CONDITION BASED OPERATIONAL RISK ASSESSMENT AN INNOVATIVE APPROACH TO IMPROVE FLEET AND AIRCRAFT OPERABILITY: MAINTENANCE PLANNING

P. Papachatzakis, N. Papakostas, G. Chryssolouris[1]
Laboratory for Manufacturing Systems and Automation,
Department of Mechanical Engineering and Aeronautics,
University of Patras, Patras 265 00, Greece

OVERVIEW

This paper describes a short term planning methodology of line maintenance activities, in the airports, during Turn Around Time (TAT). The proposed methodology supports decision making for deferring a maintenance action that affects the dispatch of the aircraft, aiming at high fleet operability and low maintenance cost. Based on health assessment information as well as on any additional information on operational and economical constraints, at the operators' fleet level, a multi criteria mechanism evaluates whether a maintenance action should be executed in the current airport or in a successive one. The selected decision making criteria are Cost, Remaining Useful Life (RUL), Operational Risk (OR) and Flight Delay.

1. INTRODUCTION

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 occurrence of unscheduled maintenance can introduce costly delays and cancellations if the problem cannot be rectified in a timely manner. The trade-off is very complex and priorities may vary significantly depending on the airline's policy.

The work presented in this paper is part of an integrated operational risk assessment framework, partially developed and demonstrated in the Integrated Project "Technologies and techniques for new maintenance concepts – TATEM"[13]. In this framework, maintenance planning is performed, based on generated reliable condition views and on operational risk assessment. The paper discusses the maintenance planning module of this integrated operational risk assessment framework.

1.1. Problem description

The process of line maintenance takes place within the TAT, between two flights, with the aim to guarantee both in time and reliably the aircraft's dispatch. Within TAT, a GO/NOGO decision is typically taken with respect to the aircraft's next flight. The decision support is currently based on the assessment of the MMEL (Manufacturer Minimum Equipment List), namely the assessment of the good functionality of the minimum number of aircraft critical components. If all MMEL relevant constraints could be satisfied, the aircraft status would become a GO and the aircraft could perform the next flight turn.

1.2. State of the Art

A number of approaches have been reported addressing the problem of the maintenance task allocation, between the arrival and the consecutive departures of the aircrafts. Saraca *et al.*[10] address an operational aircraft maintenance routing problem formulation having used a branch-and-price algorithm. Sherali *et al.*[11] present an overview of the models and approaches that have been developed for the Fleet Assignment Problem (FAP) having also considered maintenance activities. Quana *et al.*[9] address a cost effective multi-objective preventive maintenance scheduling problem, at the aircraft service centers, using evolutionary algorithms. Moudani and Mora-Camino[8] present a mix of the Dynamic Programming approach (to cope with the fleet assignment problem) and a heuristic technique to solve the embedded maintenance schedule problem. The objective of Sriram and Haghani[12] was to minimize the aircraft maintenance cost and all the associated costs incurred, based on a mathematical formulation for modelling the maintenance-scheduling problem and using a combination of depth first search and random search to arrive at a solution. Clarke and Ryan[7] provide an overview of the extensive use of operations research and management science methodologies, in all areas of the airline operations, including fleet scheduling and maintenance routing.

These approaches have some significant limitations though, since they typically require a series of restrictive assumptions for the problem to be formulated. Thus current aircraft maintenance management, planning and execution costs remain unacceptably high.

This paper discusses a maintenance decision framework[2],[3],[4],[5] in order to support decisions for deferring any maintenance actions that may affect the dispatch of aircrafts. The major requirements, in the allocation of maintenance actions, are high fleet operability and low maintenance costs. Based on health assessment information and additional information of operational and economical constraints at aircraft and fleet level, the short term planning of the maintenance activities, in Line Maintenance, should be optimised, executed and

[1] Corresponding author: Email: xrisol@lms.mech.upatras.gr

accordingly be adjusted to the long term scheduled maintenance planning.

2. METHOD DESCRIPTION, MODELLING, FRAMEWORK IMPLEMENTATION

2.1. Method Description

The proposed approach includes the use of an Artificial Intelligence framework, taking advantage of concepts and techniques originating from the multi-criteria decision making, utility theory and simulation, in order to produce and assess different maintenance plans[1], [2], [3].

The approach is based on the fact that within the TAT (between two flights), a decision should be made for each of the pending aircraft's maintenance tasks that can be deferred: the decision may either be for this task to be released and executed at the current airport or to be executed at one of the successive airports. The following steps are followed at each decision point, when an allocation decision should be made for each aircraft's maintenance task[1], [4], [5]:

- Identify required maintenance task
- Determine decision criteria and weights for evaluating alternatives
- Form alternatives
- Determine the consequences of the different alternatives and their utility

According to the proposed approach, a set of feasible alternatives is produced per task constituting a decision matrix. The possible allocation of a pending maintenance task is an alternative to a suitable resource, either at the current or at successive airports within the timeframe of the respective component's Remaining Useful Life (RUL) prediction. A task may represent a standalone activity or a group of activities together (e.g., disassembly, inspection and/or replacement).

Figure 1, depicts the short term planning process to support decisions for the execution of a maintenance task. 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 are identified for each task. The alternatives are simulated and their performance against each criterion is estimated in the form of a decision matrix (TAB 1). The alternative with the best utility is the one eventually proposed by the system[6].

For each deferred task T_y of each aircraft x, a decision matrix (TAB 1) is produced.

Alt.	**Criteria**				**Utility**
	Cost	***RUL***	***Operat. Risk***	***Flight Delay***	
Al_1	c_{ij}^1	rul_{ij}^1	r_{ij}^1	fd_{ij}^1	U_1
Al_2	c_{ij}^2	rul_{ij}^2	r_{ij}^2	fd_{ij}^2	U_2
Al_3	c_{ij}^3	rul_{ij}^3	r_{ij}^3	fd_{ij}^3	U_3
…	…	…	…	…	
Al_k	c_{ij}^k	rul_{ij}^k	r_{ij}^k	fd_{ij}^k	U_k

TAB 1. Decision Matrix

Where,

– ***x*** is aircraft identical identifier
– ***y*** the running number of pending tasks for aircraft ***x***
– ***i*** the running number of resources at the ***j*** airport
– ***j*** is the running number of airports
– T_y is a specific maintenance task ***y*** for the aircraft ***x***
– Al_k the alternative ***k***
– ***k*** is the running number of feasible alternatives
– c_{ij}^k is the performance value of ***k*** alternative against ***cost*** criterion
– rul_{ij}^k is the performance value of ***k*** alternative against ***RUL*** criterion
– r_{ij}^k is the performance value of ***k*** alternative against ***Operational risk*** criterion
– fd_{ij}^k is the performance value of ***k*** alternative against ***flight delay*** criterion

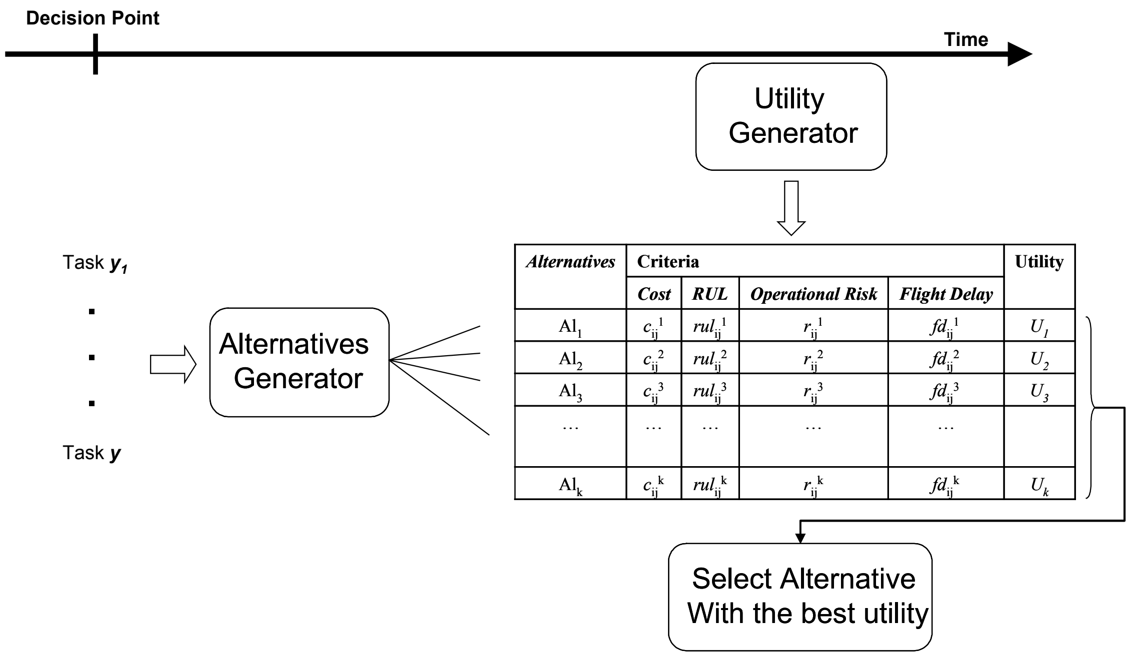

FIG 1. Maintenance alternatives generation and evaluation at a decision point

At each decision point, i.e., when the aircraft is expected for landing or during inspection, the mechanism can be activated.

2.1.1. Utility generator mechanism

In formulating the A/Cs maintenance strategy during TAT, trade-offs among cost, operational risk, flight delay and RUL must be considered[6] explicitly. The execution of each alternative may result in different economical and operational risk consequences. The different values of the economical and operational parameters, related to each alternative, alter their utility and can be measured, based on the selected criteria. The preference function *P* can be used for calculating the performance of each alternative[1], [3].

If the alternative with the best utility represents the allocation at the current airport, it will be the one to be selected. If the alternative with the best utility does not represent the allocation at the current airport, the task will not be executed there and the decision for the allocation of this task, will be taken at a next decision point.

Four criteria have been identified so far as being suitable for the evaluation process of the alternatives: *Cost*, *operational risk*, *flight delay* and *Remaining Useful Life - RUL*. For each criterion, a parameterised function is identified for calculating the performance.

2.1.2. Cost function

A "techno-economical" model, Equation (1)[1], could describe the relationships of the maintenance attributes, to the cost of the aircraft maintenance. This classification provides a general framework as to how cost issues can be addressed by establishing a systematic way of measuring the cost performance of the different solutions, projecting costs on the Operational rates at the maintenance tasks level. The contribution of these attributes is proportional to the operating time.

(1)
$$\text{Maintenance cost per task per component} = \left(\left(\text{Equipment rate} + \text{Labour rate} + \text{Overhead rate} \right) \times \text{Operating time per component} \right) + \text{Component procurement costs}$$

where:

– *Maintenance Cost per task per component*: The cost of completing a maintenance activity for a component
– *Equipment rate*: rate related to ground equipment and facilities' costs
– *Labour rate*: the labour rate at the respective airport, where the task can be executed
– *Overhead rate*: the rate of the overheads including Maintenance Management costs
– *Operating time per component*: Duration of the related task
– *Component procurement costs*: the cost related to the procurement of the respective components as well as the transportation costs

2.1.3. RUL function

RUL function calculates the time that the respective maintenance task is completed against the operator's due date policy for maintenance and replacement. The definition of the due date will be based on the respective component's probability of failure and on the operator's policy, e.g., for the components with soft degradation curve, a loose due date policy may apply, whilst the hard time components may follow a conservative due date policy. This criterion is used in order for the lost of RUL to be considered during the assessment of the alternatives.

$$(2) \quad Rul_{Al_k} = t^{comp}_{al_k} - t^{due}$$

The variable t^{comp} represents the completion time of task T_y and t^{due} is the due time of T_y. Rul_{Al_k} is the amount of RUL lost for the alternative *k.*

2.1.4. Operational risk function

Operational risk refers to the potential disruption of the fleet operational plan which may cause additional costs by unscheduled maintenance event. The Expected values have been used for modelling the operational risk function. The symbolic expression of this concept is:

$$(3) \quad r_{ij}^{k} = (DV_k \times DP_k) + (UnDV_k \times UnDP_k)$$

Where,

– r_{ij}^{k} = expected value for *k* alternative
– DV_k = desirable value, i.e., cost of scheduled events
– DP_k = probability of desirable value
– $UnDV_k$ = undesirable value, i.e., cost of unscheduled events
– $UnDP_k$ = probability of undesirable value

2.1.5. Flight delay function

An important criterion during the decision making process is the flight delay. A probability for a delay measure is used for assessing the performance of the alternatives in terms of A/C delay, due to maintenance action. A probability is provided based on statistical analysis of historical data to describe any possible flight delay per airport for the respective maintenance task execution. $\boldsymbol{fd_{ij}^{k}}$ is the identifier of the performance value of the flight delay criterion for the k alternative.

3. PILOT

The proposed decision support framework has been developed as a part of a software. There is a scenario following that demonstrates the capabilities of the framework.

3.1. Scenario

A scenario has been assumed that an airplane has to make flights to 4 different airports. One of which will be to the base airport. Therefore, the plane may have access to 4 line maintenance facilities, and 1 hangar facility on its own base. As deferred is considered the task that can be executed in all of the airports. Components are available in the base airport and higher costs are incurred in the other airports. It is assumed that when the aircraft is grounded there is no degradation. According to the estimated probability of failure and consequently, the probability of the due date, the component must be inspected and perhaps be replaced within the next 10 FH. A task is produced for this replacement. The TAB 2 depicts the maintenance operational time per airport.

Airport	Alternatives	Operational time (min)
FRA	Al$_1$	60
FRA	Al$_2$	70
CDG	Al$_3$	80
MUC	Al$_4$	80
MAD	Al$_5$	80
FRA	Al$_6$	60
FRA	Al$_7$	70

TAB 2. Task duration per airport facility

TAB 3 shows the flight plan.

GMT/ Flight	FROM-TO
0600–0645 / FL100	FRA-CDG
0830-0950 / FL101	CDG-MUC
1200-1400 / FL102	MUC-MAD
1600-1800 / FL103	MAD-FRA

TAB 3. Flight Plan

3.1.1. Cost criterion

In TAB 4, cost data are provided for the cost criterion value calculation per alternative using Equation (1). Indicative cost rates are considered.

Alt.	Cost rates (€/min)			Operat. time (min)	Parts cost (€)	Criterion value (€)
	Equip	Lab.	Over.			
Al$_1$	5	5	5	60	200	1100
Al$_2$	5	5	5	70	200	1250
Al$_3$	10	10	5	80	300	2300
Al$_4$	5	5	5	80	300	1500
Al$_5$	10	10	5	80	300	2300
Al$_1$	5	5	5	60	200	1100
Al$_2$	5	5	5	70	200	1250

TAB 4. Cost criterion data

3.1.2. RUL criterion

FIG 2, depicts the RUL per alternative. In case that the allocation takes place later than the operators' due date policy, the RUL is zero. The pilot examines two cases: Loose due date policy (75%) and conservative due date policy (25%). TAB 5, shows the RUL based on the respective due date policy.

Alt.	*Compl. date*	*Loose Due date*	*RUL (min)*	*Conserv. Due date*	*RUL (min)*
Al$_1$	06:00	13:00	-420	09:00	-180
Al$_2$	06:00	13:00	-420	09:00	-180
Al$_3$	08:30	13:00	-270	09:00	-30
Al$_4$	12:00	13:00	-60	09:00	0
Al$_5$	16:00	13:00	0	09:00	0
Al$_6$	19:00	13:00	0	09:00	0
Al$_7$	19:10	13:00	0	09:00	0

TAB 5. RUL criterion values calculation

3.1.3. Operational risk criterion

TAB 6, shows the respective Operational Risk criterion calculations. Indicative costs related to an unscheduled event (Hire last moment personnel, any extra costs, etc.) are assumed in this scenario to be doubly compared with the respective costs of a scheduled event.

Alt.	DV$_k$ (Euro)	DP$_k$ (%)	UnDV$_k$ (Euro)	UnDP$_k$ (%)	Exp. Value
Al$_1$	1100	95	2200	5	115500
Al$_2$	1250	95	2500	5	131250
Al$_3$	2300	88	4600	12	257600
Al$_4$	1500	62	3000	38	207000
Al$_5$	2300	20	4600	80	414000
Al$_6$	1100	3	2200	97	216700
Al$_7$	1250	3	2500	97	246250

TAB 6. Operational risk criterion values calculation

3.1.4. Flight delay criterion

TAB 7 shows the expected flight delay values that have been assumed for each maintenance alternative executed at the respective airport.

Alt.	*Probability for delay (%)*
Al$_1$	0
Al$_2$	0
Al$_3$	30
Al$_4$	0
Al$_5$	30
Al$_6$	0
Al$_7$	0

TAB 7. Probability for a delay measure

3.2. Results - Decision matrix

A set of scheduling experiments is conducted in order to validate and test the approach. The experiments have considered two different due dates; one is conservative at the 25% expected probability for failure and another one, rather loose at 75%. Criteria Weights are equally weighted. After criteria values normalisation, the TAB 8 and TAB 9 depict criteria values per due date policy, respectively. The alternative with the higher utility is proposed to be the best. Alterations to the criteria weights, meeting the operators' policy per case, may affect the results.

Alt.	Criteria				Utility
	Cost	RUL	Operat. Risk	Flight delay	
Al$_1$	*0,150*	*0,107*	*0,155*	*0,167*	0,144
Al$_2$	*0,147*	*0,107*	*0,153*	*0,167*	0,143
Al$_3$	*0,131*	*0,128*	*0,140*	*0,083*	0,121
Al$_4$	*0,144*	*0,158*	*0,145*	*0,167*	0,153
Al$_5$	*0,131*	*0,167*	*0,123*	*0,083*	0,126
Al$_6$	*0,150*	*0,167*	*0,144*	*0,167*	**0,157**
Al$_7$	*0,147*	*0,167*	*0,141*	*0,167*	0,155

TAB 8. Case 1: Loose due date, criteria Weights equally distributed

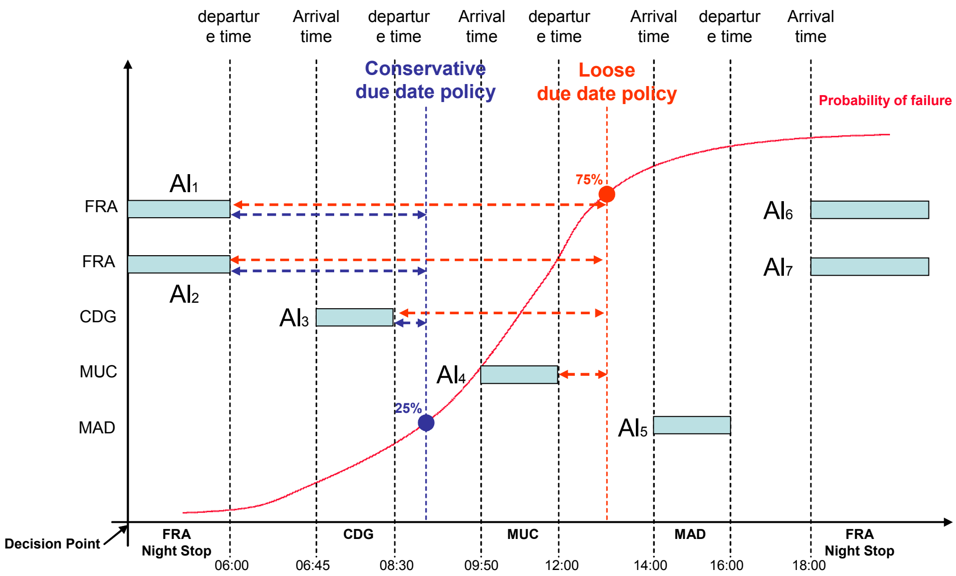

FIG 2. Operators due date policy for a maintenance action

Alt.	Criteria				Utility
	Cost	RUL	Operat. Risk	Flight delay	
AI_1	*0,150*	*0,090*	*0,155*	*0,167*	0,140
AI_2	*0,147*	*0,090*	*0,153*	*0,167*	0,139
AI_3	*0,131*	*0,154*	*0,140*	*0,083*	0,127
AI_4	*0,144*	*0,167*	*0,145*	*0,167*	0,155
AI_5	*0,131*	*0,167*	*0,123*	*0,083*	0,126
AI_6	*0,150*	*0,167*	*0,144*	*0,167*	**0,157**
AI_7	*0,147*	*0,167*	*0,141*	*0,167*	0,155

TAB 9. Case 2: Conservative due date, criteria Weights equally distributed

Alt_6 seams to be the best suitable option for both cases.

4. RESULTS – DISCUSSION

Analysing the use of the criteria, the *Cost* criterion is related to the operator's costs and describes the scheduled event costs. The *operational risk* criterion is used for introducing unscheduled event consequences. As the maintenance alternative execution approaches the component's expected end of life, the utility of the alternative, in principle, is decreased since the possibility to have an unscheduled event is high. *Flight delay* is strongly dependant on the availability and load of resources at each airport. A probability measure is considered as the most appropriate, since accurate resource availability information may not be available in advance. The *RUL* criterion introduces the use of the component's useful life thus, helping the operators to determine due date policy.

5. ACKNOWLEDGEMENTS

The work presented in this paper is partially supported by the Integrated Project "Technologies and techniques for new maintenance concepts – TATEM"[13], which is funded by the European Commission.

The authors would also like to specially thank Dr. Matthias Buderath from EADS Germany for his support in carrying out this work.

6. REFERENCES

[1] Chryssolouris, G. Manufacturing Systems: Theory and Practice, 2nd Edition. Springer-Verlag, New York; 2005

[2] Chryssolouris, G., K. Dicke and M. Lee, "On the Resources Allocation Problem", International Journal of Production Research, (Vol.30, No.12, 1992), pp. 2773-2795.

[3] Chryssolouris, G., J. Pierce and K. Dicke, "A Decision-Making Approach to the Operation of Flexible Manufacturing Systems", International Journal of Flexible Manufacturing Systems, (Vol.4, No.3/4, 1992), pp. 309-330.

[4] Chryssolouris, G., M. Lee and K. Dicke, "An Approach to Short Interval Scheduling for Discrete Parts Manufacturing", International Journal of Computer Integrated Manufacturing, (Vol.4, No.3, 1991), pp. 157-168.

[5] Chryssolouris, G., J. Pierce and K. Dicke, "An Approach for Allocating Manufacturing Resources to Production Tasks", Journal of Manufacturing Systems, (Vol.10, No.5, 1991), pp. 368-382.

[6] Papachatzakis P., Papakostas N., Mourtzis D., Chryssolouris G., «An Approach to Aircraft Maintenance Planning", working paper to be submitted to International Journal of Computer Integrated Manufacturing, Taylor & Francis

[7] Clarke M., Ryan D. Airline industry operations research. Encyclopedia of Operations Research

and Management Science; Kluwer Academic Publishers; Netherlands, 2001

[8] El Moudani W., Mora-Camino F. A dynamic approach for aircraft assignment and maintenance scheduling by airlines. Journal of Air Transport Management; Volume 6; Issue 4; October 2000; 233-237

[9] Quana G., Greenwoodb G., Liuc D., Huc S. Searching for multiobjective preventive maintenance schedules: Combining preferences with evolutionary algorithms. European Journal of Operational Research; Volume 177; Issue 3; March 2007; 1969-1984

[10] Saraca A., Battab R., Rumpc C. A branch-and-price approach for operational aircraft maintenance routing. European Journal of Operational Research; Volume 175; Issue 3; December 2006; 1850-1869

[11] Sherali H., Bish E., Zhu X. Airline fleet assignment concepts, models, and algorithms. European Journal of Operational Research; Volume 172; Issue 1; July 2006; 1-30

[12] Sriram C., Haghani A. An optimization model for aircraft maintenance scheduling and re-assignment. Transportation Research Part A: Policy and Practice; Volume 37; Issue 1; January 2003; 29-48

[13] TATEM (Technologies and Techniques for New Maintenance Concepts). FP6 EU Integrated Project; EC contract no. AIP3-CT-2004-502909; 2004-2009