CHAPTER 5

METHODOLOGY

5.1 INTRODUCTION

This Chapter explains how the fatigue life cycles can be calculated with the help of Life Usage Monitoring system. It also discusses the results of existing and proposed methods of Reliability and MTBF calculations. It highlights the merits of proposed method over the existing method in forecasting accurate Mean Residual Life for engines.

5.2 FATIGUE LIFE CALCULATIONS

5.2.1 Fatigue

Fatigue is the progressive and restricted structural damage. This type of failure occurs when a component is exposed to recurring loading and unloading. Normally, the maximum stress acting on the component is less than the ultimate tensile stress limit of that material. It is lesser than the yield point of the material. If the loads exceed certain limit then microscopic cracks will be developed at the stress concentrated areas. Ultimately a crack will attain a critical size, and the structure will fail suddenly.

5.2.2 High Cycle Fatigue

HCF also called as Stress Life Approach that occurs for a Fatigue Cycle range of $10^5$ to $10^8$. The failures will be rapid and totally unpredictable. Normally such failures are resulted by micro-structural damages. This approach is applicable for occasions where elastic deformations are predominant.
5.2.3 Low Cycle Fatigue

LCF also known as Strain Life approach occurs when Fatigue cycles are less than $10^5$. During this phase the components are subjected to high amplitude alternating stresses. These stresses will be greater than the yield strength of the material. The fatigue failures of this category are dominated by their propagation. They are controlled by alternating strain amplitude and also by the ductility of the material. As high stresses are applied on the components, they will be subjected to macroscopic plasticity. This approach is more suitable for Plastic deformations. As Aero-engine and its components are subjected to high stresses and high temperatures, LCF approach is more suitable than HCF.

5.2.4 Conditioning monitoring using LCF calculation

LCF approach will consider the local volume of the material in and around the critical points or the points where the material has become plastic. The input for LPSA method is the stress and strain near the critical volume. These input values are obtained from FEA of either elastic to plastic state or simple elastic state. If the inputs are obtained from FEA of elastic state then the outcomes of this analysis will be amended to suit the plastic state or non-linear behaviour of material. In addition the LPSA method need inputs such as co-efficients that define the weariness deeds of materials.

\[ \sigma_f^f, b, c_f, c_f \] - fatigue strength coefficient, \( b \) - fatigue strength exponent, \( c_f, c_f \) - fatigue ductility coefficient and \( c \) - fatigue ductility exponent.

It is necessary to conduct experiments to obtain values for all these terms or can be obtained from database. In order to identify the properties such as Young’s Modulus, \( \nu \) -Poisson’s ratio, K-cyclic stress hardening coefficient, n-cyclic stress hardening exponent, it will be subjected to testing.
Then only it is possible to conduct the Finite Element Analysis. This analysis would fetch the values for Strain and Strain components of the critical locations in LP blades. The results of FEA of Elastic states are fictive, whereas the FEA of Elastic-Plastic state provides us the correct results and they are denoted with a subscript \( \nu \). The equivalent stress and strain can be computed from the results of FEA. Then it is essential to compute the Fictive elastic equivalent upper stress \( \sigma_{h,\text{fic}} \) and mean stress \( \sigma_{m,\text{fic}} (\sigma_{m,\text{fic}} = \sigma_{h,\text{fic}}/2) \) for the true plastic state of the notch. The amplitude of strain will be calculated with the help of cyclic deformation curve. The true strain amplitude \( \varepsilon_a \) is obtained directly from the FEA of elastic-plastic state of material. The Palmgren-Miner approach of damage accumulation uses the uni-axial damage parameters for finding out the number of start-ups required for crack initiation. LCF life estimation procedure is found on local strain approach. Non-linear finite element analysis of the fan rotor assembly is carried for a various combinations of engine parameters (rotor rpm / temperature) for generating the input data for LCF life calculation. Response surface methodology is used for establishing the relation between the engine parameters and the response variable i.e., strains range \( \varepsilon_r \). Local strain approach is used to for relating the evaluated values of \( \varepsilon_r \) to fatigue life. Non-linear damage accumulation methodology that accounts for decreasing fatigue strength with increasing fatigue damage would be actively pursued for development of algorithm. Running the engine run data obtained from Gas Turbine Research Establishment validates the developed algorithm. During the validation phase, special attention is paid to the isolation of high frequency cyclic loads from low frequency base line cycles.

The schematic diagram of LCF is shown in Figure 5.1
5.2.5 Procedure

i) **Development of LCF evaluation algorithm** - This algorithm is based on local strain approach, which in turn would source the data from non-linear finite element analysis of gas turbine rotor assembly. Configuration corresponding to a contemporary power generation turbine engine rotor blade is considered for this analysis. Material
properties of the above-referred rotor (Ti6Al4V) are used in the analysis. Through fractional factorial approach or orthogonal array approach, minimum of nine engines run combinations with corresponding values of speed and temperature is considered for analysis. For reducing the engine run data or mission cycle data into standard stress reversal format, proven algorithms of Rain Flow Analogy are employed. DOE principles (Response Surface Methodology) are used for finding the relation between strain and gas turbine operational parameters. Regression analysis is applied for determining the correlation coefficients.

ii) Evaluation of the impact of the residual stress measurement - From the interactions that the guide had with DRDOs gas turbine designers / scientists, it is understood that fan rotor blades are susceptible to residual stresses caused by material processing and/or machining procedures. Through specimen level testing, an attempt is made to evaluate the influence of residual stresses over LCF life. Two separate sets of tests are conducted on Ti6Al4V specimens with the first set representing stress-free status and the second set representing residual stress superposition. Residual stresses are introduced through micro-peening and the magnitude of residual stresses is varied in gradual between 20% and 80% of ultimate tensile strength. Standard ASTM or MSRR procedures are adhered to for the experimentation. Results from the above-referred LCF tests would also be compared with the stress based LCF evaluation approach wherein effect of mean stress is directly
integrated into LCF calculations by referring of modified Goodman diagram.

**iii) Development of Life Usage Monitoring System (LUMS)** -
A life monitoring system, as shown in the schematic diagram in Figure 5.1, is custom designed and developed with processors / display devices / interfaces indicated as below. LUMS would have the provision for both online and off-line engine data processing. LCF life evaluation algorithm is ported into this system and a quality checks is conducted with trial data. LUMS system would have provision for indicating the speed and temperature exceedances compared to stipulated limits. The engine run data, material data and the limits of critical parameters are made available to the LCF counter in the form of files through a Secure Digital (SD) memory card as shown in figure 5.2.

![Figure 5.2 Block Diagram of LUMS with processors](image)

**Figure 5.2 Block Diagram of LUMS with processors**

**5.2.6 Engine Menus**

When one of the items in the engines menu is selected, the directories in that engine directory is read from the SD Card and components
menu is populated on the LCD as shown in the figure 5.3(a). When a component say “BLADE1” is selected, a Compute Menu is displayed on the device. The title of the menu shown in figure 5.3(b) is an indication of selected component of a particular engine. Selecting the row “Type” can change the calculation type. Now 2 indicators appear to the left of “Stress”. Use the up and down navigation keys to change calculation type to stress or strain.

![Figure 5.3 a) Components Menu and b) Compute Menu](image)

Use the procedure described above to change Threshold damage fraction and temperature values. Figure 5.4 shows display state when damage fraction and temperature value can be changed by using the up and down navigation keys.

![Figure 5.4 Display images](image)
Selecting the row “File” can choose the log file that contains the engine run data. Now the log files in the corresponding component directory are listed on the display as shown in the Figure 5.5(a). Select the appropriate log file. To begin computation of damage fraction select row “Compute DF”. A computing pop up box appears on the display indicating computation is in progress as shown in Figure 5.5(b). After computation is complete, result screen as shown in the Figure 5.5(c) appears on the display. If the damage fraction is above Threshold Damage Value (TDV) then a warning beep is heard with a flashing light, red in visuals.

![Component directory](image1)

![Result Screen](image2)

Figure 5.5 (a) & (b) Component directory and (c) Result Screen

If the “System Status” row is selected from menu, then System Status Screen as shown in figure 5.6 is displayed on the LCD. The system status menu provides size of the SD card inserted into the device and the battery life.
5.3 MTBF CALCULATIONS

The failure rate curve is identical for all mechanical systems. The Aero-engines are not exception to that. Theoretically they may have identical curves for failure rate. But there are many factors, like variation during manufacturing, assembly, operations and maintenance that affect the failure rate and frequency of failures for aero-engines. Even if the engines are operated and maintained by same operator, their failure patterns will be differing from engine to engine. This research work considers all such potential factors that lead to variations in performance and prediction of residual life for engines. This research work proposes a method to minimize the percentage of errors in prediction of reliability and mean residual life.

As noted by Ascher et al (1993), there is very little literature on aero-engine reliability and residual life estimations. Zhang Chuan-Chao (2011) says that with constant improvement of aero-engine performance, the demand for working conditions of aero-engine components increases, which in turn the monitoring and fault diagnosis of aero-engine system in time can avoid the accident occurring effectively and reduce huge losses resulting in that.
Weckman et al (2001) states that Aero-engine is an example of a complex system that periodically requires repair or restoration and also it has many failure modes that can cause the removal characteristics to have substantial variation in the expected time on wing or an item considered as airworthy.

5.3.1 Existing Methodology

As mentioned by Weckman et al (2001), Weibull process is widely used in modelling life of repairable systems like jet engine. It is the weibull distribution with a Shape parameter denoted by $\beta$ and a Scale parameter or Characteristic Life denoted by $\lambda$. It is often used to analyse field or test failure data to understand how items are failing and what specific underlying failure distribution is being followed by failures that occur.

The shape parameter $\beta$, can be interpreted directly as follows:

- If $\beta < 1$ - Decrease in failure rate;
- If $\beta = 1$ - Failure rate is constant over time;
- If $\beta > 1$ - Failure rate increases with time.

In general, the Weibull Distribution is used in the following areas;

- Survival analysis
- Reliability engineering and failure analysis
- Industrial engineering to represent manufacturing and delivery times
- Weather forecasting
- To describe the wind speed distributions
Step 1: Failure data is collected from all operators from all over the world.

Step 2: The Reliability & MTBF are calculated using Weibull distribution (Xie et al, 2002).

The parameter estimations are:

The random variable x has a Weibull distribution if its probability density function takes of the formula:

\[ u(t) = \lambda \beta t^{\beta-1}; t > 0 \]  

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

\[ N = \sum_{q=1}^{k} N_q \]  

For each of the k-systems, the failures are denoted as \( X_{iq} \) where “i” represents the number of failures in a given system. Then the Shape parameters can be represented as:

\[ \lambda = \frac{N}{kT^{\beta}}; \beta = \frac{N}{\sum_{q=1}^{k} \sum_{i=1}^{N_q} x_{iq}^{-\lambda}} \]  

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

5.3.2 Proposed Methodology

In order to eliminate the effects of variations or to reduce the percentage of error, the failure data will be subjected to different tasks like testing of hypothesis and regression analysis.
Step 1: Data collection from single source or multiple sources

As airliners are not willing to disclose the failure history and also they are very sensitive information, the data from (Weckman et al 2001) is used for the analysis and it is given in Table 5.1.

Table 5.1 Engine Failure Data

<table>
<thead>
<tr>
<th>Engine No.</th>
<th>Engine No.</th>
<th>Cumulative Failure Time</th>
<th>Total Failures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Engine No.</td>
<td>Failure-I</td>
<td>Failure-II</td>
</tr>
<tr>
<td>1 150</td>
<td>2 291</td>
<td>407</td>
<td>526</td>
</tr>
<tr>
<td>2 291</td>
<td>3 93</td>
<td>179</td>
<td>357</td>
</tr>
<tr>
<td>3 93</td>
<td>4 53</td>
<td>203</td>
<td>275</td>
</tr>
<tr>
<td>4 53</td>
<td>5 2</td>
<td>188</td>
<td>265</td>
</tr>
<tr>
<td>5 2</td>
<td>6 65</td>
<td>250</td>
<td>370</td>
</tr>
<tr>
<td>6 65</td>
<td>7 183</td>
<td>290</td>
<td>545</td>
</tr>
<tr>
<td>7 183</td>
<td>8 144</td>
<td>338</td>
<td>523</td>
</tr>
<tr>
<td>8 144</td>
<td>9 223</td>
<td>531</td>
<td></td>
</tr>
<tr>
<td>9 223</td>
<td>10 197</td>
<td>367</td>
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<td>10 197</td>
<td>11 187</td>
<td>215</td>
<td>357</td>
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<td>13 213</td>
<td>14 171</td>
<td>332</td>
<td>539</td>
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<td>14 171</td>
<td>15 197</td>
<td>312</td>
<td>435</td>
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<td>15 197</td>
<td>16 200</td>
<td>312</td>
<td></td>
</tr>
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<td>16 200</td>
<td>17 262</td>
<td>509</td>
<td></td>
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<td>17 262</td>
<td>18 255</td>
<td>395</td>
<td></td>
</tr>
<tr>
<td>18 255</td>
<td>19 286</td>
<td>452</td>
<td></td>
</tr>
<tr>
<td>19 286</td>
<td>20 206</td>
<td>383</td>
<td>479</td>
</tr>
<tr>
<td>20 206</td>
<td>21 179</td>
<td>444</td>
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<tr>
<td>21 179</td>
<td>22 232</td>
<td>488</td>
<td></td>
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<tr>
<td>22 232</td>
<td>23 165</td>
<td>417</td>
<td></td>
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<tr>
<td>23 165</td>
<td>24 155</td>
<td>373</td>
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<td>24 155</td>
<td>25 203</td>
<td>292</td>
<td>469</td>
</tr>
<tr>
<td>25 203</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Step 2 : Sub-Group Formation**

To assure airworthiness and air safety, it is mandatory that all vital decisions be made with utmost care. Vital decision about airworthiness should not be made on single outcome or result. It is indeed necessary to have as many results as possible from a single set of data. The outcome must be precise for a given set of data. If so, then the results are reliable in nature, then vital decision about maintenance planning and scheduling, etc can be made based on the forecast or results. In order to achieve this, it is proposed to form several possible sub groups. For example, if failure data have been collected for 10 engines and sub groups will be formed with a sub group size of 8 engines. This approach generates $10C_8$ possible solutions i.e.45 solutions are possible. If majority of 45 possible results are either repetitive or the standard deviations are minimum, then our predictions can be assumed to be more accurate than the existing method.

For example, Subgroup A will be \{3,4,5,6,7,8,9,10\}, Subgroup B will be \{2,3,4,5,6,7,8,9\} and so on. Similarly it is possible to get 45 subgroups for generating 45 possible solutions.

**Step 3 : Use of Testing of Hypothesis to eliminate the variations between engines**

Randomized Block Design (RBD) is one of the best Design of Experiments (DOE) tools to identify the variations within and between operating systems. The sample has been collected from two operators of same operating environment; the variations within the engine may not be significant. This thesis considers both the variations within and between Aero-engines.
Mean is called overall mean or ground mean of all observations and it is given by
\[ \bar{y} = \frac{\bar{y}_1 + \bar{y}_2 + \ldots + \bar{y}_r + \ldots + \bar{y}_a}{a} \]  
(5.5)

The Failure time \( Y_{ij} = \mu + \alpha_i + \beta_j + \epsilon_{ij} \) for \( i = 1,2,\ldots,a \) & \( j = 1,2,\ldots,b \)

This equation is called as Model equation for randomized block design. Here \( \mu \) is the grand mean, \( \alpha_i \) is the effect of the \( i^{th} \) treatment, \( \beta_j \) is the effect of the \( j^{th} \) block, and \( \epsilon_{ij} \) are independent, normally distributed random variables having zero means and the common variance \( \sigma^2 \).

Analogous to the model for the one-way classification, we restrict the parameter by imposing the conditions that
\[ \sum_{i=1}^{a} \alpha_i = 0 \quad \text{and} \quad \sum_{j=1}^{b} \beta_j = 0 \]  
(5.6)

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 \( \bar{y}_1 \) that is, to test the null hypothesis \( \alpha_1 = \alpha_2 = \ldots = \alpha_a = 0 \).

It may also be desirable to test whether 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 \( H_1 \) is that atleast one of the effect is different from zero. The \( \alpha \)'s are not equal to zero; the \( \beta \)'s are not equal to zero.

Convenient formulae are available to calculate Total Sum of Square (SST), Treatment Sum of Square (SS(Tr)) and Block Sum of Square (SS(Bl)).
\[ SST = \sum_{i=1}^{a} \sum_{j=1}^{b} y_{ij}^2 - C \] 

(5.7)

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

(5.8)

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

(5.9)

where \( C \) is the correction term is given by \( C = \frac{T^2}{ab} \) 

(5.10)

\[ SSE = SST - SS(Tr) - SS(Bl) \] 

(5.11)

The results obtained in this analysis are summarized in the following analysis of variance table 5.2:

**Table 5.2 ANOVA Table**

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Degree of Freedom</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>Ratio F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatments (Between Rows)</td>
<td>( a-1 )</td>
<td>( SS(Tr) )</td>
<td>( MS(Tr) = \frac{SS(Tr)}{a-1} )</td>
<td>( F(Tr) = \frac{MS(Tr)}{MSE} ) (F-ratio for Treatments)</td>
</tr>
<tr>
<td>Blocks (Between Column)</td>
<td>( b-1 )</td>
<td>( SS(Bl) )</td>
<td>( MS(Bl) = \frac{SS(Bl)}{b-1} )</td>
<td>( F(Bl) = \frac{MS(Bl)}{MSE} ) (F-ratio for Blocks)</td>
</tr>
<tr>
<td>Error</td>
<td>((a-1)(b-1))</td>
<td>( SSE )</td>
<td>( MSE = \frac{SSE}{(a-1)(b-1)} )</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>((ab-1))</td>
<td>( SST )</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
F(Tr) and F(Bl) are greater than one. The null hypothesis is rejected if \( F(Tr) > F_\alpha \) with degrees of freedom (a-1) and (a-1) (b-1) at the level of significance \( \alpha \); the null hypothesis is rejected if \( F(Bl) > F_\alpha \) with degrees of freedom (b-1) and (a-1) (b-1) at the level of significance \( \alpha \), where \( F_\alpha \) is the Variance Ratio.

**Step 4 : Reliability & MTBF calculation by Weibull distribution**

As 48 possible sub-groups have been formed, there are many outcomes that are repetitive in nature. This makes it feasible to minimize the effects of all potential factors that lead to error in prediction.

**Step 5 : Regression Analysis**

The data will be subjected to regression analysis to obtain the shape parameters for Exponential Inverted Weibull distribution (EIWD) for all sub groups. The standard Shape parameters are \( \beta \) and \( \theta \).

\[
y = \ln \left\{ \ln \left(1 - \ln R(t)\right) \right\} \quad \text{and} \quad x = \ln (t) \quad (5.12)
\]

The straight line equation is \( y = \beta x - \beta \ln \theta \) \quad (5.13)

Here \( \beta \) is the slope of the regression line and \( \theta \) is obtained for individual subgroup from the y intercept.

**Step 6 : Reliability & MTBF calculation by Exponential Inverted Weibull Distribution (EIWD)**

As proposed by Flaih et al (2012), the Reliability & MTBF for each group is calculated with the results of regression analysis. EIWD performs in similar manner as that of WD. It is considered for validating the results of WD.
The Random variable ‘x’ has a standard EIWD if its distribution function takes the form

\[ F_\theta(x) = \left(e^{-x^{-\beta}}\right)^\theta; \ x, \beta, \theta > 0 \] (5.14)

This is the \( \theta \)th power of the distribution function of standard EIWD. Here \( \beta, \theta \) are the Shape parameters (Xie et al, 2002).

The probability density function is

\[ f(x) = \theta \beta x^{\beta-1} \left(e^{-x^{-\beta}}\right)^\theta; \ x > 0 \] (5.15)

The corresponding reliability function is

\[ R(t) = 1 - \left(e^{-x^{-\beta}}\right)^\theta \] (5.16)

The data has to be subjected to standard regression analysis for obtaining values of \( \beta \) and \( \theta \).

\[ y = \ln \left\{ \ln(1 - \ln R(t)) \right\} \quad \text{and} \quad x = \ln(t) \] (5.17)

\[ y = \beta x - \beta \ln(t) \] (5.18)

Here \( \beta \) is the slope of the regression line and \( \theta \) is obtained from the \( y \) intercept.

5.4 LEAN SIX SIGMA TOOLS FOR AERO ENGINE MAINTENANCE

5.4.1 Lean Maintenance

Lean Maintenance is a systematic approach to identify and eliminate Non-Value Added Activities, which are called as wastages. Lean maintenance may be defined as liberation of maintenance activities that aim to deliver customers with less waste as possible. This promotes accomplishment of a desirable maintenance outcome with fewest possible
inputs. Inputs may include the resource of labour, spare parts, tools, energy and economy. This process aims for improved plant reliability and repeatability. One of the most vital aspects of lean maintenance is to develop an understanding of the maintenance and applying a risk-based approach. This involves evaluating each element in maintenance practice, which adds value to the product and benefits the customer. Lean maintenance drives efficiency and effectiveness where it ensures improved quality, equipment performance and profitability.

Waste maintenance practices are associated with the following activities:

- Unproductive work – work done inefficiently which does not increase equipment reliability.
- Delays in motion – waiting for equipment availability to carry out preventive maintenance.
- Unnecessary motion – surplus trips to parts stores & searching of tools for required job.
- Poor management of inventory – short of an adequate amount of the suitable parts at the essential time.
- Rework – repeatable task due to poor workmanship.
- Under-utilization of resources – maximizing resources available and harnessing the skill of maintenance teams.
- Ineffective data management – collection of unnecessary data instead of required information.
- Misapplication of machinery – during exact operations or deliberate operational strategies leading to maintenance work being done when it is not required.
It is important to note that lean maintenance is not simply an approach to do more with fewer resources. It enables us to focus the resources where they are meant to meet production and regulatory requirements. Lean principles were being used by Toyota over 40 years ago to help and standardize a methodology for company improvement.

Lean Maintenance principles as applicable to Aero Engine Maintenance are;

i) Develop benchmark exercises to regulate and increase engine and its system’s normal operating life and reduce quality defects.

ii) Raise those standards to optimize process capability and increase the Time between failures for all components

iii) Administer reassignment of Scheduled Maintenance activities to service personnel and ensure quality in maintenance.

iv) Improve the Maintenance systems of stores, planning, reporting and analysis for implementing Kaizen Culture.

v) Detect and rectify the impending breakdowns to assure defect less operation of engine.

vi) Pursue perfection in all maintenance related activities.

5.4.2 Lean Tools

- Value Stream Mapping (VSM)

Value Stream Mapping, as indicated in figure 5.7, at Elcho helps management to visualize the flow of information and product, helps to see
waste, shows the relationship between information and material flow, and forms the basis for prioritizing lean actions.

This technique is one of the effective tools in Lean Program for identifying value added and non-value added activities. It will also help the organizations to identify the opportunities for improving the lead-time, logistics and Maintenance systems. This tool is very useful for analyzing the movement of items and information flow that are associated with repair and maintenance activities. It is also known as "Material and Information Flow Mapping". The Valued added activities are adding value to the product or service for which the operators would like to spend. The non-value added activities are those for which the operator is spending money unnecessarily. The activities that produce mistakes, errors or non-conformance are adding no value to the maintenance tasks.

Figure 5.7  Value Stream Mapping(http://www.value-stream-mapping.co.uk/)
The seven wastes in process that VSM helps to identify are (Elcho 2007) Over Production, transportation, inventory, motion, waiting, defects and over Processing

- **Total Productive Maintenance (TPM)**

  It is estimated that the cost of unscheduled equipment downtime in lean manufacturing environments without excessive inventory buffers is 5 to 30 times what it is in other manufacturing environments (Cooper 2004). This situation leads to lost opportunity, failed shipping schedules, and lost sales either directly or indirectly.

- **Kaizen Culture**

  Kaizen, given in figure 5.8, means gradual, orderly and continuous improvement in maintenance management. It is the ongoing attitude of continuous improvement that can be made. The basic five elements are: Quality Circle, Improve Moral, Team Work, Personal Discipline and Suggestions for improvement.

![Figure 5.8 Continuous Improvement](http://t1.gstatic.com/images)

This tool is very useful for achieving workplace effectiveness, elimination of waste, strain and discrepancy and standardization.
• **Hoshin Kanri Planning**

Hoshin planning is more a management methodology to set forth a future plan. At Elcho, each staff with responsibilities in respective plant has goals for a period of one year. Each and every goal will be tied directly to the goals of the superior wherever he or she reports and holds same level of truth above it.

• **Cross training**

To reduce idle workforce time while achieving better and constant flow system.

• **5S Implementation**

This tool which as all other lean manufacturing tools is based on continuous improvement and therefore it is important to keep improving the manufacturing parameters to promote the philosophy. In this case we assumed a reduction of the processing time as the result of 5S implementation (changes to the model to simulate the alternatives); this assumption allows us to simulate alternative using variables that the simulation models require. The interrelationship among these tools is shown in figure 5.9.

**Sort**: Eliminate unnecessary items, supplies and equipment from the work place. Only necessary items, tools and equipments must be positioned in the workstation.

**Set In Order**: Specify appropriate places for all items, tools, spare parts, job and equipments. It enables everyone to locate these things easily and eliminates unnecessary movement and idling of work force.
Shine: Clean the work area so that they are maintained in order for next shift.

Standardize: Check whether there is a need for improving this process or not.

Sustain: Ensure this tool is efficiently adopted and adhered to.

5S tools help us to eliminate the following;

i. Waste of Motion - the searching of items, equipment and supplies

ii. The waste in movement that is moving items, equipment and supplies to work place.

iii. The waste of stores by overstocking of items equipment

iv. The waste of storage space

v. Defects due to wrong selection of item or tools.

vi. Defects due to usage of equipment that is improperly working.

vii. Injuries produced by equipment and supplies left in walkways, or unsafe locations.

Figure 5.9 5S Tools
(http://sitemaker.umich.edu/fm_gmeig_practice_management_s5/files/5s.gif)
• **Takt time alternative**

The ideal takt time set by the company is a week or one module for every two hours. The system has also transformed to a pure pull system; all the buffer stations represented in current value stream map should be eliminated; these are changes to be done in simulation model.

• **Standardized work**

Jobs are broken into elements and examined to resolve best and safest method for each.

• **Visual factory**

Information is made available and comprehensible at a glance.

• **Point-of-use-storage**

Locate all parts, raw materials, tools and fixtures as close as possible.

• **Quality at source**

Foolproof devices are used for example (pokayoke)

• **Teams**

Department barriers are to be eliminated and replaced with cross-functional teams.

• **One piece flow**

To minimize work in process, operators focus on completing one part through the operation before starting next part.

• **Cells**

Proper placement and usage of machines.
5.4.3 Six Sigma Maintenance

Lean Six Sigma (LSS) is practiced by all industries for achieving dramatic performance improvements in their operations, maintenance and engineering processes. When considering the Aviation industries, reducing defect rate and cycle time is the ultimate goal. Six sigma technique is a business performance improvement strategy that aims to reduce the number of mistakes/defects as low as 3.4 Parts Per Million (PPM).

As per the survey in aircraft manufacturing industries the medium aircraft consists of about 10,000 different parts. At Three Sigma quality (currently adopted methodology), 27 of those parts in an assembled aircraft would be defective. Since Three Sigma quality level cannot be accepted as good enough quality level, we are proposing a solution for improving the quality level. DPMO (Defects Per Million Opportunities) is a primary measure in Six Sigma.

Last several decades the commercial airlines have been facing the problems of high operating costs. There are many airline industries that were unable to sustain in the market. Not only the commercial airlines but also the flying clubs, The Aircraft maintenance industries and other aviation related manufacturer & maintenance industries are also facing the same problem.

These problems are all due to improper and inefficient management principles that are adopted in these industries. The high operating cost is due to lots of wastages (in management language). It is suggested to incorporate Lean-Six Sigma tools in Planning, Scheduling and Execution of maintenance activities in order to reduce the wastages in men, machine and material and also the unnecessary downtime of aircraft and its components.
While comparing with other industry the lean concepts should have several constrains for the aviation industry. Because, products from these industries may not endanger the human lives but the aviation industries do. The airworthiness requirements do not provide sufficient platform for implementing all Lean Management principles. A compromise formula has to be worked out to provide a bridge between lean thinking and airworthiness requirements.

### 5.4.3.1 DMAIC Methodology

This focuses on improving an existing process or product.

The methodology consists of five phases: a) Define business opportunities, b) Measure performance, c) Analyze opportunity, d) Improve performance, and e) Control performance. The relation among these phases is shown in figure 5.10.

**Define:** It means defining the maintenance tasks

**Measure Performance:** Identify appropriate measures to evaluate the maintenance activities and also identify the target performance. This step also involves measuring the actual performance so that potential factors that affect the cost to quality are identified.
**Analyze:** This step involves identification of causes of defects. It also evolves the cause and effect diagram to locate the root causes.

**Improve:** This step identifies the maximum limits of key variables. It also proposes a new system to measure the deviation of these variables.

**Control:** In this phase, all tools are kept in order to assure all key variables are contained within the permissible range.

### 5.4.3.2 DMEDI Methodology

DMEDI deals with new product, service or process creation.

The phases are: Define business opportunities, Measure performance, Explore options, Develop a new product, process or service, and implementing the best solution. The comparison of DMAIC and DMEDI is depicted in figure 5.11.

![Figure 5.11 DMAIC Vs DMEDI](image)
Define: It means defining the maintenance tasks.

Measure: Define Customers’ needs using Voice of the Customer and Quality Function Deployment (QFD). The operators and flight planners are the customers for the maintenance department. The maintenance department will be the customer for other departments like stores, reliability control department, quality assurance department etc.

Explore: While planning and scheduling the maintenance task, try to evolve the concepts that produce a high quality maintenance system.

Develop: Innovate and optimize the Maintenance System.

Implement: Authenticate the new maintenance system design with trial projects, launch Controls, and ensure unrestrained execution.

5.4.3.3 LS³ Methodology

i) Lead:

Lead the process enhancement projects by consideration of the Voice of Customer (VOC)

- Recognize the process development project
- Describe the project performance parameters
- Select the crew for project
- Carry out the project charter and job assignments
ii) **Study:**

Study and scrutinize the current status of beleaguered process to get the Voice of Process (VOP):

- Monitor the real process, and quantify the baseline.
- Investigate the composed data to recognize the current state

iii) **Smooth:**

Suggest the counter measures, and renovate them into the Voice of Server (VOS) to balance the service process:

- Represent the development countermeasures
- Employ the countermeasures to speed up the service delivery
- Corroborate the results by performance measures

iv) **Sustain:**

Sustain and manage the mission outcome, and broaden the organization to be the Voice of Business:

- Regulate the effective countermeasures to sustain the results
- Continuous control of the improvement level
- Devise the job value of employees in the service process
- Knowledge diffusion and application
5.4.4 Need for Lean and Six Sigma Tools

- Waste minimization
- Lean + Six Sigma: Effective Production and Service
- Enhanced Safety of Aircraft
- Overall equipment effectiveness
- Reduced tool expenses for 40%
- Reduced costs of poor quality for 55%
- Reduced labors expenses for 59%
- Production/Service time reduction for 38%
- Index cost/volume reduction for 31%

This research work aims to apply the six-sigma quality standards that will realize 3.34 defectives per million components without compromising the airworthiness requirements or air safety. Implementation of Lean Six Sigma (LSS) in aero-engine repair and maintenance is proposed mainly to achieve substantial improvements in waste reduction as listed in Table 5.3. It can be realized if all maintenance activities are planned in accordance with the reliability or alert value of the respective system. The lean and six sigma tools can be utilized if the lead-time of all maintenance tasks is accurately calculated. In the current work, two methods are used to calculate the lead-time for two different conditions. One is during actual operating condition and the other after engine failure. The current work also aims to improve the accuracy level of alert values.
<table>
<thead>
<tr>
<th>Process</th>
<th>Tools</th>
<th>Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Logistics or Spare Parts Control</td>
<td>5S, Kanban</td>
<td>Work force may be reduced. Complexity may be reduced. Time waste may be reduced.</td>
</tr>
<tr>
<td>Disassembly</td>
<td>Cell, Team &amp; DMAIC</td>
<td>Labor moral can be increased. Down time may be reduced. Source can be utilized effectively.</td>
</tr>
<tr>
<td>Cleaning</td>
<td>5S, one piece flow, Just in Time</td>
<td>Time waste can be reduced. Process efficiency may increase. Labor and machine utilization may increase.</td>
</tr>
<tr>
<td>Visual inspection</td>
<td>Documentary, one piece flow, cell</td>
<td>Innovation. Complexity &amp; Capacity increase.</td>
</tr>
<tr>
<td>Machining processing</td>
<td>Cell, Cross training &amp; LS³</td>
<td>Floor space reduction. Reduction of defects. Utilization of work force effectively.</td>
</tr>
<tr>
<td>Testing of Components</td>
<td>TAKT time, Visual factory</td>
<td>Total lead time reduction. Reduction in false function.</td>
</tr>
<tr>
<td>Surface coating</td>
<td>One piece flow, cell, point of use storage</td>
<td>Utilization of machines. Time reduction.</td>
</tr>
<tr>
<td>Assembly section</td>
<td>Cell, team, quality &amp; source, Point-of-use storage</td>
<td>Labor moral may increase. Down time can be reduced.</td>
</tr>
<tr>
<td>Testing the a/c performance</td>
<td>Workplace organization, kaizen</td>
<td>Total lead time reduction. Reduction in false function.</td>
</tr>
<tr>
<td>Dispatching the aircraft or its component</td>
<td>5S, Kanban</td>
<td>Labor moral may be increased. Down time and inventory can be reduced. On time delivery improvement.</td>
</tr>
<tr>
<td>DMEDI (Whenever a methodology is to be devised for rectifying an engine failure)</td>
<td>1.Define 2.Measure 3.Explore 4.Develop 5.Implement</td>
<td>The DMEDI methodology deals with new product, service or process creation. The Objectives are elimination of Rework; Quality at all levels of maintenance and Better utilization of resources.</td>
</tr>
</tbody>
</table>