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An approach to operational aircraft maintenance planning

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A B S T R A C T

This paper describes a short-term planning methodology of the line maintenance activities of an airline operator, at the airports, during turn-around time (TAT). The proposed methodology supports decision making for deferring maintenance actions that affect the dispatching of the aircrafts, aiming at high fleet operability and low maintenance cost. Based on health assessment and additional information regarding operational and economical constraints at the operator's fleet level, a multi-criteria mechanism evaluates a set of generated maintenance plan alternatives. An alternative is defined as the possible allocation of all deferred maintenance tasks to a set of suitable airport resources. The selected decision making criteria are cost, remaining useful life (RUL), operational risk and flight delay. A series of experiments is conducted in order to validate and test the approach.

1. Introduction

Airline operators' scheduling logistics deal with the following four areas [24]: a) the schedule preparation, where airlines identify a list of flight legs along with departure and arrival times; b) the fleet assignment problem, whose objective is to identify the aircraft types that will be flying specific flight legs; c) the aircraft routing area, where aircrafts (tail numbers) are assigned to routes and d) the disruption recovery problem, whose objective is to react to all operational disruptions due to extreme weather conditions, breakdowns or equipment failures that may take place during the daily operation. Long-term maintenance plans are developed in the context of the first three areas. However, any unexpected events occurring daily upset these plans and lead to less effective maintenance policies. Taking into consideration the estimations reported by the industry of aeronautics, the maintenance activities range from 10% to 20% of an operator's direct operating costs depending on the fleet size, age and usage. According to the International Civil Aviation Organization [14], the average figure is 11% but this average includes individual figures as high as 25%. The contribution of the maintenance costs to the average direct operating costs has not been reduced significantly over the last two decades. Additionally, 80% of the inspection and access activities do not lead to a repair that would be increasing the overall cost.

Aircraft operability is considered a major requirement by each airline operator. The occurrence of unscheduled maintenance can introduce costly delays and cancellations if the problem cannot be rectified in a timely manner. Aircraft operability is the aircraft's ability to meet the operational requirements in terms of operational reliability (the percentage of scheduled flights, which depart and arrive without incurring a chargeable – technical – operational interruption), operational risk (the risk of causing additional costs by unscheduled maintenance events) and costs (maintenance and operational). The trade-off is very complex and priorities may vary a lot depending on the airline's policy.

1.1. Basic concepts

The process of line maintenance takes place within the turn-around time (TAT) between two flights with the aim to guarantee in time and reliable aircraft dispatch. The line maintenance process includes a routine check, post-flight inspection and malfunction rectification to be performed en-route and at base stations during transit, turn-around or night stop. Within TAT, a GO/NOGO decision is typically taken with respect to the aircraft's next flight. The current GO/NOGO decision making process is based on the assessment of the MMEL (Manufacturer Minimum Equipment List), namely the certification of the proper functionality of the aircraft's minimum number of critical components. If all MMEL relevant constraints could be satisfied, the aircraft status would become a GO and the aircraft would be able to perform the next flight turn. Today's decision support process is reactive and is based on unscheduled maintenance, during which, a troubleshooting process identifies the real root-cause, so that the necessary maintenance actions may then be carried out.

1.2. State of the art

A number of publications address airline planning problems (fleet assignment, aircraft routing, maintenance management, etc.) particularly,

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in the Operations Research literature. In [24], one of the relevant and most recent publications as to the work of this paper, an operational aircraft maintenance routing problem formulation is addressed with the use of a branch-and-price algorithm aiming at minimizing the number of the aircraft's unused legal flying hours. The problem formulation includes maintenance resource availability constraints, where a branch-and-price algorithm is used for exploring the efficiency of the maintenance routing solutions. In [25], overviews of the recent advances in models and approaches that have been developed for the fleet assignment problem (FAP) are presented, integrating maintenance activities as well. Similarly, in [8] and [9], an overview of the extensive use of operations research and management science methodologies, including fleet scheduling and maintenance routing, is given in all the areas of airline operations. Quana et al. [23] address a cost effective multi-objective preventive maintenance-scheduling problem at aircraft service centers using evolutionary algorithms. Dijkstra et al. [11] investigate a capacity planning problem of the aircraft maintenance personnel with the use of mathematical models and approximation techniques based on Lagrangian relaxation. In [12], a combination of a dynamic programming approach (to cope with the fleet assignment problem) together with a heuristic technique (to solve the embedded maintenance schedule problem) is presented. In [30], a mathematical programming model is described for optimizing maintenance person-power allocation in order for flight schedule punctuality to be ensured. In [26], the objective is to minimize the aircraft maintenance cost and all associated costs incurred, based on a mathematical formulation for modelling the maintenance-scheduling problem and for using a combination of “depth first search” and “random search” in order for a solution to be derived. Gopalan and Talluri [13] propose the use of Eulerian graphs, involving concepts, such as: fleet assignment, maintenance opportunities and flight numbering, which are taken into consideration when making a decision for a flight schedule. In [10] with a given set of flights and specified maintenance locations, durations, and needed frequency, Lagrangian relaxation and sub-gradient optimization are used in order for the aircraft rotation problem to be solved by maximizing the benefit derived from specific connections made.

Research in maintenance planning has often been associated with relevant maintenance procedures in nuclear plants. In [19], a genetic algorithm (GA) implementation is utilized for optimizing the components maintenance periods. In [17], a maintenance risk–cost model is established for maintenance optimization in a nuclear power plant using a GA. In [28], a maintenance-scheduling solution that optimizes both cost and reliability simultaneously by using an evolutionary algorithm has been described.

An increasingly competitive marketplace in aeronautics, where a number of applications are claimed to provide decision support for maintenance planning, has been developed over the last years. AIRBUS claims that with AIRMAN®, one of the most widely known commercially available Maintenance Information Systems, maintenance actions can be planned according to the fleet schedule [1]. Boeing claims that AHM can provide support to make fix-or-fly decisions and to avoid maintenance related schedule delays [2]. Mxi Technologies claims that Maintenix® [21] processes significant amounts of data, yielding numerous performance indicators including maintenance hours per flight hour, maintenance incurred flight delays, inventory efficiency as well as various reliability metrics such as the mean time between failures, removals, and unscheduled removals (MTBF, MTBR, and MTBUR, respectively). These market tools integrate information from various data sources and provide a well developed user interface environment for data retrieval and visualisation on assisting the planner to make a decision. Decision support systems addressing similar problems in other domains include the ones dealing with the dynamic vehicle refuelling problem, where the objective is to minimize the cost of buying fuel in a given route by selecting optimal truck stops and quantities [27], as well as agent-based systems for addressing the distributed constrained scheduling problem, for improving the supply chains' level of cooperation [18].

Although much progress has been accomplished over the last decade and more sophisticated Maintenance Information and Decision Support Systems have been implemented, most of these approaches have limitations. GO/NOGO decisions are not directly supported and the academic demonstrators so far supporting this kind of functionality have limited intelligence without concurrently taking into consideration parameters such as possible flight delay, cost consequences and actual remaining useful life of aircraft systems and components. Another aspect the paper addresses is the time and the effort required for the maintenance engineer, at line maintenance, to go through the information available and to make the best possible decision for a maintenance task allocation between two flights. These arguments are also supported by the fact that there is a lack for communication between operational planning and maintenance planning, resulting in high operational costs and low operational reliability despite the materialization of operational and maintenance planning approaches into software systems [29].

Despite the similarity of all these studies, none has addressed the problem as this paper has. Most of these studies focus on long-term planning problems rather than on short-term operational decisions. In the few studies that are relevant, the actual remaining useful life of the aircraft components, the maintenance cost, the risk for an unscheduled event and the resource constraints (i.e., flight delay or maintenance opportunity) at the maintenance stations have not been considered concurrently. In practice, most of the current approaches batch the multiple maintenance requirements, corresponding to the aircraft's components, into a package. The remaining flying hours of this package are defined as the minimum of the remaining flying hours of the components belonging to this package [24]. Furthermore, the time variable, including arrivals, TAT, departures and possible delays is not taken into account at full extent, considering the overnight stations only and therefore excluding possible maintenance actions that could take place during the TAT.

This paper discusses a maintenance decision support framework based on previous research carried out by Chryssolouris et al. [4–7], for addressing short-term operational maintenance decisions at line maintenance and for deferring maintenance actions that affect the aircrafts' dispatching. The major driver is the requirement for high fleet operability and the inevitable requirement for low maintenance costs. Based on health assessment information and additional information on operational and economical constraints at aircraft and fleet level, the short-term planning of the operational maintenance activities at line maintenance is modelled and executed. At the next level, the long-term scheduled maintenance planning could be controlled accordingly.

The software development of the maintenance planning framework described in the context of this paper fits well in the Decision Support layer of the Open System Architecture — Condition Based Maintenance (OSA-CBM) specifications promoted by the MIMOSA organization. The OSA-CBM specification is a standard architecture for moving information into a condition-based maintenance system. The reasons that this architecture has been selected are that as concluded from [15], [16] and [22], future developments on maintenance head towards the diagnostics, prognostication and Condition Based Maintenance (CBM) technology and systems.

1.3. Description of the problem and the proposed approach

Scheduling the maintenance activities at Line Maintenance combines the information from health assessment procedures with the data available related to the flight operations, the maintenance costs, the maintenance resources availability and the overall maintenance programme in order for the most efficient maintenance schedule, according to the operator's maintenance policy, to be generated.

The proposed approach takes advantage of concepts and techniques originating from the multi-criteria decision making models as well as from simulation, in order for different maintenance plans to be produced and evaluated.

Based on the approach introduced by Chryssolouris et al. [3,6] for addressing decision making problems in manufacturing, the steps followed at each decision point, where a decision should be made for the aircraft's maintenance tasks, are:

- identify required maintenance tasks;
- determine decision criteria and weights for evaluating alternatives (maintenance plans);
- form alternatives (maintenance plans); and
- determine the consequences of the different alternatives and their utility.

When the aircraft arrives at the airport, the line maintenance process is initiated, including maintenance data acquisition, aircraft status assessment as well as maintenance decision tasks to be executed. If all MMEL relevant constraints could be fulfilled, the aircraft status would become a GO and the aircraft would be able to perform the next flight turn. The proposed approach supports the decisions that should be made for the aircraft's pending maintenance tasks (that can be deferred): the decision may refer either to the tasks that are to be released and executed at the current airport or to be executed at the successive airports.

According to the proposed approach, at any point of time and location that a maintenance decision should be made concerning the maintenance tasks that can be deferred by the Line Maintenance engineer, a set of feasible alternatives is produced constituting a decision matrix [6]. An alternative is the possible allocation of pending maintenance tasks to suitable resources either at the current or at successive airports, desirably, within the timeframe of the respective component's remaining useful life (RUL) prediction. A suitable resource is an airport station capable of dispatching a specific maintenance task. A maintenance task may represent a standalone activity or a group of activities together (e.g., disassembly, inspection and/or replacement) for a particular aircraft component or subsystem. The availability of each station is expressed in terms of person-power per specific time period, taking into account the demand posed by other airline operators and aircrafts.

Each decision alternative constitutes of Y maintenance tasks assignments, denoted as $R_{i,j},T_y$. An assignment $R_{i,j},T_y$ is the assignment of task T_y on station i of airport j. The total number of *different* alternatives (*TNA*) that can be investigated is equal to:

$$TNA = \prod_{y=1}^{Y} r_y \tag{1}$$

where r_y is the total number of candidate airport stations that could be used for carrying out maintenance task T_y.

The proposed approach employs two search parameters [3,6]:

- the maximum number of alternatives *MNA* ($MNA \leq TNA$), which represents the upper limit of the alternatives generated and evaluated and
- the sampling rate (*SR*), which represents the number of times an alternative is simulated; since duration of flights, maintenance times and departure delays are considered being stochastic variables following a statistical distribution, an increased sampling rate would normally lead to more accurate estimates of the alternatives' performance.

Each time a decision point is reached, i.e. when an aircraft is brought to a landing and one or more components are considered for maintenance, *MNA* alternatives are randomly generated and each one of them is simulated *SR* times.

Fig. 1 depicts the short-term planning process for supporting decisions in order for the TAT maintenance actions to be executed. This process has been implemented in the form of a software system. Based on the list of tasks for which a decision should be made, a set of feasible alternatives is identified. The alternatives are simulated *SR* times and their average performance against each criterion is estimated in the form of a decision matrix (Table 1). The alternative with the best utility is the one eventually proposed by the system.

The following indices and variables are used in the proposed approach:

x	the aircraft identity identifier
y	the running number of pending tasks for aircraft x
$R_{i,j}$	the resource i at the airport j
$RTS_{i,j,p}$	the start time of period p of the resource i at the airport j
$RTE_{i,j,p}$	the end time of period p of the resource i at the airport j
$RTP_{i,j,p}$	the person-power available during period p of the resource i at the airport j
i	the running number of resources at the j airport
j	the running number of airports
T_y	the maintenance task y
$t(T_y,R_{i,j})^{\text{start}}$, $t(T_y,R_{i,j})^{\text{comp}}$	start and completion time of the dispatch of maintenance task y in $R_{i,j}$
t_y^{dur}	the time required for the completion of the maintenance task y
t_y^{person}	the person-power required for the completion of the maintenance task y
t_y^{rul}	the due time of T_y according to the airline's policy
$t(T_y,R_{i,j})^{\text{rul}}$	the remaining useful life of the component corresponding to task T_y, which is allocated to the resource $R_{i,j}$
Al_k	the alternative k
k	the running alternative number
$Cost(Al_k)$	the overall performance value of alternative k against the cost criterion
$RUL(Al_k)$	the overall performance value of alternative k against the RUL criterion
$Risk(Al_k)$	the overall performance value of alternative k against the operational risk criterion
$fd(Al_k)$	the overall performance value of alternative k against the flight delay criterion
$Utility(Al_k)$	the overall performance value of alternative k against the four criteria used.

Summing up, at each decision point, i.e., when the aircraft is expected to land or during inspection, the mechanism can be activated for the deferred tasks, in order to be identified where each task is to be dispatched.

1.3.1. Alternatives and utility

The possible execution of each alternative results in different economical and operational risk consequences. As already mentioned, an alternative is defined as the possible allocation of pending maintenance tasks to suitable resources either at the current or at successive airports.

In calculating the performance of the alternatives (i.e., utility), let us assume the situation in which there are K decision alternatives denoted $Al_1, Al_2, \ldots, Al_k, \ldots, Al_K$. Four criteria have been identified as being suitable for the evaluation process of the alternatives: *cost*, *operational risk*, *flight delay* and *remaining useful life — RUL*. The objective of a maintenance engineer would be to minimize, if possible, all four criteria. The consequences of the assignments can be measured taking into consideration the average values of the *SR* samples of each alternative for the selected *C* criteria.

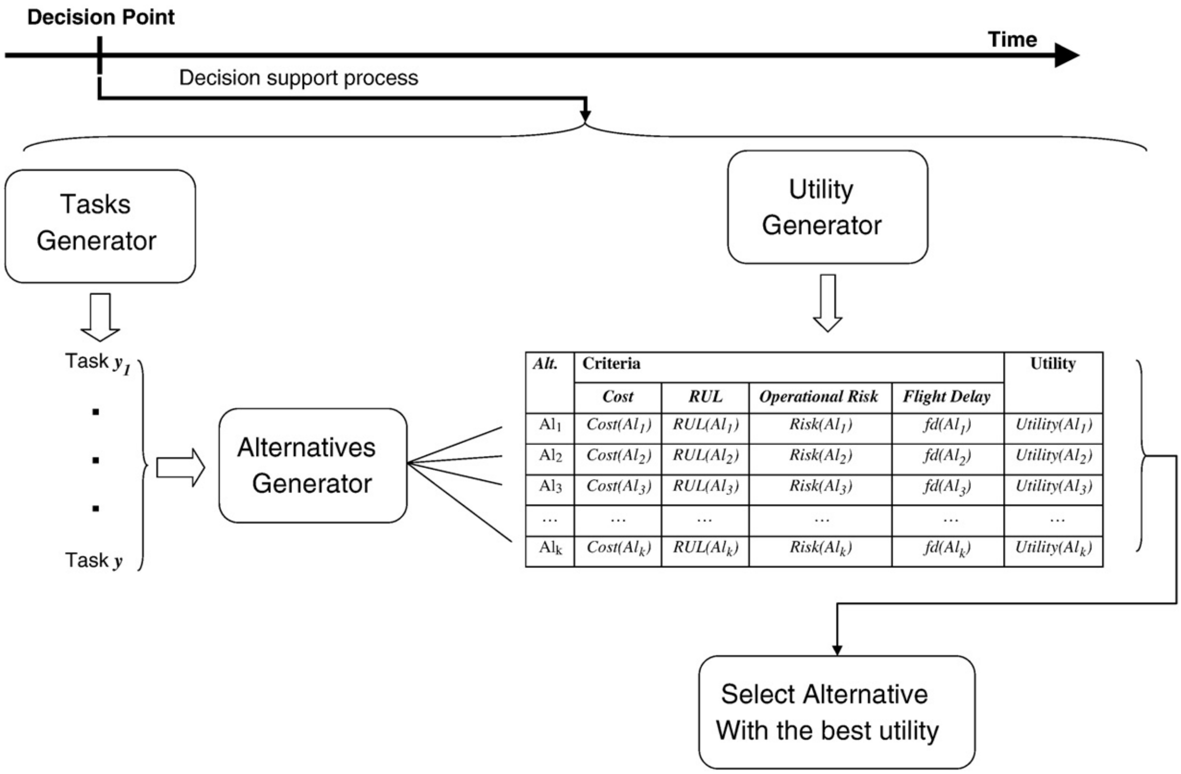

Fig. 1. Maintenance alternatives generation and evaluation at a decision point.

These values are then normalised according to Eq. (2).

$$\overline{c_{c,k}} = \frac{c_c^{\max} - c_{c,k}}{c_c^{\max} - c_c^{\min}} \tag{2}$$

where, $c_c^{\max}$, $c_c^{\min}$ are the maximum and minimum values observed for criterion c for all K alternatives. Consequently, the utility of each alternative can be calculated according to Eq. (3), having combined the consequences of all criteria with weights w_c.

$$u_k = \sum_{c=1}^{C} w_c \cdot \overline{c_{c,k}}. \tag{3}$$

In case that the alternative with the best utility allocates tasks at the current airport stations, then the respective tasks could be selected by the maintenance engineer for execution in the current airport at the current decision point. If the alternative with the best utility does not include assignments for the current airport, then the tasks may not be executed at the current airport and the decision for their allocation could be transferred to the next decision point (one of the next bases).

1.3.2. Constraints

In this paper, we adapt and extend the constraints model introduced by Sarac et al. [24] to account for the different components' maintenance requirements as well as for the time aspects, including the exact arrival, departure and maintenance times in addition to possible flight delays. The number of suitable airports' maintenance stations is finite, while their available person-power is limited and provided to other airline operators and aircrafts as well.

An example of an airport's resource of person-power availability is depicted in Fig. 2. The maintenance engineer is aware of this information and constitutes input to the proposed system.

If $Q_{i,j,y}$ is equal to 1 when the task y is dispatched to airport j and resource i and 0 otherwise, then for each alternative Al_k:

$$RTP_{i,j,p} \geq \sum_{y=1}^{Y} \left(t_y^{\text{person}} \cdot Q_{i,j,y}\right), \forall p : RTS_{i,j,p} \leq t(T_y, R_{i,j})^{\text{start}} \wedge RTE_{i,j,p} \geq t(T_y, R_{i,j})^{\text{comp}}. \tag{4}$$

Eq. (4) implies that the total amount of the person-power required for dispatching the tasks of the alternative Al_k should not exceed the available person-power in the existing resources per period coinciding with the start and the end of each task T_y. The start time of each maintenance task T_y is therefore the closest time to an aircraft's arrival at the airport j, satisfying the person-power availability of resource i, while:

$$t(T_y, R_{i,j})^{\text{comp}} = t(T_y, R_{i,j})^{\text{start}} + t_y^{\text{dur}}. \tag{5}$$

1.3.3. Cost criterion

The costs related to aircraft maintenance encompass a number of different factors, which can be classified into the following categories:

Table 1
Decision matrix.

Alt	Cost	RUL	Operational risk	Flight delay	Utility
Al_1	$Cost(Al_1)$	$RUL(Al_1)$	$Risk(Al_1)$	$fd(Al_1)$	$Utility(Al_1)$
Al_2	$Cost(Al_2)$	$RUL(Al_2)$	$Risk(Al_2)$	$fd(Al_2)$	$Utility(Al_2)$
Al_3	$Cost(Al_3)$	$RUL(Al_3)$	$Risk(Al_3)$	$fd(Al_3)$	$Utility(Al_3)$
…	…	…	…	…	…
Al_k	$Cost(Al_k)$	$RUL(Al_k)$	$Risk(Al_k)$	$fd(Al_k)$	$Utility(Al_k)$

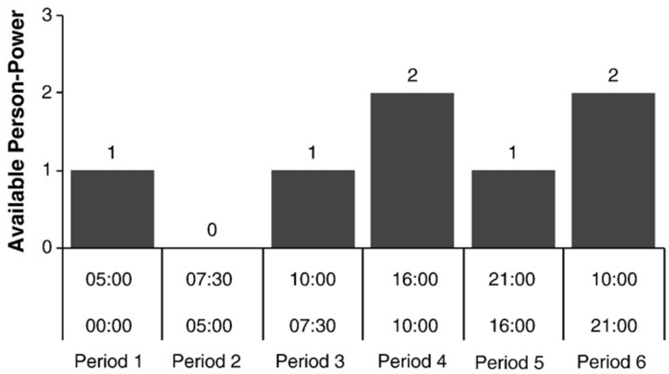

Fig. 2. Available person-power per period for an airport resource (station).

- *Equipment and facility costs*. These include the costs of equipment necessary for the maintenance processes, the facilities used for hosting the equipment, for maintaining the infrastructure, for hiring equipment, etc.
- *Supplies and logistics costs*. Costs of components, logistics and transportation including excess inventory and backlog.
- *Personnel costs*. The labour cost required for the execution of the maintenance tasks, including costs of overtime, extra shifts, subcontracting, hiring maintenance engineers and technicians.
- *Overhead*. This is a part of the cost that is not directly attributable to the maintenance operations, nonetheless, it is required.

A "techno-economical" model [3] is used in Eq. (6) for modelling the impact of the maintenance attributes on the cost of aircraft maintenance. The overall contribution of these attributes is proportional to the operating time.

$$\begin{array}{l}\textit{Maintenance}\\ \textit{cost per task}\\ \textit{per component}\end{array} = \left(\left(\textit{Equipment rate} + \textit{Labour rate} + \textit{Overhead rate}\right) \times \textit{Operating time per component}\right) + \textit{Component procurement costs} \quad (6)$$

where:

Maintenance cost per task per component the cost of completing a maintenance activity for a component on a specific resource.
Equipment rate the rate related to ground equipment and to the costs of facilities.
Labour rate the labour rate at the airport where the task can be executed.
Overhead rate the rate of the overheads including Maintenance Management costs.
Operating time per component (t_y^{dur}) the duration in minutes, required for the related maintenance task to be executed at the respective airport.
Component procurement costs the cost related to the respective component's procurement and transportation costs.

$$Cost(Al_k) = \frac{\sum_{s=1}^{SR}\sum_{y=1}^{Y} Cost(T_y, R_{i,j})_s}{SR} \quad (7)$$

where $Cost(T_y,R_{i,j})_s$ is the consequence cost value of the $T_y,R_{i,j}$ assignment with respect to the cost criterion for the s^{th} sample of alternative Al_k.

1.3.4. RUL criterion

The RUL criterion takes into consideration the time during which the respective maintenance task is completed against the operator's due date policy for maintenance or replacement. The definition of the due date is based on the respective components' probability of failure and on the operator's policy, e.g., for components with soft degradation curve, a loose due date policy may be applied, while components that degrade fast may follow a more conservative due date policy. This criterion is used in order for the RUL to be considered during the alternatives' assessment, aiming at minimizing the remaining useful life or the degree of exceeding the due time of the components.

$$RUL(T_y, R_{i,j}) = t(T_y, R_{i,j})^{\text{rul}}. \quad (8)$$

The variable $t(T_y,R_{i,j})^{\text{rul}}$ represents the remaining useful life of task T_y when it is allocated to the resource $R_{i,j}$.

The RUL criterion value of an alternative k, $RUL(Al_k)$, is calculated by the following equation:

$$RUL(Al_k) = \frac{\sum_{s=1}^{SR}\sum_{y=1}^{Y} \{wr_y \cdot |RUL(T_y, R_{i,j})_s|\}}{SR} \quad (9)$$

where wr_y is the weight per task, reflecting the relative importance, in terms of RUL, of different components.

1.3.5. Operational risk criterion

The operational risk (OR) stands for the risk of disrupting the fleet operational plan and causing additional costs due to unscheduled maintenance events. The operational risk assessment is the estimation of both cost and probability of unscheduled maintenance events that interrupt the fleet operational plan. The *expected values* as defined in the probability theory are used for modelling the operational risk function. Particularly, the expected value of a random variable is the sum of the probability of each experiment's possible outcome, multiplied by the outcome value (or payoff). Comparatively, the expected gain of a maintenance task allocation regarding the operational risk could be a measure of the cost of scheduled and unscheduled events of the respective allocation, weighted by the probability of failure. The symbolic expression of this concept is simple:

$$Risk(T_y, R_{i,j}) = [DV(T_y, R_{i,j}) \cdot DP(T_y, R_{i,j})] + [UnDV(T_y, R_{i,j}) \cdot UnDP(T_y, R_{i,j})] \quad (10)$$

where,

$Risk(T_y,R_{i,j})$ expected OR value for a $(T_y,R_{i,j})$ allocation
$DV(T_y,R_{i,j})$ desirable value, i.e., cost of scheduled events
$DP(T_y,R_{i,j})$ probability of a desirable value
$UnDV(T_y,R_{i,j})$ undesirable value, i.e., cost of unscheduled events
$UnDP(T_y,R_{i,j})$ probability of an undesirable value

The OR utility value of an alternative k, $Risk(Al_k)$, is calculated by the following equation:

$$Risk(Al_k) = \frac{\sum_{s=1}^{SR}\sum_{y=1}^{Y} Risk(T_y, R_{i,j})_s}{SR}. \quad (11)$$

1.3.6. Flight delay criterion

An important criterion during the decision making process is the one related to the flight delay. It is important that the aircraft leave on time, or in case there is a delay, to be the least possible.

A *delay* measure is used for assessing the alternatives' performance in terms of the aircraft delay due to a maintenance action. The flight duration, the maintenance task duration and the departure delay are modelled as stochastic variables following a normal distribution [20], according to the data available for each specific leg of a route. The flight delay value of an alternative k, $fd(Al_k)$, is calculated by the following equation:

$$fd(Al_k) = \frac{\sum_{s=1}^{SR}\sum_{l=1}^{L}\{\max[(AT_{l,s}-AT_l^{\text{due}}),0] + \max[(DT_{l,s}-DT_l^{\text{due}}),0]\}}{SR} \tag{12}$$

where AT_l^{due}, DT_l^{due} the planned arrival and departure times per leg l of the route, and $AT_{l,s}$, $DT_{l,s}$ the actual arrival and departure times observed in the sample s of the alternative Al_k.

2. Pilot case

The proposed decision support approach has been materialized in a prototype software framework. This software prototype consists of a java library (jar), utilizing XML files for handling the input and output data. A scenario follows that demonstrates the framework's capabilities.

2.1. Scenario

An aircraft has to perform a route consisting of a set of flights connecting 4 airports. One of them is the base airport. So it may have access to four (4) line maintenance facilities, and one (1) hangar facility at its own main base. The route concerns one day flights: FRA>>CDG>>MUC>>MAD>>FRA. Two (2) deferred tasks corresponding to two parts are considered with different degradation curves and a due date policy for inspection and maintenance. All the airports are capable of undertaking both maintenance tasks, having at least one suitable resource (station) for each task. The availability of each station is different and is expressed in terms of person-power available per specific time period. The base airport (FRA) has two facilities. The maintenance tasks include inspection and the parts' maintenance. Both component parts are available at the base airport as well as at the other airports, but at a higher cost, in case they need to be replaced. It is assumed that when the aircraft is grounded, there is no degradation. We assume it is now 04:00 in the morning, the aircraft is located in the base airport (FRA) and the maintenance engineer has to decide in which airport station the two maintenance tasks will be carried out.

2.2. Maintenance tasks description

The types of activities addressed in today's TAT are GO or NOGO decision for the aircraft's next flight, based on the assessment of the MMEL (Manufacturer Minimum Equipment List). A major difficulty in proactively planning the Line Maintenance operations is to react shortly and decide, taking into consideration information related to the health assessment of the components, the availability of resources and alternative maintenance opportunities. Therefore, a major issue for the planning of the short-term maintenance activities is the ability to assess maintenance alternatives in the form of deferring tasks, in the main base or in the outer base, while being flexible and adaptive to operational and economical constraints.

According to an assumed probability of failure, which leads to a due date, the two parts of the pilot case should be inspected and maintained within the next 10 flight hours (FH). The model assumes that both tasks, T1 and T2, are mutually independent (there are no pre-condition relations to force other sequences of maintenance events). Table 2 depicts the time requirements corresponding to every airport's suitable maintenance resource.

The flight plan to be considered in calculations along with the characteristics of the normal distributions representing the flight duration and the departure delay is depicted in Table 3.

Table 2
Task duration per airport facility.

Airport	Resource ID	Task	Operation time mean, deviation (min)	Person-power required
FRA	R_{FRA_1}	T_1	60,10	1.0
FRA	R_{FRA_1}	T_2	40,5	1.0
FRA	R_{FRA_2}	T_1	70,10	1.0
FRA	R_{FRA_2}	T_2	60,20	1.0
CDG	R_{CDG_1}	T_1	80,20	1.0
CDG	R_{CDG_1}	T_2	70,10	1.0
MUC	R_{MUC_1}	T_1	80,20	1.0
MUC	R_{MUC_1}	T_2	60,10	1.0
MAD	R_{MAD_1}	T_1	80,15	1.0
MAD	R_{MAD_1}	T_2	80,15	1.0
FRA	R_{FRA_1}	T_1	60,10	1.0
FRA	R_{FRA_1}	T_2	40,5	1.0
FRA	R_{FRA_2}	T_1	70,10	1.0
FRA	R_{FRA_2}	T_2	60,10	1.0

Table 4 shows the availability of the airports' maintenance stations in terms of person-power. For instance, the station R_{FRA_1} appears to be having 2 technicians available from 10:00 to 16:00 and from 21:00 to 10:00 next day.

2.3. Alternatives generation

In the case that the number of alternatives is large, and an exhaustive search may not be performed, the alternatives' generation mechanism takes advantage of the approach proposed in [4] and [5]. Two adjustable parameters, namely the maximum number of alternatives (*MNA*) and the sampling rate (*SR*) are used by the alternatives' generation mechanism for guiding the search through the solution space. *MNA* controls the number of alternatives formed and thus, the breadth of the search. The *SR* determines the accuracy of the consequences estimation procedure. These parameters allow the search to be tuned to the requirements of the problem and they may

Table 3
Flight plan.

Date	GMT/flight	From–to	Duration (min) mean, deviation	Departure delay (min) mean, deviation
1/11/09	0600–0645/FL100	FRA–CDG	45,5	10,3
1/11/09	0830–0950/FL101	CDG–MUC	80,10	20,5
1/11/09	1200–1400/FL102	MUC–MAD	120,10	30,10
1/11/09	1600–1800/FL103	MAD–FRA	120,10	20,5

Table 4
Available person-power per airport station and period.

Airport	Resource ID	P1	P2	P3	P4	P5	P6
FRA	R_{FRA_1}	00:00–05:00	–07:30	–10:00	–16:00	–21:00	–10:00n
		1.0	0.0	1.0	2.0	1.0	2.0
FRA	R_{FRA_2}	00:00–06:00	–10:00	–16:00	–22:00	–10:00n	
		1.0	2.0	1.0	0.0	1.0	
CDG	R_{CDG_1}	00:00–06:00	–11:00	–14:00	–22:00	–10:00n	
		0.0	1.0	0.0	1.0	0.0	
MUC	R_{MUC_1}	00:00–06:00	–11:00	–15:00	–22:00	–10:00n	
		0.0	2.0	1.0	1.0	0.0	
MAD	R_{MAD_1}	00:00–06:00	–15:00	–18:00	–21:00	–10:00n	
		1.0	2.0	1.0	2.0	0.0	

Table 5
Cost criterion data.

Airport	Resource ID	Task	Cost rates (€/min)			Parts cost of T1 (€)	Parts cost of T2 (€)
			Equipment rate	Labour rate	Overhead rate		
FRA	R_{FRA_1}	T_1	5	5	5	200	200
FRA	R_{FRA_1}	T_2	5	5	5	200	200
FRA	R_{FRA_2}	T_1	5	5	5	200	200
FRA	R_{FRA_2}	T_2	5	5	5	200	200
CDG	R_{CDG_1}	T_1	10	10	5	300	200
CDG	R_{CDG_1}	T_2	10	10	5	300	200
MUC	R_{MUC_1}	T_1	5	5	5	300	200
MUC	R_{MUC_1}	T_2	5	5	5	300	200
MAD	R_{MAD_1}	T_1	10	10	5	300	200
MAD	R_{MAD_1}	T_2	10	10	5	300	200
FRA	R_{FRA_1}	T_1	5	5	5	200	200
FRA	R_{FRA_1}	T_2	5	5	5	200	200
FRA	R_{FRA_2}	T_1	5	5	5	200	200
FRA	R_{FRA_2}	T_2	5	5	5	200	200

influence the quality of the solution as well as the computational effort for making a decision.

The total number of alternatives for the example is given by Eq. (1) and is equal to 49.

2.3.1. Cost criterion

In Table 5, the cost data are provided for the calculation of the cost of each alternative, using Eq. (6). Indicative cost rates are considered.

2.3.2. RUL criterion

Fig. 3 depicts the RUL for the 7 alternatives out of a total 49, where both tasks are dispatched in the same airport station.

The present case examines a loose due date policy at 75% of the probability of failure regarding the remaining useful life of the parts. Table 6 shows the nominal RUL values, based on the respective due date policy, while Table 7 shows the weight factor per task: the component of T1 is more important, in terms of RUL, than the respective component of T2.

Table 6
RUL criterion nominal values calculation.

Airport	Due date of part of T1 (75%)	RUL (min)	Due date of part of T2 (75%)	RUL (min)
FRA	13:00	185	09:00	75
CDG	13:00	140	09:00	30
MUC	13:00	60	09:00	−50
MAD	13:00	−60	09:00	−170
FRA	13:00	−180	09:00	−290

Table 7
Criteria weights.

Cost	RUL	Operational risk	Flight delay
30%	40% $wr_1 = 70\%$ $wr_2 = 30\%$	20%	10%

2.3.3. Operational risk criterion

The values of the operational risk criterion, calculated using Eqs. (10) and (11), are considered as follows:

- $DV(T_y,R_{ij})$ is assumed to be the cost of the respective scheduled event as calculated for the cost criterion
- $DP(T_y,R_{ij})$ is assumed to be equal to $100\% - UnDP(T_y,R_{ij})$
- $UnDV(T_y,R_{ij})$ is the cost related to an unscheduled event (hire last moment personnel, any extra costs, etc.) and is assumed in this case that it is in principle twice as much as the respective scheduled event cost
- $UnDP(T_y,R_{ij})$ is the probability of failure during arrival time (Fig. 3).

2.3.4. Flight delay criterion

Flight delays may be caused when the maintenance tasks are carried out in stations whose availability is low. Delays taking place in one leg of the route may be propagated to the next legs of the route as well, leading to large – overall – departure and arrival delays.

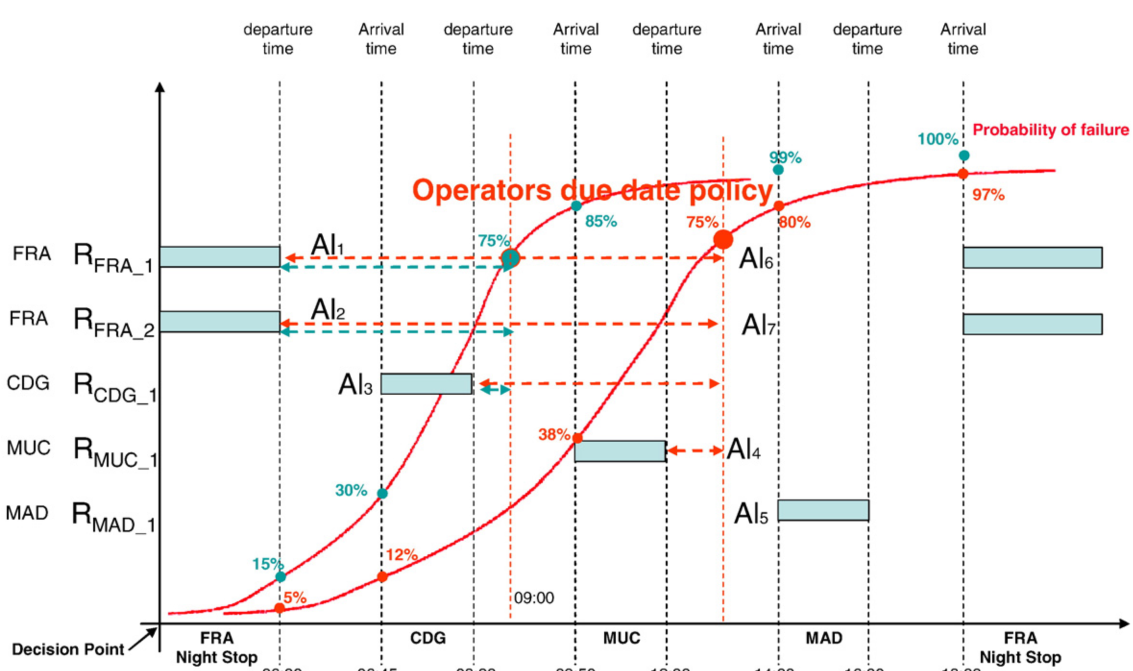

Fig. 3. Operator's due date policy for a maintenance action.

Table 8
Best alternatives.

Alternative rank	Assignment, leg	Maintenance task	Resource/airport	Utility (%)
1	$T_1R_{MUC\_1}$, 3	T1	Base/MUC	89.26
	$T_2R_{FRA\_1}$, 1	T2	Hangar/FRA	
2	$T_1R_{MUC\_1}$, 3	T1	Base/MUC	83.50
	$T_2R_{FRA\_2}$, 1	T2	Base/FRA	
3	$T_1R_{MUC\_1}$, 3	T1	Base/MUC	82.81
	$T_1R_{MUC\_1}$, 3	T2	Base/MUC	

2.3.5. Criteria weights

The criteria weights are shown in Table 7. Different sets of criteria weights could reflect the different operator's maintenance policies.

2.4. Results

An experiment is conducted in order to test and validate the approach. In the specific example presented in this paper, the solution space is exhaustively searched, since the overall number of possible alternatives is rather low. A sampling rate (*SR*) equal to 10 was used, meaning that every alternative has been simulated 10 times, using different values for the flight duration, maintenance duration and departure delay, following the characteristics of the statistical distribution representing these variables (Tables 2 and 3). The best three alternatives yielding the highest utility are presented in Tables 8 and 9.

All three alternatives make sense. For the best ranked alternative, in particular, it should be noted that although R_{FRA_1} and R_{FRA_2} seem to be the less expensive options for both tasks, the availability of R_{FRA_1} at the beginning of the route is limited and in case it was selected for carrying out T1, the remaining useful life would still be high. R_{MUC_1} seems to be a good alternative for T1, since the RUL obtained is just above its due time, while the operational risk is still low, compared to what it would be if R_{FRA_1} was selected in the last leg of the route.

3. Discussion

Examining the different criteria used, the *cost* criterion is related to the operator's costs and is used for representing the scheduled event costs. The *operational risk* criterion is used for modelling the unscheduled event consequences. As a component approaches the end of its life during a maintenance alternative, the utility of the alternative, due to the operational risk criterion, decreases in principle, since the possibility to have an unscheduled event is high. The *flight delay* depends strongly on the availability of the resources at each airport. The *RUL* criterion introduces the use of the component's useful life that helps the operator determine the components' due date policies. The weight factors per task employed may be used for reflecting the relative importance of different components in terms of RUL.

Today's decision support process is reactive in principle and mostly focuses on resolving unscheduled maintenance activities (troubleshooting). This research work aims at reducing unscheduled maintenance events and probably any inevitable consequences (e.g., flight delay and high maintenance cost) by providing an operational maintenance planning decision making framework, where short-term maintenance decisions are analyzed in terms of the selected criteria. The framework is highly beneficial for components whose condition is continuously monitored. In order to accommodate the different policies followed by operators and maintenance engineers, an innovative aspect introduced by the proposed research is the development of a framework that introduces criteria weights, thus allowing for the modelling of the specific operator's maintenance policy. The decision matrix facilitates the overall process of evaluating maintenance alternatives, leading to the selection of the best alternative (the one with the best utility). The deployment of the proposed framework requires an installation phase, during which different scenarios and flight plans have to be executed in order for the criteria weights per component to be analyzed and fine-tuned. The resource availability at the airports' stations as well as the time aspects are all introduced in detail. The sampling mechanism employed is of high importance, since it can detect how uncertainty and delays may propagate to the remaining legs of an aircraft's route.

The major point of the approach proposed is that based on the health assessment information (RUL) and on additional information related to operational (flight delay) and economical variables (cost, operational risk) at the operator's level, the performance of the maintenance planning activities at Line Maintenance can be improved. The proposed approach has been evaluated in the context of the Research Project TATEM [29], where the proposed planning framework has been tested against a number of use cases for different aircraft health monitored components and operational scenarios.

Table 9
Best alternatives criteria performance.

Alternative rank	Cost [€]	RUL [min]	OR [€]	Flight delay [min]
1	2260.0	62.6	2968.2	150.3
2	2589.0	65.8	3322.2	160.8
3	2639.1	57.2	4110.0	151.2

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