OPTIMIZING AIRCRAFT LINE MAINTENANCE THROUGH TASK RE-CLUSTERING AND INTERVAL DE-ESCALATION

A.K. Muchiri and K. Smit

Abstract—This paper presents an adaptation of maintenance interval de-escalation to line maintenance planning. The necessity to optimize maintenance follows from a need to reduce line maintenance visits that interrupt routine aircraft operation due to their frequent occurrence. Further, frequent opening and closing of panels results in significant wear and tear, and thus reducing the inherent reliability of the aircraft. A simulation model has been developed to predict the maintenance requirement of aircraft in an airline operating under known conditions. Construction and validation of the model are based on knowledge and statistical data of actual operations and maintenance practices. The main use of the model is to group maintenance tasks into manageable packages that can be executed at extended maintenance intervals and within specified periods, and thus increasing aircraft availability. The model can also be used to vary and adapt line maintenance packages in case an aircraft visits the hangar for non-routine maintenance. The concept of initial de-escalation of maintenance intervals is introduced and its positive effects are demonstrated.

Keywords—Aircraft maintenance, clustering, simulation, optimization, Boeing 737NG

I. INTRODUCTION

WITH the increasing need to reduce maintenance costs and increase aircraft availability, the need to simplify the way maintenance is planned and executed has become a major issue in the aircraft industry. Aircraft manufacturers continue to develop aircraft with a low maintenance demand, while airlines strive to keep their maintenance costs as low as possible.

The Boeing 737 Next Generation (737 NG) is an example of such an aircraft, developed to demand less maintenance, as compared to previous versions of the Boeing 737 series. This 737 NG aircraft has a Maintenance Planning Data (MPD) document that is based on the Maintenance Steering Group (MSG)-3 philosophy. This is a task-based maintenance philosophy that looks at maintenance more at a task-level, as compared to previous philosophies, which were more focused on maintenance processes. The MPD is the document that airlines use to develop a customized maintenance planning. Many airlines that have this aircraft as part of their fleet tend to stick to the general method of developing maintenance plans that have been entrenched in the organization.

This paper is aimed at demonstrating a cost-effective maintenance planning and packaging concept that can lead to the reduction in direct maintenance costs, yet maintaining the reliability of the 737 NG fleet. Data used to develop the concept has been collected from an airline operating both scheduled (regular) and unscheduled (charter) flights within Europe.

Department of Mechatronic Engineering, JKUAT (Tel: +254733374133; fax: +2546752711; e-mail: muchiri@eng. jkuat.ac.ke).

Faculty of Aerospace Engineering, Delft University of Technology (e-mail: k.smit@lr.tudelft.nl).

II. MAINTENANCE PLANNING AND OPTIMIZATION

Maintenance engineers establish tasks and interval limits for various maintenance tasks; either based on the MPD (routine maintenance), Aircraft Modifications (AM), Repair Instructions (RI), Airworthiness Directives (AD) and Maintenance Instructions. Such maintenance tasks may be based on two maintenance activities:

(i) *Routine maintenance*:This is performed in accordance with the instructions stated in the Operator's Maintenance Planning (OMP) document. Such instructions and consequently utilization limits serve as a basis for the planning of aircraft maintenance.

(ii) *Non-routine maintenance*: In cases of component failure, rectification may be performed immediately or may be deferred, depending on the severity. Operational critical items and safety related items (listed in Minimum Equipment List - MEL) would require immediate corrective action, while non-safety and non-critical items will be put on a Deferred Defect Sheet (DDS) for rectification when opportunity arises.

Maintenance at the airline is broadly categorized into Line Maintenance (maintenance performed by the airline itself), and Base Maintenance (Maintenance work contracted out). For purposes of this paper, line maintenance will be defined as all maintenance work that cannot be performed outside a hangar. Line maintenance is performed at short intervals (given in weeks). For this case study, line maintenance is performed at a frequency of 5 weeks. Every line maintenance visit is planned in a so-called hangar slot. A single hangar slot is 7.75 hours long and it can produce 55 maintenance man-hours, while 2 slots produce 100 man-hours. Three slots lead to 300 man-hours. The reason why the man-hours do not increase in a linear pattern may be attributed to the amount of work that can be done simultaneously on a plane. For example, maintenance activities inside the cabin and cockpit do not interfere with external activities, hence more personnel can be engaged. Long maintenance slots also provide opportunity for tasks to be carried out that may

require mechanized equipment with operators.
Each aircraft receives about 15 maintenance slots a year for routine line maintenance. These slots have a repeating distribution rhythm of 1-1-2-1-1-3-1-1-2-, and are also planned in this rhythm as illustrated in Figure 1. In the given

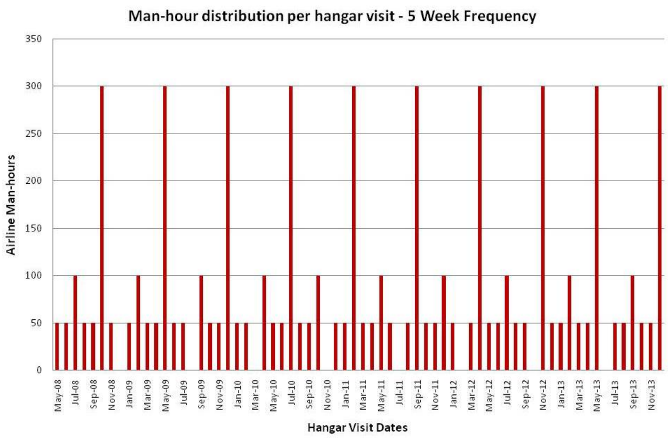

Fig. 1. Current hangar visit sequencing per aircraft

planning horizon of 5 years, the airline will require to provide 6,000 Man-hours (1,200 Man-hours per year) for maintenance of one aircraft. However, the realization of the planning for these slots deviates from the pattern above, as illustrated in Figure 2 below. The figure samples the total number of

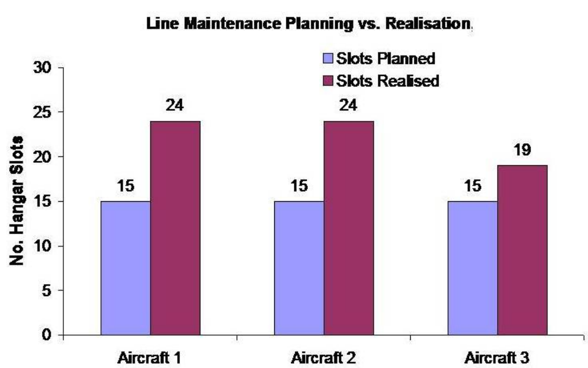

Fig. 2. Planned vs. Actual hangar visits in 2009

hangar visits for three difference aircraft in a random year (2009) of the planning horizon. A reason for this deviation may be attributed to the dependence of maintenance on the utilizations of the aircraft, unpredictable events, large work packages that are not executable within the stipulated time, and aircraft operations.

The effectiveness of the maintenance program and the aircraft maintenance characteristics are monitored through a Reliability Monitoring Program, maintained by the engineering department. Performance indicators used to monitor the maintenance program and fleet performance include: the Technical Dispatch Reliability (TDR), Pilot Reports (PIREPS), Hold item Lists (HIL), Unscheduled Removals, No Fault Found (NFF) Reports, and Confirmed Failures [1]. For each of these parameters, an alert level (an upper control limit) is set, at which action is necessary.

III. THE SIMULATION MODEL

A. Maintenance clusters definition and development

Clustering is the process of grouping maintenance tasks together into packages that can be planned in for execution. Clustering can be done by following two approaches, namely the Top-Down approach (answering the questions When maintenance and What maintenance), and the Bottom-Up approach (answering the questions What maintenance and When maintenance).

The Top-Down approach defined by time availability. It begins by analyzing the aircraft utilization (in Flight Hours and Flight Cycles) requirement at an annual, weekly and daily level. Figure 3 illustrates the airline's annual utilization. The annual level reveals a seasonal pattern. Weekly and the daily levels do not reveal specific patterns. However, it is possible to establish the average daily utilization from the seasonal pattern.

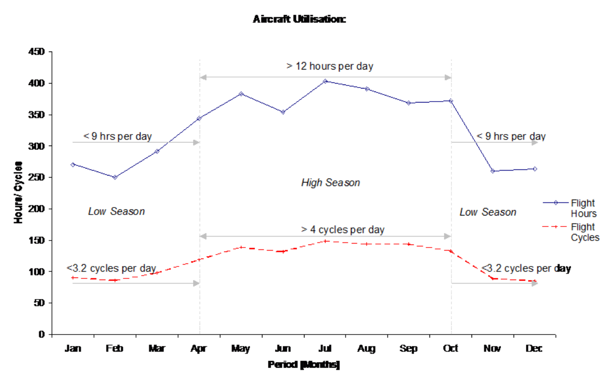

Fig. 3. Annual Flight Hour/Flight Cycle output per aircraft

The Bottom-Up approach is defined by the maintenance demand. It begins by evaluation what maintenance has to be done. By considering that the MPD document is a task-based maintenance document, a look is taken into the properties of each maintenance task. The property considered per maintenance task is its maintenance interval. Maintenance intervals may have any of the following intervals: Limited by Days (D), limited by Flight Hours (FH), limited by Flight Cycles (FC), limited by Days or Flight Hours - whichever comes first (D/FH), limited by Days or Flight Cycles - whichever comes first (D/FC). Thereafter, all tasks requiring the same fixed conditions/procedure/cost, and the same maintenance interval limit, are grouped together to form Maintenance Task Packages. This applies to all maintenance tasks intended for line maintenance. All other tasks are grouped together based on their maintenance interval, and become Base Maintenance Checks.

This conclusion on the weekly and daily utilization becomes more apparent when each of the weekdays is considered separately. Maintenance slot allocation follows these patterns; fixed slots are allocated at an annual level (for line and base maintenance). Ad-hoc slots can be located at a weekly and daily level (for line maintenance).

B. Cluster formation and evaluation

Through the implementation of the Bottom-Up and the Top-Down approach, Maintenance Task Packages and Maintenance Checks can be grouped together into maintenance clusters. Such clusters can either be static (base maintenance clusters) or dynamic (line maintenance clusters). Static clusters have a fixed content and are performed at predefined periods, while dynamic clusters may have a variable content and are performed frequently.

The clustering process is done using a computer model, developed in Visual Basic and MS Excel. The software is used mainly because of simplicity in programming, and also due to the fact that data available within available from the organizations is presented in Excel format. This model is also referred to as the Maintenance Item Allocation Model (MIAM). It is modeled to serve the following purposes: (1). Simulate the aircraft utilization (2). Calculate when a maintenance item turns due (3). Fit each maintenance item into a cluster (4) Generate maintenance clusters. It is hence a Hybrid Simulation model [2], [3].

A Normal distribution is normally chosen for periodic distributions [4]. But owing to the fact that the seasonal pattern has to be incorporated into the model, the Monte-Carlo simulation method is used. A uniformly distributed range is specified, and from this, a random number is drawn. To cater for variations in utilization that might differ significantly from the current utilization, ten utilization scenarios are considered. These scenarios are based on three assumptions, as described by Bratley et. al [2]. The assumptions are of (1) A conservative utilization: minimum conceivable daily utilization, (2) Most-likely utilization: utilization that resembles current pattern in airline, and (3) Optimistic utilization: maximum conceivable utilization. The ratio FH/FC is also varied to cater for changes within each scenario. The airline will ordinarily not operate an aircraft for less than seven hours in a day. Further, utilization for more than thirteen hours rarely happens. Below is an example of the resulting utilization scenarios.

Utilization	**Scenarios**	**FH**	**FC**
Conservative	Scenario 1	7 - 9 hrs/day	1.9 - 2.1
	Scenario 2	7 - 9 hrs/day	2.2 - 2.7
	Scenario 3	7 - 9 hrs/day	2.8 - 3.1
Most likely	Scenario 4	9 - 11 hrs/day	1.9 - 2.1
	Scenario 5	9 - 11 hrs/day	2.2 - 2.7
	Scenario 6	9 - 11 hrs/day	2.8 - 3.1
Optimistic	Scenario 7	11 - 13 hrs/day	1.9 - 2.1
	Scenario 8	11 - 13 hrs/day	2.2 - 2.7
	Scenario 9	11 - 13 hrs/day	2.8 - 3.1
	Scenario 10	(Actual)	(Actual)

MIAM combines maintenance item intervals with simulated aircraft utilization scenarios (high, average and low utilization) and maintenance scenarios (such as low maintenance frequencies). From these, the Maintenance Demand (in number of visits and maintenance man-hours) is calculated [5]. Further, the model also calculates losses following from maintenance performed before the interval limits are reached.

The general routine for calculating when a maintenance item is due is illustrated in Figure 4:

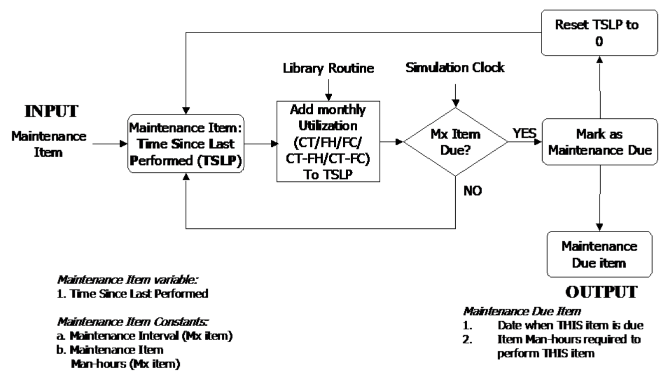

Fig. 4. MIAM Top-model

Maintenance scenarios serve as the simulation clocks. The simulation increment may either be in months or weeks, depending on type of maintenance being considered (Line of Base).

The MIAM top-model is refined to cluster line maintenance packages (Figure 5). The evaluation on whether a maintenance task package is due is based on the availability of a maintenance slot (planned maintenance visit) or a maintenance window (opportunity to perform maintenance when aircraft is on the ground and there is hangar space).

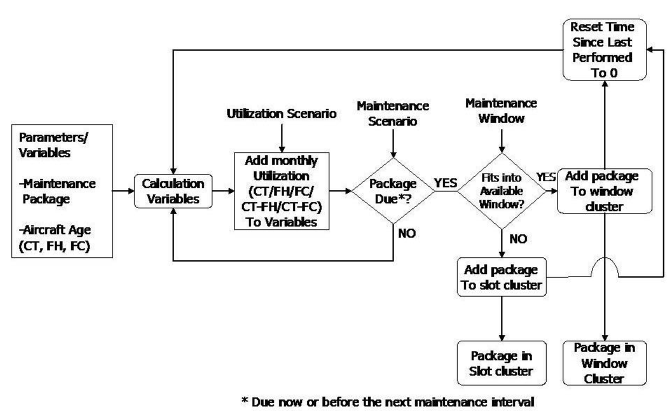

Fig. 5. MIAM model: Line Maintenance clustering criteria

The model above is dynamic in that it does not just rely on the normal planning but also on occasional long downtimes of aircraft.

Unless otherwise stated, the following initial conditions apply:

Initialization Routine	Inital Value
System State Variables	0 CT, 0 FH, 0 FC
Aircraft samples	A single aircraft is considered
Event Routine	0
Library Routine	As stated

C. Maintenance item interval de-escalation

De-escalation can be interpreted as a loss, in that maintenance items end up being performed more frequently than they ought to be performed. The loss will therefore be expressed in terms of repetitive man-power utilization, increased downtime and repeated set-up activities. The last two losses cannot be calculated directly. However, this paper will work further with the assumption that man-hour losses represent all de-escalation losses.

Maintenance item clustering normally results in the de-escalation of maintenance item intervals. These are the maintenance intervals allocated to individual tasks by the engineering department (as indicated on the OMP). It is calculated as a fraction of the interval that is not utilised, that is:

$$\text{interval de-escalation} = \frac{AI_i - lastP}{AI_i} \quad (1)$$

where:

AI_i = Airline Interval (in D, FH, FC)

$lastP$ = Time since last performed (accumulated utilization)

$and \quad lastP \leq AI_i$

Hence the man-hour de-escalation may be calculated as follows:

$$\textbf{Man-hour de-escalation} = \frac{AI_i - lastP}{AI_i} \times AMhrs \quad (2)$$

where

$AMhrs$ = Airline man-hours(Boeing Man-hours $\times$ 1.7)

The pre-multiplication factor 1.7 is derived from work-floor experience on how Boeing man-hours compare with the airline personnel performance, observed over a long period of time.

D. Model validation and verification

1) Validation: Actual Process vs. The MIAM: Model Validation is done in order to ascertain that the model is a reasonable representation of the real life process: that it reproduces system behavior with enough fidelity to satisfy analysis objectives [3].

(i) Assumptions made:
  - The aircraft considered makes flights on a daily basis, throughout the entire period considered
  - The aircraft performs flights solely for the airline, hence sticking to the airline's seasonal utilization pattern
  - Maintenance clusters are performed as scheduled. No escalations and extensions are considered

(ii) Inputs and Distributions:
  - Maintenance dates (Due dates, Time Since Last Performed) have a MM/YY format.
  - Maintenance is always performed at intervals larger than 28 days(4 weeks)

(iii) Outputs:Maintenance man-hour demand is also regarded as downtime. The process concentrates more on man-hour demand variations, and downtime is expected to decrease if the maintenance frequency decreases.

2) Verification: MIAM Design and MIAM Realisation: Verification is intended to ensure that the model does what is intended to do (often referred to as debugging)

(i) The model calculates all possible inputs; with the exclusion of line maintenance frequencies lower than 4 weeks. If certain boundary conditions are violated (e.g. escalation of maintenance interval limits), the model returns erroneous outputs (N/A, #VALUE etc.). This ensures that no invalid results are evaluated further.

(ii) The modeled scenarios produce the desired utilization patterns which still corresponds with the airline's actual utilization.

(iii) Base Maintenance does not vary greatly with changes in the maintenance utilization. Minimal changes are observed within each utilization scenario groups (conservative, most likely or optimistic). Sampling one scenario from each group may be considered to be representative enough for the other two.

(iv) Line maintenance shows significant variations within the various utilization scenarios. Considering that the maintenance demand is calculated at short intervals, such variations cannot be ignored. Hence, all the 10 scenarios should be considered.

IV. RESULTS AND DISCUSSION

Line Maintenance clusters are evaluated for frequencies ranging between 4-6 weeks, for a period of 6 years. Frequencies above 6-weeks would lead to the escalation (exceeding) of maintenance interval limits. The results of the evaluation are tabulated in Figure 6. It follows that the maintenance demand decreases with a decreasing maintenance frequency, as does the de-escalation. The 6-weeks interval

		Maintenane Demand (Manhours)			De-escalation (Man-hours)		
	Frequency	4 Weeks	5 Weeks	6 weeks	4 Weeks	5 Weeks	6 weeks
Year	2008	122.14	115.22	102.32	14.65	9.36	5.93
	2009	380.44	269.04	124.32	29.42	19.81	13.51
	2010	347.76	356.46	262.64	27.39	21.25	18.58
	2011	399.64	219.22	370	24.15	17.75	12.95
	2012	356.92	397.14	230.36	28.03	29.92	17.03
	2013	351.14	367.26	385.04	26.77	26.64	18.95
	2014	320.22	359.14	443.54	28.4	13.16	17.2
	2015	482.02	222.1	302.36	32.67	16.94	17.56
	Average	345.035	288.1975	277.5725	26.435	19.35375	15.21375

Fig. 6. Maintenance man-hour-demand per aircraft by varying maintenance frequencies

may not be viable due to the possibility of some tasks running over their maintenance interval (escalation).

Another interesting result is on the distribution of hangar slots.

The theoretical distribution is as suggested in figure 1. This was not achievable during the first year of implementation as illustrated in figure 2. After the re-clustering of tasks, the estimated maintenance demand for the new Maintenance Task Packages (MTP) is as illustrated in figure 7. These new packages have been put against the old packages for comparison. The un-evenness of the demand pattern can be

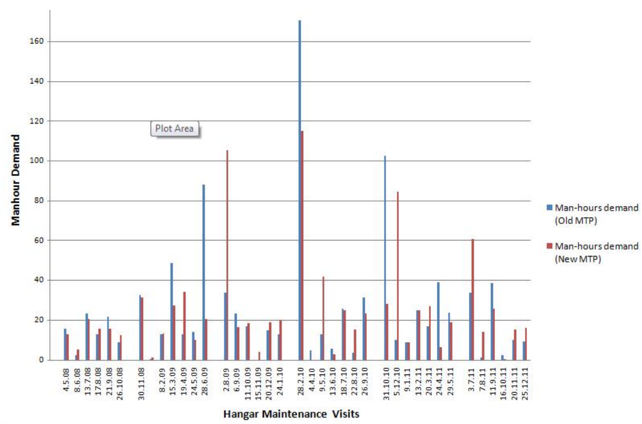

Fig. 7. Man-hour demand before and after re-clustering of tasks

harmonized if the maintenance slots are re-allocated. It is also important to note the time of the year during which the peaks occur, for this has an effect on the availability of the aircraft, especially during the high season.

Ultimately, the purpose of optimizing maintenance process is to reduce the total cost of maintenance. By comparing the maintenance cost between the old 5-week clusters and the new clusters over a period of 7 years, a positive gain can be observed and is illustrated in figure 8

	Annual maintenance demand in man-hours	Total Man-hours cost (in Euros)	Lost Man-hours cost (In Euros)	Maintenance cost per flight hour (In Euros)
Old MTPs at 5 weeks	539.57	15,361.10	1,260.29	4.11
New MTPs at 5 weeks	309.59	13,931.70	831.66	3.81

Fig. 8. Total cost of maintenance man-hours

It can be observed that there is a reduction of about EUR 1,400 per aircraft per year with the deployment of the new MTPs. This translates into a lower cost of maintenance per flight hour, an important Performance Indicator (PI) for airlines that save per hour for maintenance.

V. Conclusion

It can be concluded that the re-clustering of the maintenance tasks using the strategy described above, and the subsequent variation of the maintenance interval, results in a reduction in the total cost of performing maintenance. The reduction may not be significant (EUR 1,400 per year), but this will translate into a significant amount for an airline that operates a large fleet of the Boeing 737NG. Airlines are looking for ways to reduce their cost of operation, and such a saving will be most welcome.

It is important to note that this simulation and costing is based on deployment of human labor only. Costs associated with part and other overheads have not been included for purposes of simplifying the simulation. However, the total man-hour cost is known to form a good indicator of other costs related to maintenance. Further work is still pending on the integration of other maintenance factors and cost overheads in order to refine the simulation.

References

[1] Muchiri A. K. and Smit K., "Application of maintenance task interval de-escalation in base maintenance planning," *Enterprise Risk Management*, vol. 1 No. 2, pp. 63–75, 2009.

[2] Bratley, *A Guide to Simulation*. Springer-Verlag New York Inc, 1987.

[3] J. Hillston, "Modelling and simulation," in *Seminar Proceedings, Department of Informatics*, University of Edinburgh, 2001.

[4] Mattila V., Kai V., Tuomas R., "A simulation model for aircraft maintenance in uncertain operational environment," tech. rep., Systems Analysis laboratory, HUT, Helsinki, 2003.

[5] Smit K., "Besturing onderhoud met behulp van computers (computer-assisted maintenance management)," *TU Delft J2020*, p. 8, 1994. Department of Industrial Engineering Management.