 94 times), only 10 out of the 94 times (which is the sum of $y_{p,t} = 1$, when a C-type maintenance occurs, throughout the planning horizon), are done in weeks of the High Season period. This means that approximately 89.36% of C-type maintenance actions are scheduled out of the High Season, which is aligned with the availability strategy to avoid heavy maintenance checks during high demand peaks. During the planning horizon of 2 years, the total number of times the aircrafts are unavailable is 510, the total number of A-type maintenance checks is 463, and the total number of C-type maintenance checks is 47.

5.3. Analysis and comparison between approaches

Since the exact method could not achieve any feasible solution for a long computational time, the comparison of both approaches will be based on smaller sized problems. Both approaches are compared for an increasing number of aircrafts. This will show the evolution of the computational time required to achieve a solution, but it will also allow to compare the solutions themselves from both approaches. Since the heuristic approach solves the problem approximately, the heuristic might not achieve the optimal solution, as the exact method approach can, as long as it runs for the computational time needed. Therefore, this comparison will consider both the achieved solutions and the computational time needed to compute them. Note that the solution value of the exact method, is the best solution reached. If the exact method does not reach an optimal solution, the MIP search is analysed, and the best solution considered will be the last solution before the model computation is stopped. A maximum computational time is set equal to 12 hours. In this case the optimality gap value is also provided for analysis. Moreover, the criteria for the order of the aircrafts in the heuristic approach is the same as in the case study.

Table 4 – Comparison between approaches

Number of aircrafts Np	Exact method approach				Heuristic approach		
	Best Solution Value	Optimality gap (%)	Solution cost (k€)	Elapsed Time (s)	Best Solution Value	Solution cost (k€)	Elapsed Time (s)
$Np = 5$	5,699.1	-	5,600	39,371	5,699.1	5,600	53
$Np = 10$	11,279.2	1.10	11,100	43,200	11,280.4	11,100	134
$Np = 15$	17,874.5	6.60	17,560	43,200	17,120.6	16,820	276
$Np = 20$	27,784.1	21.02	27,340	43,200	23,328.8	22,970	632
$Np = 25$	53,765.7	49.65	53,260	43,200	28,926.2	28,470	680
$Np = 30$	-	100	-	43,200	34,691.7	34,120	966

Table 4 shows that the heuristic approach achieves solutions approximately equal or lower than the exact method, with much less computational time needed. Therefore, the heuristic approach can be considered a reasonable method to solve the problem in practice. Again, note that the reduction in the total elapsed computational time is quite visible, which represents benefits in practice when comparing the heuristic approach with the exact method.

Some additional sensitivity analyses are conducted and are available in the dissertation document.

6. Conclusion and future research

In this final section, the main conclusions are emphasized, as well as limitations. Further research is also discussed.

The main objective of this research is to design an optimal aircraft maintenance schedule for the case study of TAP Air Portugal narrow-body fleet. Although a comprehensive real case study of maintenance scheduling could not be totally guaranteed for this work, which make the comparison between schedules not possible in a fair manner. Thus, a comparison between the exact approach using the branch-and-bound method and a heuristic approach developed during this work is studied and analysed. In fact, the main contribution of the present research is the application of a heuristic approach to solve the aircraft maintenance scheduling problem. The comparison shows that the heuristic approach can achieve the same or quite similar values as the exact method, while requiring a much lower computational time. The study also shows that with an increasing number of planes, the reduction in computational time also increases, in terms of percentage, which means that using the heuristic approach for larger sized problems becomes even more relevant. Furthermore, a mixed-integer linear programming model is developed, which considers several technical and business aspects for the aviation industry. Regarding the technical aspects, the model considers not only the A-type and C-type maintenance checks and their limits/thresholds of flight hours, flight cycles and weeks between each type of maintenance check, which are set from the aircraft manufacturer, but it also considers the availability of the hangar and its capacity, as defined by the maintenance company of TAP Air Portugal, TAP M&E. Regarding the business aspects, the model takes into account the unavailability cost (or downtime cost) of the aircraft during the time it is scheduled for maintenance, and it also considers the influence of seasons in the aviation industry. Therefore, the model contributes with an additional penalty cost given for C-type maintenance checks that occur during the considered high season for the aviation industry, which includes summertime, and Christmas and new years' time, and thus avoiding C-type maintenance checks to occur during this period. To sum up, the main contribution of this work is to provide an improved scalable decision framework for optimizing aircraft maintenance scheduling, by solving the entire problem with a competitive computational time, using a heuristic approach, while considering all the airline company requirements and constraints, such as flight estimations and hangar facilities availability.

One of the limitations is not considering the necessary skilled workforce to perform each maintenance check type, i.e., the model considers the hangar availability only by the available space, but not the different number of technicians needed to execute such tasks, which can influence the hangar slots s_t available for each week. Another limitation of the current model is the fact that in the first and last four weeks, not a single maintenance check is scheduled for the case study. The way the model is formulated assumes that if the aircrafts have to perform a maintenance check at week 106, which means it will try to optimize the available limit interval, and that will result in scheduling the last check as further from the last week as possible. The third term of the objective function tries to minimize this effect, and that is the reason the first aircrafts to be scheduled occur nearer the planning horizon end than the following aircrafts. Of course, when the slots available for these last weeks reach the maximum capacity, the model will schedule the last check nearer the end, but it still does not schedule it on the last four weeks. This limitation requires that the airline company should plan and run the model annually or each semester, in order to check for any changes for the maintenance schedule and adjust it accordingly. Other limitation is that this model requires exact input data from the real-world, in order to be feasible and reliable. One of the main problems and limitations is the uncertainty associated with the prediction of flight hours and flight cycles for every week during the planning horizon, due to unexpected events (e.g. cancelled flights).

Due to some limitations stated above, one aspect that can be improved is the integration of the scheduling of skilled workforce, in order to create a more realistic and reliable aircraft maintenance scheduling. As previously mentioned, this can give a more precise input of the maintenance hangar availability, while considering costs associated with these operations. This way, the operational costs of maintenance can be more realistic, as it includes a wider range of the costs supported by aircraft maintenance. Furthermore, a study on the routing problem should be considered, as it can support the airline companies to consider more hangar facilities and provide a higher cost reduction on maintenance operations. For this specific case study, taking into account the routing could take advantage of the two maintenance facilities in Brazil, run by TAP M&E Brazil. This means more hangar slots available, which can reduce the need of aircrafts performing maintenance checks early due to the lack of hangar availability. Lastly, an improvement that could be studied is the consideration of eventual discrepancies on the estimation of weekly flight hours or flight cycles, because of cancelled flights or any other events. Although this could prove to be a difficult task to implement, analysing previous data from each aircraft to assess an average value of divergence between estimations and what was observed, could be an option to take into account unexpected events throughout the planning horizon.

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