Aero-Engine Maintenance Cost Optimization by RCM

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Abstract: The need for reducing the operating cost keeps escalating day by day. The survivability of Airline Industries relies on their ability to optimize the operating cost. The cost of maintenance is 12% of Total Operating Cost. If the wastages of men power, machines, materials and downtime are properly eliminated appropriately means, then the cost of maintenance can be minimized. Implementation of Lean & Six Sigma principles in Aircraft & Aero engine maintenance can optimize the maintenance cost. But it requires right decisions to be needed at right time. Continuous assessment of reliability based in past and on condition data will empower the operator to take right decision about maintenance planning. Reliability Centered Maintenance will be an useful aid for implementing Lean or Six Sigma principles in aircraft maintenance industries without jeopardizing the safety or airworthiness requirements. And hence the optimization of maintenance cost and increase the availability of aircraft and its components can be realized.
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1. Introduction

Due to the complex structure, differences in utilization, operating environment, maintenance polices& variations in technical crew, engine failure may take place at any time [1]. Aero engine is the core component of aircraft and monitoring and diagnosis of faults of aero engine system in time can avoid the accident occurring effectively and reduce huge losses due to accidents. The healthy or reliable aero engine is the fundamental way to guarantee flight safety of aircraft and regular attendance on time [2]. Airline industries need huge initial investment as well as high operational cost. It comprises of 60% of fixed and 40% direct operating cost[12]. The Direct Operating Cost consists of cost of fuel, the labour cost and material cost etc. At times, the failures are totally unpredictable. And these unexpected failures affect the airline industries very badly. They do hesitate a lot to take any cost cutting measure. Because the airworthiness regulations, loss due to flight cancelation and loss of customer good will etc do not permit them to implement any new method to reduce the maintenance cost. In order to meet out all these factors, airline industries have not taken any adequate steps to minimize the maintenance cost. Cost optimization needs careful planning and execution of maintenance activities.

Regular maintenance and inspections do ensure that aircrafts are airworthy and prevent component and system failures during operation [12]. There is always a tension within airlines between the need to maximize the availability of aircraft for operations and having sufficient downtime for maintenance. While commercial departments want to maximize aircraft utilization, maintenance departments need to have the aircraft available in the right locations for reasonable periods of time [12]. Unexpected failures of components or a shortage of parts or mechanics with particular skills and qualifications add to the complexity and stress of planning maintenance. Many inputs need to be juggled by maintenance planners to produce a workable solution: the flight schedule; the aircraft technical status; material availability; hangar space; mechanics' availability; and the scheduled tasks themselves. The cost savings derived from efficient maintenance planning, however, can be substantial. It is possible to reduce only a part of direct operating cost that is cost of maintenance. Condition monitoring of engine and its systems and analysis of failures do help us to figure out the impending failures or time to failure. Hence, it is easy to take any cost cutting measure in scheduled maintenance.

2. Proposed Methodology

Step 1: Data Analysis

There are many potential factors that lead to failure of an aero-engine. These factors do vary from place to place and time to time. Hence the Failure pattern and failure interval will not be same for all engines. The variations in operating crew, maintenance men, operating environment and inherent problems of individual engines have major say in the failure pattern and failure interval. Whenever the impending failures are to be predicted it is necessary to analyze the data for consistency. As RBD is the simpler and best one to identify the level of significance within and among engines, we are considering RBD for our analysis.

- ***Randomized – Block Design:***

The aim of design experiment is to control the extraneous variables and hence to minimize the experimental error. The results of the experiments could be attributed only to the experimental variables.

The experimenter has available measures pertaining to 'a' treatment distributed over 'b' blocks. All the observations are classified according to two factors, one column-wise and other row-wise.

Let y_{ij} denotes the observation pertaining to the i^{th} treatment and j^{th} block, $\bar{y}_i$ the mean of the 'b' observation for the j^{th} treatment, $\bar{y}_j$ the mean of the 'a' observation for the j^{th} block and $\bar{y}_i$ the grand mean of all the 'ab' observations.

- ***Parameter Estimation:***

The equation $Y_{ij} = \mu + \alpha_i + \beta_j + \varepsilon_{ij}$ for $i = 1,2,\ldots a$ & $j = 1,2,\ldots b$

This equation is called as Model equation for randomized block design. We restrict the parameter by imposing the conditions that

$$\sum_{i=1}^{a} \alpha_i = 0 \qquad \sum_{j=1}^{b} \beta_j = 0$$

In analysis of a two-way classification where each treatment is represented once in each block, the major objective is to test for the significance of the different among the $\bar{y}_i$ that is, to test the null hypothesis $\alpha_1 = \alpha_2 \ldots = \alpha_a = 0$.

It also be desirable to test the blocking has been effective that is, whether the null hypothesis $\beta_1 = \beta_2 \ldots = \beta_b = 0$ can be rejected. In either case, the alternative hypothesis is that atleast one of the effect is different from zero.

Convenient formulae are available to calculate SST, SS(Tr), SS(Bl)

$$SST = \sum_{i=1}^{a} \sum_{j=1}^{b} y_{ij}^2 - C$$

$$SS(Tr) = \frac{\sum_{i=1}^{a} T_i^2}{b} - C$$

$$SS(Bl) = \frac{\sum_{j=1}^{b} T_j^2}{a} - C$$

Where C, the correction term is given by $C = \frac{T^2}{ab}$

The results obtained in this analysis are summarized in the following analysis of variance table:

Source of Variation	Degree of Freedom	Sum of Square	Mean Square	Ratio F
Treatments (Between Rows)	a-1	SS(Tr)	$MS(Tr) = \frac{SS(Tr)}{a-1}$	$F(Tr) = \frac{MS(Tr)}{MSE}$ (Fraction for Treatments)
Blocks (Between Column)	b-1	SS(Bl)	$MS(Bl) = \frac{SS(Bl)}{b-1}$	$F(Bl) = \frac{MS(Bl)}{MSE}$ (Fraction for Blocks)
Error	(a-1)(b-1)	SSE	$MSE = \frac{SSE}{(a-1)(b-1)}$	
Total	ab-1	SST		

Here, we have introduced Random block Design to observe the significant difference between and within the machines. This method deserves more works to check the consistency between and within machines with more applicable combinations. The Data[3] has been tested with RBD and it is found to be 90% consistent

<u>Step 2</u>: Reliability Estimation

There are many standard tools available for reliability estimation. But the tools used for our estimations are ***Weibull Distribution*** [1], ***New Weibull Distribution*** [4] and **Exponentiated Inverted Weibull Distribution**[6] . These are the proven and standard mathematical tools available for *reliability calculations of bath tub failure rate*. So far *Weibull distribution* alone is used for estimating the *reliability of aero-engines*. Under normal circumstances all the three tools may provide more or less same result. But at odd times they will exhibit significant difference among them. The accuracy of reliability estimation has to be as maximum as possible for our methodology. Hence we use best among the best for a given condition.

- ***Weibull Distribution* [1]*:***

The random variable x has a Weibull distribution if its probability density function takes of the form $f(t) = \lambda\beta t^{\beta-1} e^{-\lambda t^{\beta}}$; t>0

The corresponding reliability function is $R(t) = e^{-\lambda t^{\beta}}$ and its Hazard function is

$z(t) = \lambda \beta t^{\beta-1}$

If $\theta^{\beta} = \frac{1}{\lambda}$ then $MTBF = \theta \sqrt{(1+(1/\beta))}$

In the case where there are k-systems with N total failures, N is calculated as

$N = \sum_{i=1}^{k} N_i$

For each of the k-systems, x_{ik} represents the number of failures in a given system.

Then $\lambda = \frac{N}{T^{\beta}}$; $\beta = \frac{N}{\sum_{j=1}^{k}\sum_{i=1}^{N_k} ln\frac{T}{X_{ij}}}$

- ***New Weibull Distribution* [4]*:***

For new Weibull distribution, the cumulative distribution function is given by $f(t) = 1 - e^{\lambda\alpha\left(1-e^{\left(\frac{t}{\alpha}\right)^{\beta}}\right)}$

Its probability density function is $F(t) = \lambda\beta\left(\frac{t}{\alpha}\right)^{\beta-1} e^{\left(\frac{t}{\alpha}\right)^{\beta} + \lambda\alpha\left(1-e^{\left(\frac{t}{\alpha}\right)^{\beta}}\right)}$

Its reliability function of our distribution is $R(t) = e^{\lambda\alpha\left(1-e^{\left(\frac{t}{\alpha}\right)^{\beta}}\right)}$

- **Exponentiated Inverted Weibull Distribution [6]:**

The Random variable x has a standard Exponentiated inverted Weibull distribution if its distribution function takes the form

$F_{\theta}(x) = \left(e^{-x^{-\beta}}\right)^{\theta}$; $x, \beta, \theta > 0$

This is the θ^{th} power of the distribution function of standard inverted Weibull distribution. Here β, θ are the Shape parameters [6].

The probability density function is $f(x) = \theta \beta x^{-(\beta+1)} \left(e^{-x^{-\beta}}\right)^{\theta}$; x > 0

The corresponding reliability function is $R(t) = 1-\left(e^{-x^{-\beta}}\right)^{\theta}$

<u>Step 3</u>: Estimation of parameters for New Weibull and Exponentiated Inverted Weibull Distribution

The data has to be subjected to *standard regression analysis* for obtaining values of β and α.

$Y = \ln \{\ln(1 - \ln R(t))\}$ and $y = \ln(t)$

∴ The straight line equation is $y = \beta x - \beta \ln \alpha$

Here β is the slope of the regression line and α is obtained from the y intercept.

<u>Step 4</u>: Implementation of Lean and Six Sigma Tools for Cost Optimization

Now days, a centralized data management system, managed by the OEM, is used for analyzing the engine failures. They do not take into account the variation due to operating environment, operating crew and maintenance crew etc. But these variations can be eliminated if the Failure analysis is restricted to a single operator or operators of same region etc.

The cost optimization can be realized if and only if the airline industries adopt lean and six sigma tools in maintenance planning, execution and control. But the implementation of these tools needs a reliable forecast of impending engine failure to work with. Hence we suggest planning the maintenance activities based on the reliability of engines that is ***Reliability Centered Maintenance***.

The potential areas for implementing the Lean and Six Sigma Tools are identified and possible outcome have also been listed here.

PROCESS	***TOOLS***	***OBJECTIVES***
Logistics or Spare Parts Control	5S, Kanban	Work force may be reduced. Complexity may be reduced. Time waste may be reduced.
Disassembly	Cell, Team, Quality & source, Point-of-use-storage&DMAIC 1.Define 2.Measure 3.Analyse 4.Improve 5.Control	Labor moral to be increased. Down time may be reduced. Source utilized effectively. The DMAIC methodology focuses on improving an existing process or product. These are mostly "real-life" problems, which need to be solved
Cleaning	5S, one piece flow, Just	Time waste to be reduced.

	in time	Process efficiency may increase Labor and machine utilization may increase
Visual inspection	Documentary, one piece flow, cell	Innovation Complexity & Capacity increase
Machining processing	Cell, Cross training & LS^3 1.Lead 2.Study 3.Smooth 4.Sustain	Floor space reduction Reduction of defects Utilization of work force effectively. Lead the process improvement projects by hearing the voice of customer (VOC) Study and analyze the current status of targeted process to get the voice of process Propose the countermeasures, and transform them into the voice of server (VOS) to smooth the service process Sustain and control the project results, and spread out the organization to be the Voice of Business
Testing the ac components	TAKT time, Visual factory	Total lead time reduction Reduction in false function
Surface coating (or) protecting coating	One piece flow, cell, point of use storage	Utilization of machines Time reduction. Reduction in downtime may
Assembly section	Cell, team, quality & source, Point-of-use-storage	Labor moral may increase Down time is reduced.
Testing the a/c performance	Workplace organization, kaizen	Total lead time reduction Reduction in false function
Dispatching the aircraft or its component	5S, Kanban	Labor moral may be increased. Down time is reduced. Inventory reduction On time delivery improvement.
DMEDI (whenever a methodology is to be devised for rectifying an engine failure)	1.Define 2.Measure 3.Explore 4.Develop 5.Implement	The DMEDI methodology deals with new product, service or process creation. The first two steps of this methodology are the same as for DMAIC. This is due to the same need to define business opportunities and measure inputs and outcomes.

The Maintenance cost can be minimized even if anyone of the wastages in Men Power, down time, Inventory and Ground equipment is minimized. As Lean and Six Sigma tools have produced world of good in all other industries, we expect a similar or somewhat better results from these tools once the airliners imbibe them.

Step 5: Control Chart for Failure Rate

As our analysis is for a single user, we suggest the airliner to use control charts as one of the tools for performance monitoring. The Control chart is a simple graphical device which will help to identify the presence of any assignable cause. Here it is used as an aid to indicate how well the individual engine is running when compared with all other engines.

Parameter estimation:

$\bar{n} = \frac{\sum n_i}{N}$, $\bar{p}$ = average of proportion

$$UCL = \bar{p} + 3\sqrt{\frac{\bar{p}(1-\bar{p})}{\bar{n}}}$$

$$LCL = \bar{p} - 3\sqrt{\frac{\bar{p}(1-\bar{p})}{\bar{n}}}$$

3. Result Analysis

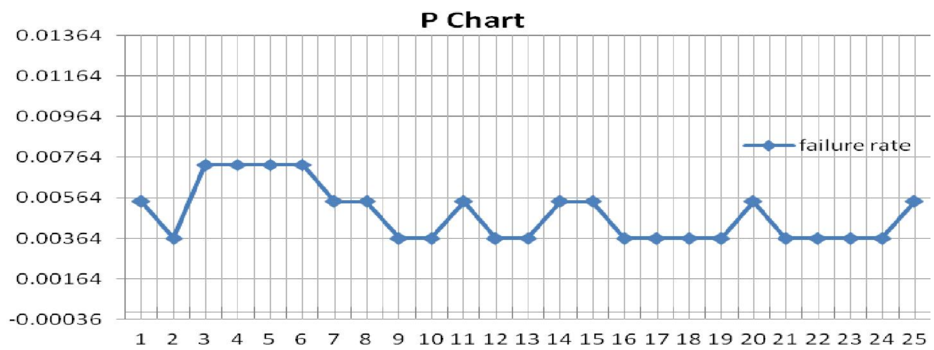
The proposed methodology provides the following results for Shape parameter β, Failure Rate λ and Mean Time between Failures for the sample data.

The results comparison is shown below.

Methods	β	λ	MTBF (hrs)
W.D.	1.3551	0.0005167	266
N.W.D.	1.2452	0.0010224	252
E.I.W.D	1.1226	0.0021032	249

The least one among the MTBF values will be taken for consideration for reliability calculations. Then efficient planning the maintenance activities can be made without jeopardizing the airworthiness requirements so that the improved safety and airworthiness of engine is ensured. As the impending failures can be predicted by this methodology, appropriate decisions can be made with respect to allocation of resources for maintenance well in advance and hence all cost optimizing tools can be utilized in aero-engine maintenance industries.

The control chart for monitoring the performance of an engine with other engines is given below.



UCL= 0.01364 & LCL = -0.004041; Since LCL is negative, let us consider that LCL = 0.

∴ Control Limits are (0, 0.01364) & Central line y =0.0047992

4. Conclusion

This proposed methodology re-evaluates the reliability of engine or its module by considering condition monitoring parameters, pilot report etc or previous operating data. Using these results, the MTBF can be calculated. Based on the lead time available for rectification action, all maintenance tasks may be planned well in advance. This will enhance the possibility of implementing Lean and Six sigma principles in Aircraft or Aero engine maintenance through RCM. Normally airliners do rely on the OEM for reliability assessment. This is the simplest model that is more suitable for airlines with any fleet size. With this model, the airline operator can continuously monitor the performance of the engine so that he can focus on engines that are more susceptible to failures.

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