SciEn
Journal of Engineering Advancements Vol. 03(03) 2022, pp 112-130 https://doi.org/10.38032/jea.2022.03.006

Prioritization of Effective Lean Tools for Reliability Analysis and Maintenance Strategy

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Received: March 25, 2022, Revised: August 16, 2022, Accepted: August 17, 2022, Available Online: September 28, 2022

ABSTRACT

Asset or equipment reliability and availability have occupied extensive attention because of an emerging competitive environment and the overall operating and production cost. The main focus of this manuscript is to prioritize the lean tool and select an appropriate maintenance strategy for the repairable assets in the maintenance shop of the SIMGA[1] shipyard. Five (5) assets of that maintenance shop such as an air compressor machine, 500-ton press machine, overhead crane machine, VDF lathe machine, and Roller machine were under breakdown maintenance. Due to the continuous degradation of those assets, attempts should be taken to enhance the reliability parameters by predicting upcoming failure events for each equipment or asset. QFD-AHP is a rapid tool in which quality function deployment is integrated with AHP to make an optimal selection. Firstly, the integrated QFD-AHP method is employed to prioritize the lean tools for that maintenance shop. 5S and KPI are the best fit for that shop among ten lean tools. Non Homogenous Poisson Process (NHPP) is a model which represents the no. of failure experienced up to time (t). NHPP and Weibull analysis are utilized to predict future failure events and analyzed the nature of the failure accordingly. From the results of the Weibull analysis and NHPP analysis, it is shown that the slope (β) of the failure rate is greater than 1 for all assets. Overhead crane m/c and 500-ton press m/c are the most critical m/c according to equipment criticality analysis. Finally, a decision diagram is utilized to extract the most congruent maintenance strategies based on the reliability parameter of five (5) assets. The approach employed in this study helps maintenance practitioners to achieve lean maintenance.

Keywords: Reliability, Availability, Weibull Analysis, Non-homogenous Poisson Process, QFD-AHP, Maintenance Excellence, MTBF.

1 Introduction

Maintenance is defined as the activity obtained to confirm that an asset or equipment performs its intended function and maintains the actual production requirement. Moreover, the reduction of cost and the enhancement of the asset or asset reliability and performance will be acquired by the execution of a standard maintenance policy. The longevity of the asset might be expended with a huge profit on investment by the execution of little changes in the strategy for maintenance. Several factors must be optimized which affect the reliability and availability. To get good profitability the level of reliability and availability of machinery should be high. The availability and reliability of the machine may influence the effectiveness of the asset. As the size and equipment complexity is increasing, the implications indication of equipment failure has become more critical. Equipment or facility failure turns not only productivity loss but also quality loss. Since it is not possible to prevent failure entirely, the probability of occurrence as well as failure impact can be minimized by a maintenance strategy. It is considered one of the important roles of reliability analysis and maintenance.

Quality function deployment-Analytic Hierarchy Process (QFD-AHP) that gains wide acceptance for using the Analytic Hierarchy Process with associated techniques as Quality Function Deployment in multiple decision-making problems. This approach is pursued to enhance the effectiveness of the decision-making process. Sometimes, it is applied to deal with subjective linguistic judgments in location problems and to evaluate the effectiveness of the hardware. QFD-AHP approach is used in the area of lean thinking, particularly in the maintenance environment [1].

In reliability application, the Weibull distribution is ordinarily applied as a longevity distribution. It describes a constant, decreasing, or increasing failure rate. The three parameters of this distribution are β, η, and ϒ which are known as the shape parameter, the scale parameter, and the location parameters accordingly. A Weibull distribution having two parameters can be expressed as W (β, η). The Probability density function with time is represented by it [2]. In three-parameters Weibull distribution, eta (η) represents characteristic life at which it is assumed that 63.2% of the sample failed. Beta (β) determines what the Weibull probability density function looks like. It is also positive Gamma (ϒ) is a location parameter. It is called failure-free time or a guaranteed time. The recognition of the mode of failure for an asset is exhibited by the beta value. It is necessary for choosing the appropriate maintenance strategy. By the use of Weibull analysis software, it is checked whether the data follows a distribution of Weibull or not. This can be determined by the use of the Weibull probability plot where data is manually plotted. If the data is conforming to a Weibull distribution, a plot gives a straight line. Different beta values represent the following Weibull parameter and reliability matrix conditions [2].

1) $\beta < 1$, it represents infant mortality. A new part is not acceptable. An old part is better than a new part because the failure rate is lower as weak units have been eliminated from the population.

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2) $\beta = 1$, it represents chance failures. An old part has the same failure rate as a new part. Thus, nothing is gained by a replacement strategy that throws away unused life until the failure mode changes to a wear-out mode.
3) If $\beta=1$, there must have an optimum replacement strategy if the cost or safety consequences have a very high-cost ratio for an unplanned failure compared to a planned replacement cost which then drives a preventive replacement strategy.

Non-homogenous Poisson process is a process along with a simple parametric model used to represent events with a failure recurrence that are not constant [3]. It does not require stationary increments, which means that failures may be more likely to occur at certain times. NHPP describes the cumulative number of failures up to time (t) and it follows a Poisson distribution with parameter λ (t) for a counting process. NHPP model works when the occurrence rate depends only on time and stationary increment is not required. Data acquisition is simpler for C-A plots than for Weibull plots. For C-A plots, chronological time is on the x-axis. It is also named the cumulative number and the y-axis is named as cumulative events, reliability is made visible by them. When plotted, this data usually provides results in a straight line [4]. After plotting, this data gives information about two statistics. These are line slope β, and y-axis intercept at time t=1, λ. The slope β for the trend line is a potential indicator that gives information about increasing or decreasing. The y-axis provides the failure rate at a time equal to 1, which is some kind of hypothetical value by that it is easy to forecast future failure. For plotting cumulative mean time vs. cumulative time, Y-axis is converted which is simple and easy to understand. When the line slope (β) is going upward and to the right, it indicates that reliability is improving; when it is downward and to the right, it indicates that reliability is decreasing.

A maintenance strategy guides the maintenance activity. A maintenance strategy is divided into three categories. These are preventive maintenance, design out maintenance as well as corrective maintenance. Design out maintenance which aims at altering the design of the asset or product for reducing the requirement for maintenance in the period of the life cycle. Preventive maintenance is considered as maintenance which is carried out at scheduled intervals by the prescribed criteria. It is intended to minimize the probability of degradation or failure of an item. This maintenance is further divided into two maintenance those are time-based maintenance as well as condition-based maintenance [4]. Preventive maintenance is an appropriate choice if the component has a progressive failure rate which indicates the failure rate and the cost of the preventive maintenance action should be less than the total cost of corrective maintenance. Condition-based maintenance is called prediction-based maintenance which is applied to an item where failure occurs accidentally. The inspection period must be presented to enhance the reliability of facilities by using MTF. Corrective maintenance can be defined as the maintenance which is carried out after identifying a fault. It is intended to keep an item in such a state in which it may perform a required function.

In this study, a survey was carried out in the maintenance shop of the SIGMA shipyard. The foundation of the study was the survey result. In the QFD model, survey results were the input. Another set of input was necessary for developing the model which was obtained from the lean thinking literature study. Another endeavor was taken to determine the asset reliability by using the Weibull distribution & PTC Wind-chill Quality Solutions 11.0 Tryout "software. The reliability model from the NHPP analysis predicts the future failure events that will occur. The purpose of this study is to describe the method of reliability and availability analysis of a repairable asset and explore the method for improving asset availability by managing the effort using availability importance measures of each component. This analysis will also be studying the criticality of the asset for continuous improvement

The main objectives of this study are:
1. To prioritize the lean tool to achieve lean maintenance.
2. To predict upcoming failure events for each asset by using reliability analysis.
3. To develop a decision diagram and select an appropriate maintenance strategy for each asset by using reliability analysis and equipment criticality analysis.

The Limitation of the Study-

The limitations of the manuscript are given below, which are
1. Only the repairable assets are analyzed.
2. A limited number of failure data are available for the analyzed assets.
3. Data censoring and truncation are not considered.

2 Literature Review

2.1 Lean Maintenance

Maintenance, a significant function, helps an organization for achieving its strategic objectives. It serves the production facility with a guarantee of high productivity. Several maintenances have been introduced to meet specific maintenance needs. Integrating lean tools into maintenance functions can improve maintenance efficiency resulting in increasing reliability, safety, quality, and availability of equipment's production. Maintenance constitutes a significant share of operating costs in the industry. They proposed a road map to use lean thinking in maintenance functions [5]. Eight types of wastes, a scheme of lean maintenance practices and maintenance, and value stream mapping, were the scope of their work. To collect the recent maintenance philosophies and functions, lean tools, and principles in maintenance, they conducted an exhaustive literature review. Lean maintenance philosophy was driven for thriving maintenance efficiency in Thermoelectric Power Plants. The experience gathered from their approach was presented in two projects in that thermoelectric power plants. The lean techniques were constructed using a previously developed decision-making process in which the variation of the criteria was diverse that applied the Fuzzy AHP methodology to perform diagnosis and prescription tasks. This procedure permitted the application of the most appropriate lean tools to solve deficiencies in maintenance tasks. The results indicated that the maintenance function might be made more efficient and lean by using a lean technique [6]. A framework was provided to detect and calculate the usefulness of the maintenance policy embedded in the lean thinking approach for ratings of the various components of the maintenance department. DEMATEL layout on maintenance strategy was used as a guideline to develop the framework [7].

2.2 Quality Function Deployment (QFD)

The method of QFD was first exhibited in 1966 in Japan to transform the customer requirements into engineering requirements of a product. QFD is composed of two fundamental parts that are applied to the design process. A case was carried out a case study in the canning industry by relating lean attributes with lean enablers. They employed QFD to determine key LEs to enhance the leanness of the food chain. To deal with linguistic judgments needed in QFD, they used Fuzzy logic. An illustration of the practicality of this approach was exemplified with the help of a case study [8]. An approach was developed to identify the most suited enablers to be implemented by linking agile attributes and agile enablers. The approach was dependent on the quality function deployment (QFD) methodology, especially on the house of quality (HOQ). Fuzzy logic was used to transform linguistic judgments [3].

2.3 Analytic Hierarchy Approach

AHP, a structured technique, is a tool for analyzing complicated decisions with the help of mathematics and psychology. It is widely used throughout the world for prioritizing complex decisions. It provides a framework for constructing decision problems and quantifying their elements. A decision-making approach, AHP was first developed by Thomas L. Saaty. Detailed literature was provided to review versatile applications of AHP highlighting how broadly the process had been used. The study showed that AHP had been used in engineering, study, government, industry, and so on [9]. A brand-new procedure was proposed for rank preservation based on the judgment matrix consistency [4].

2.4 QFD-AHP Approach

The combined QFD-AHP approach is a useful tool for the selection and prioritization of organizational objectives. It can be extensively used in the maintenance context for selecting the appropriate lean tools and comparing them. It facilitates the acceptance of the decision-making process that provides a suitable option to select. A combined AHP-QFD was used for analyzing decision alternatives for a facility location problem rather than using a standalone AHP approach [10]. QFD-AHP method was applied for a new facility location problem where AHP was used to evaluate the relative importance of every location requirement. QFD-AHP approach was applied for the evaluation of different hardware of a mobile station. It was found that the QFD-AHP approach is better than the quality or price ranking method [2]. Many instances had provided where the QFD-AHP had been used successfully such as improving the quality, project selection, determining the composition, and also in new product development [11]. Quality Function Deployment (QFD) and Analytical Hierarchy Process (AHP) was used to enhance the decision-making processes in the maintenance function [1]. Before this, the approach was rarely used in lean thinking, especially in a maintenance environment. Their work enriched the application of this approach by using it to determine the importance of ME and how they were related to lean thinking. A survey was conducted on a maintenance department in the railway environment. The output of their effort resulted in a group of prioritized lean tools addressing a group of prioritized maintenance excellence.

2.5 Reliability Analysis

Among all other statistical models, the Weibull distribution and Crow-Army Material Systems Analysis Activity (AMSAA) are applied to prophesy the failure events of a component or an asset. The Weibull distribution is a strong tool for single mode failure whereas the Crow-AMSAA works well with the mixed failure modes. Two analyses (Weibull distribution and NHPP) are compared in this paper. These are applied to examine the cable joint failures. The methods of applying models to investigate the data of failure and to forecast upcoming failures were discussed in the preliminary section of their research. The data were collected from a local power supply company and included 16 failures and 1126 suspensions. This outcome of this manuscript claimed that the outcome of the Weibull distribution is more reliable [12]. NHPP was employed to forecast the failures of the upcoming future by using Microsoft Excel. The outcome of the study concluded that this template assisted a user to know about the upcoming degradation events that result in an increase in MTBF by adopting the correct action timely. A case study was conducted in this manuscript to illustrate the function of NHPP plots for centrifugal pumps using MS Excel. The outcome depicted that failure events for the next could be calculated successfully [13]. The Weibull and Crow-AMSAA model are statistical models used extensively in reliability analysis. The two models were compared and used in their work for the analysis of the cable failure data obtaining the prediction of the failures in the future. This study concluded that the outcome of the Weibull model gives a more reliable outcome than the Weibull and NHPP model whereas the amount of failure data is small [14].

2.6 Maintenance Strategy

A reliability-based case study was carried out in a crushing plant. The Weibull ++ was used to estimate the parameter. The failure pattern was analyzed for the improvement of the machine. A reliability-based maintenance policy was developed. The study indicated that the analysis of reliability plays a significant role in deciding on maintenance policy. A maintenance schedule was developed. They identified the characteristics of the parameter of the asset. They also suggested a maintenance policy [3]. The Distribution feeder was prioritized by a new model for RCM. They presented a reliability index model in their manuscript. This was done by determining critical components for deciding the asset performance. For the enhancement of cost-effectiveness. A Maintenance schedule was proposed for the offshore wind asset. They determined optimal individuals and grouped various maintenance schedules and various parameters were considered for this purpose [15]. A maintenance policy was selected policy by applying a fuzzy ANP approach [16].

3 Methodology

The methodology started with the analysis of the QFD-AHP approach for prioritizing the lean tool, then reliability analysis was performed on five assets discussed in the analysis section. It began with a questionnaire which was the foundation of our study. A flow chart is given in Fig. 1.

3.1 Prepare a Survey Question based on Maintenance Excellence Criteria

A survey question is prepared based on maintenance excellence criteria [1]. Maintenance excellence criteria are listed in the analysis section. This qualitative questionnaire consists of 10 questions. Each question has 5 options and these are excellent, good, average, poor, and bad (See Appendix A). The results of the survey are used to compare ME.

3.2 Rank Lean Tool for Maintenance using QFD-AHP

Maintenance lean tools are listed in the next section based on the literature survey. A relationship matrix was developed by the ME and a lean tool by the QFD approach. A rating was given to each relation between ME and the lean tool. The Analytic hierarchy approach was used to determine the importance rating of each ME. The detailed QFD–AHP approach is described in the analysis section. A flow chart of the QFD–AHP approach is given in Fig. 2.

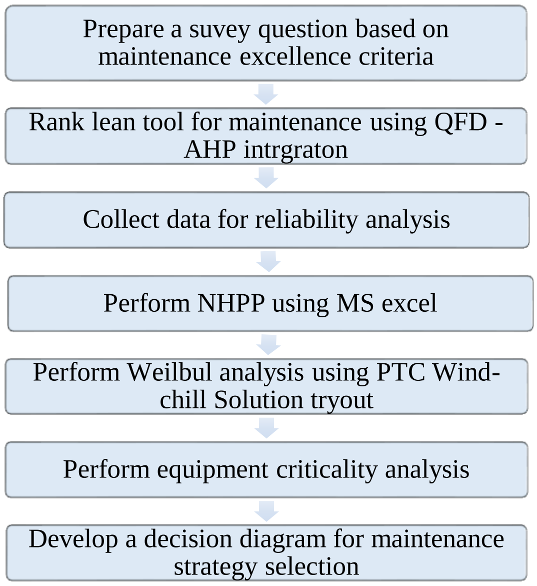


Fig. 1 Methodology of the study.

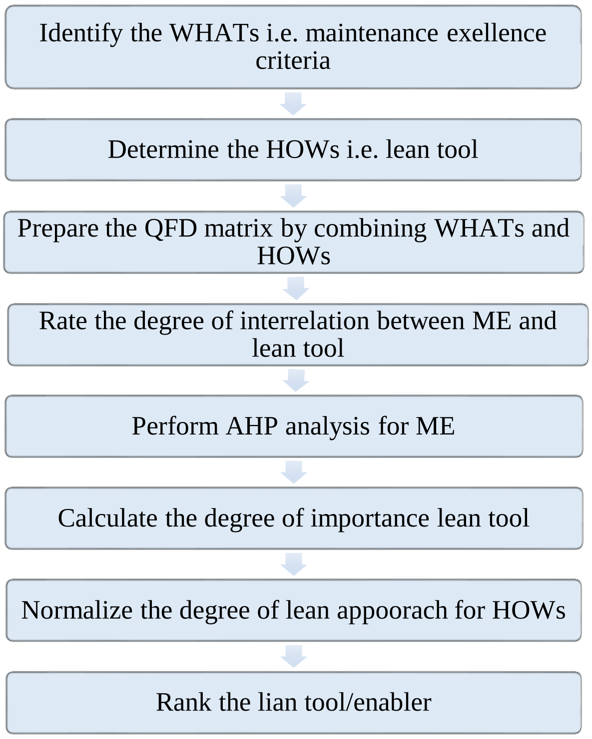


Fig. 2 An integration of QFD-AHP analysis

3.3 Collect Data for Reliability Analysis

After performing QFD–AHP analysis, reliability analysis was performed to measure the asset's availability and reliability. Data was gathered from the SIGMA shipyard. The data was collected for 10 assets. These were the air compressor machine, 500-ton press machine, overhead crane machine, VDF lathe machine, roller machine, planer machine, shaper machine, mixer machine, mixer machine, bearing machine, and paramak generator which were under breakdown maintenance. The date of failure and mean time to repair (MMTR) were collected from the logbook. Due to the lack of data, the reliability analysis was performed on five assets which are an air compressor machine, 500 press machine, overhead crane machine, VDF lathe machine, and roller machine. The historical data on those machines are given in Appendix B.

3.4 Perform NHPP analysis

NHPP analysis was performed to predict future failure events. Microsoft Excel was used for this purpose. In detailed analysis is described in a later section.

3.5 Perform Weibull Analysis

Weibull analysis was performed to determine in which state of the life cycle of equipment when failure has occurred. The results of this study were useful to choose the appropriate strategy for maintenance. The Weibull parameter was determined by the PTC Wind-chill Quality Solutions 11.0. This analysis is also described in a later section.

3.6 Perform Equipment Criticality Analysis

Equipment criticality analysis was performed to determine to what extent the equipment was critical in terms of production, safety, cost, and availability measures.

3.7 Develop a Conceptual Model for Maintenance Strategy Selection

A developed conceptual model was modified to select an appropriate maintenance strategy for each asset. This model was developed by the Weibull parameter and equipment criticality.

4 Data Analysis

This study was started with a survey in the machine shop of the SIMGA1 shipyard. A survey questionnaire was prepared based on maintenance excellence criteria [1]. This qualitative questionnaire has 10 questions. Each question has 5 options and these are excellent, good, average, poor, and bad (See Appendix A). The response to that questionnaire was collected from the experts of the machine shop of the shipyard.

Maintenance Excellence criteria: Step 1 was to define ME for the asset. By the theoretical evidence, the criteria for ME were approved. Then AHP had been employed to rank the ME. The list of ME selected for the study is given below -.

1. Spare Parts and Material Availability(SP)
2. Performance Indicators(KPI)
3. Policy and Strategy(PS)
4. Comprehensive Work Orders(CWO)
5. Organization clean up and tiding of work field areas(OCT)
6. Reduction in intervention number(RIN)
7. Reduction in process variability(RPV)
8. Implementation of preventive maintenance(PM)
9. Continuous controlling and monitoring of procedure and improving efficiency(CMPANDIE)

Lean tool selection: Step 2 was to extract a lean tool that fits maintenance standards. These lean tools were recognized from the literature. These are the input of the QFD diagram. The list of lean tool for maintenance obtained from the paper are given below:

1. Total productive management
2. Standard operating procedure

3. Single-minute exchange dice
4. Kaizen
5. Kanban
6. 5S
7. VSM (value stream mapping)
8. Key performance indicator
9. Statistical process control
10. Visual management

Rank lean tool for maintenance using QFD – AHP: The maintenance lean tool was listed based on the literature survey. A relationship matrix was developed by the ME and lean tool. AHP was used to determine the importance rating of each ME. Then the importance weighting was multiplied by rating to determine the importance degree of the lean approach. A relation matrix was developed where weak relationships, medium, and strong relationships were indicated by a white circle, rectangle, and black circle. The weak, medium and strong relationships were quantified by 1, 3, and 9 respectively. Using AHP analysis, the improvement weight of each maintenance excellence was calculated. The final QFD-AHP analysis is shown in Table 1 and the consistency ratio was also calculated for the validation of the AHP analysis shown in
Table 2.

Table 1 Final ranking matrix by QFD-AHP analysis

○ Weak relationship □ Medium relationship ● Strong relationship	TPM (Total Productive Maintenance)	Standard Operating Procedure	SMED (Single minute exchange dice)	Kaizen	Kanban	5S	VSM (Value Stream mapping)	KPI (Key Performance Indicator)	SPC (statistical Quality Control)	Poka-yoke	Visual management	Improvement weight
Spare parts and Material availability	□			○	●	□						0.046
Performance indicators				●		□		●		□	●	0.031
Policy and strategy				□		●		●			●	0.078
Comprehensive work orders				○	□	●					□	0.118
Organization clean up and tiding of work field areas	□					●	○					0.387
Reduction in intervention number	□		●		□			●		□		0.119
Reduction in process variability	□	●							●			0.126
Implementation of preventive maintenance	●	●						□				0.024
Continuous controlling and monitoring of procedures and enhancing efficiency			●			○	□	□	□	□		0.07
Importance degree of the lean approach	1.87	1.35	1.70	.68	1.13	5.5	.59	2.33	1.34	0.66	1.14	=18.3
Normalized importance degree	0.10	0.07	0.09	0.03	0.06	0.3	0.03	0.12	0.07	0.04	0.06	
Rank	3	5	4	8	6	1	8	2	5	7	6	

Table 2 Consistency ratio calculation

	SP	KPI	PS	CWO	OCT	RIN	RRV	PM	CMPANDIE	**Priority weight**
SP	1	1/3	1/3	1	1/7	1	1	3	1	0.050
KPI	3	1	1	1/3	1/7	1/3	1/3	3	1/3	0.031
PS	3	1	1	1/3	1/7	1/3	1/3	3	3	0.078
CWO	1	3	3	1	1/3	1	1	3	1	0.118
OCT	7	7	7	3	1	5	3	7	3	0.387
RIN	1	3	3	1	1/5	1	1	5	1	0.119
RPV	1	3	3	1	1/3	1	1	5	1	0.126
PM	1/3	1/3	1/3	1/3	1/7	1/5	1/5	1	1/5	0.024
CMPAN DIE	1	3	1/3	1	1/3	1	1	5	1	0.070
Total	18 1/3	21 2/3	19	9	2 7/9	10 6/7	8 7/8	35	11 1/2	
SUM PV	1	2/3	1 1/2	1	1	1 2/7	1 1/9	5/6	4/5	
λ_{max}	9 1/5									
CI	0.03									
CR	0.02									

Table 3 Data input section and result table for the overhead crane machine

Overhead Crane Machine								
Result Section			**Data Input Section**					
Input data			No of failures	Time between failure	Cum. Failure time	Cum MTBF	ln (Cum. Failure Time)	MTTR
No. of failure (n)		10						
End of observation time (T)		1134 days	1	145	145	145.00	4.98	6
Availability		0.9399	2	130	275	137.50	5.62	7
Sum ln(Cum. Failure time)		63.51	3	80	355	118.33	5.87	8.5
Estimated parameters			4	169	524	131.00	6.26	8
Slope (β)		1.46610	5	191	715	143.00	6.57	6
Lambda (λ)		0.000332/day	6	91	806	134.33	6.69	5
Calculations			7	79	885	126.43	6.79	5
Failure rate (instantaneous)	1200 days	0.0133	8	58	943	117.88	6.85	4
Instantaneous MTBF, 1/u(t)		75.34	9	86	1029	114.33	6.94	4
Cumulative failure N (t)	1200 days	10.865	10	16	1045	104.50	6.95	7
Cum. failure rate		0.0091	11	83	1128	102.55	7.03	3
Cum MTBF		110.449	12	70	1198	95.73	7.09	5
Prediction to next failure			13	43	1241	87.82	7.12	6
Next failure occurrence (t)	n=11	1210.17 days	14	15	1256	81.91	7.14	3
Time to next failure (t)		76.1696 days	15	19	1275	68.27	7.15	4
						Sum	99.04	81.5

4.1 NHPP Analysis

NHPP modeling was performed to predict future failure events. Microsoft Excel was used for this purpose. NHPP plots were illustrated with the help of various software like Fulton 2006, WIN smith software, Blockish, and Weibull. The cost of this software is pretty high and very difficult to use. Microsoft Excel was very advantageous and common software used by nearly every organization for various purposes. A reliability model constructed using MS excel was simple to use and understand. It was a very simple way to predict upcoming failures with the help of this software. By this template, cumulative failure time was entered, and then it was automatically to find out what is the value of β. Some equations were used to determine the failure rate and the slope for the maximum likelihood equation:

For failure terminated test,

$$\beta = \frac{n}{(n-1)\, ln\, Tn - \sum_{i=1}^{n} ln\, Ti} \tag{1}$$

For failure terminated test,

$$\beta = \frac{n}{n\, ln\, Tn - \sum_{i=1}^{n} ln\, Ti} \tag{2}$$

$$\lambda = \frac{n}{T} \qquad \textit{(Hence, T=total test time)} \tag{3}$$

From the λ and β values, the instantaneous failure rate can be calculated by Eq. (4). The Instantaneous failure rate,

$$\rho(t) = t^{(\beta-1)}\lambda\beta \tag{4}$$

The cumulative failure rate,

$$c(t) = t^{\beta-1}\,\lambda \tag{5}$$

The prediction of failure events,

$$N = \left(t_n{}^{\beta}\right) * \lambda \tag{6}$$

The events expected,

$$N = n\text{- actual failures number} \tag{7}$$

Table 3 shows the data input and result section of the air compressor machine. It was the first part in which cumulative failure time was given in a yellow shaded area. The other parameters were calculated by the use of a simple arithmetic equation. The result section is depicted in Table 3. After entering the observation, λ and β were calculated by using Eqs. (2) and (3). By Eq. (6), the next failure occurrence time was calculated. The instantaneous failure and cumulative failure times were calculated by this template at the given time. As in Table 3, the instantaneous failure rate was 0.0133 at a time 1210.17 days later. The slope (β) and failure rate (λ) of the rest of the machine were calculated similarly. The data input section with the result section for the rest of the machines (Air compressor machine, 500-ton press machine, VDF lathe machine, and Roller machine) are shown in Table B2-Table B5 accordingly.

4.2 Weibull Analysis

Weibull analysis was performed to determine the stage of the life cycle of mentioned assets in which failure occurred. The results of this study were useful to choose the appropriate strategy for maintenance. The Weibull parameter was determined by the PTC wind-chill solution tryout 11.

Reliability can be determined by the following equations

$$\text{Reliability, R (t)} = e^{(-\frac{t}{\eta})^{\beta}} \tag{8}$$

In two-parameter Weibull distribution, the failure rate function is described as the number of failures per unit of time. It is given as.

$$\text{Failure rate, } \lambda(t) = \frac{\beta}{\lambda} \times \left(\frac{t}{\lambda}\right)^{(\beta-1)} \tag{9}$$

The two-parameter Weibull probability density function f (t) is given as:

$$PDF = f(t) = \frac{\beta}{\eta} * \left(\frac{t}{\eta}\right)^{\beta-1} * e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{10}$$

$$CDF = F(t) = 1 - e^{-(\frac{t}{\eta})^{\beta}} \tag{11}$$

The mean time of degradation-free operation till a failure event can be defined as MTTF for non-repairable systems and MTBF for the repairable system. The MTTF or MTBF of the Weibull PDF is given as

$$MTBF = E(T) = \Upsilon + \eta * \Gamma(\frac{1}{\beta} + 1) \tag{12}$$

Using the wind-chill quality solution 10.1 tryout software, the β, η, ρ is obtained and given in Table 4.

4.3 Equipment Criticality Analysis

Equipment criticality analysis was performed to determine to what extent the equipment was critical in the perspective of production, safety, cost, and availability of the asset. Criticality analysis is a tool that may be used to evaluate the impact of equipment failures on organizational performance. Three ratings (1, 2, and 3) were used where 1 indicates less impact, 2 indicates more impact and 3 indicates a strong impact on organizational performance. Ratings were given by the expert of that machine shown in Table 5. Hence, the equipment criticality for the overhead crane machine, 500-ton press machine, air compressor machine, VDF lathe machine, and roller machine is determined and given in Table 5.

The equation for calculating EC is given below

$$EC = (30P + 30S + 25A + 15V)/3 \tag{13}$$

where EC is the equipment criticality.

5 Maintenance Strategy Selection

There were several objectives of this study. But one of the objectives was to trace a maintenance technique. This might be manifested with the help of reliability analysis. Equipment criticality was another measure that was included in the decision diagram along with reliability measures. If equipment criticality was less than 40, then fixed maintenance was used according to the decision diagram. Because the cost of the fixed maintenance was less. If equipment criticality was less than or equal to 60% and 80%, then corrective-based maintenance and major overhaul (MHO) were selected respectively. Condition-based maintenance was a very costly maintenance plan among all the maintenance plans. A decision diagram was developed by using the value of β [3]. This decision diagram is modified by combining the value of equipment criticality. This decision diagram is shown in Fig. 3.

Table 4 Weibull analysis results

Machine Name	β	η	MTBF, days	Reliability, R (t)	Cumulative density function, CDF	Failure rate, λ (t)	Probability density function, PDF
Overhead crane machine	1.35	102.78	94.231	41.09%	49.00%	0.0127/day	0.005207
500-ton press machine	1.21	41.29	42.23	35.80%	64.20%	0.029 /day	0.01005
Air compressor machine	1.39	69.36	70.36	36.81%	63.10%	0.020/day	0 .0073
VDF lathe machine	3.16	86.23	87.12	35.6%	64.44%	0.037/day	0.0133
Roller machine	2.19	81.27	82.16	35.9%	64.10%	0.027/day	0.0098

Table 5 Equipment Criticality Analysis

Machine name	Impact on production(P)	Impact on safety(S)	Availability of standby (A)	Cost(V)	Machine's Criticality
Overhead crane machine	3	1	3	3	80.00%
500-ton press machine	2	1	3	2	65.00%
Air compressor machine	3	1	2	3	71.67%
VDF lathe machine	1	1	1	1	33.33%
Roller machine	1	1	1	1	33.33%

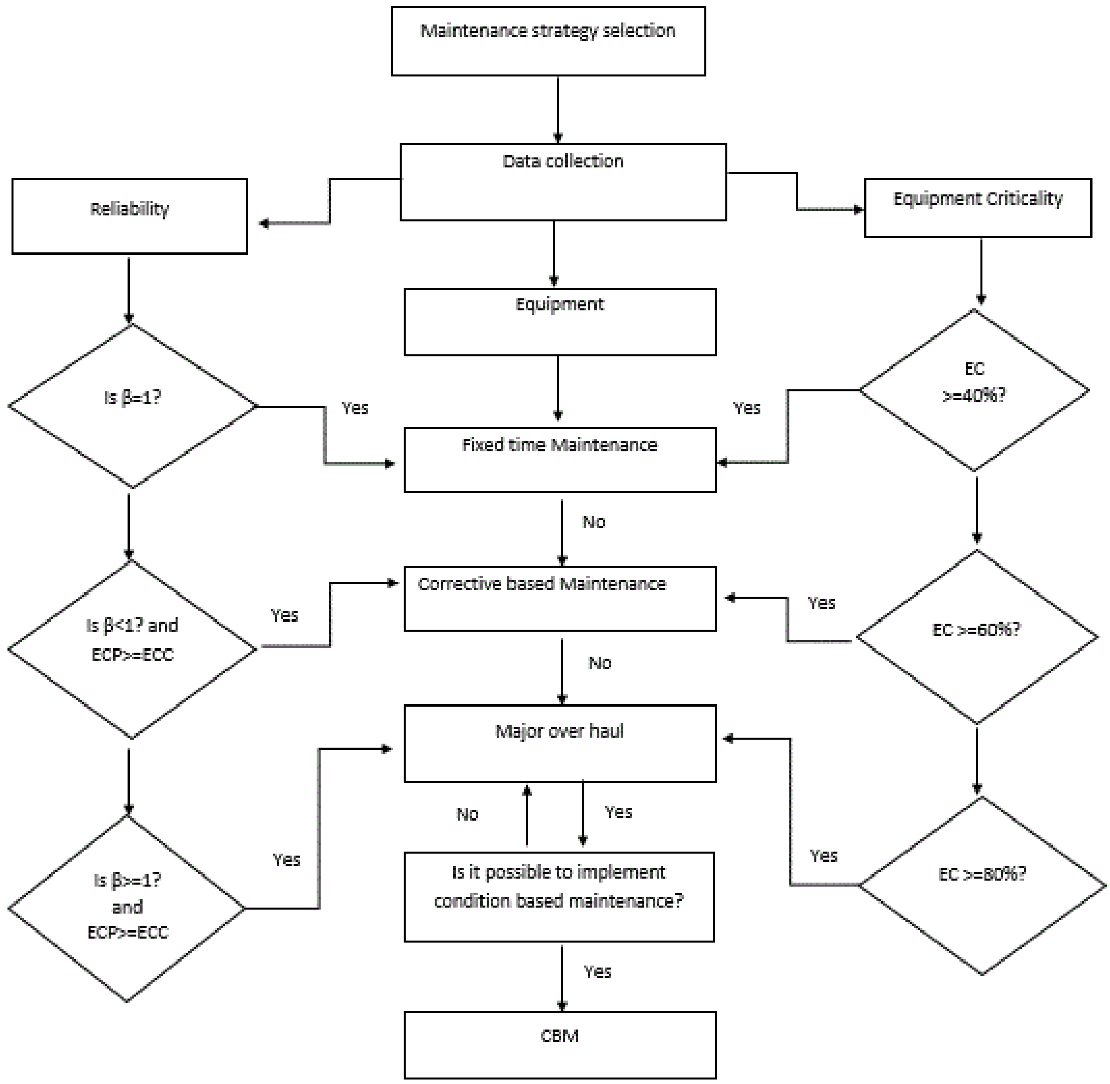


Fig. 3 A decision diagram

Hence, the value of β obtained from the Weibull analysis was greater than 1, so it was high time to replace the old one with the new one. It was also considered that the cost of equipment correction was greater than equipment preventive cost. As a result, a major overhaul was selected for all the assets. But according to the equipment criticality, a major overhaul was selected for the overhead crane machine 500-ton press machine, and air compressor machine but FTM is selected for the VDF lathe machine and roller machine. As equipment criticality was less and the cost of fixed time maintenance was less, it was the best maintenance strategy for the VDF lathe machine and roller machine.

6 Results and Discussion

The lean tools were ranked based on descending importance rating derived from the combined QFD-AHP analysis which is represented in Fig. 4. The results of NHPP analysis and Weibull analysis are given in Table 6 and Table 7 respectively. The maintenance strategy of each machine is shown in Table 8.

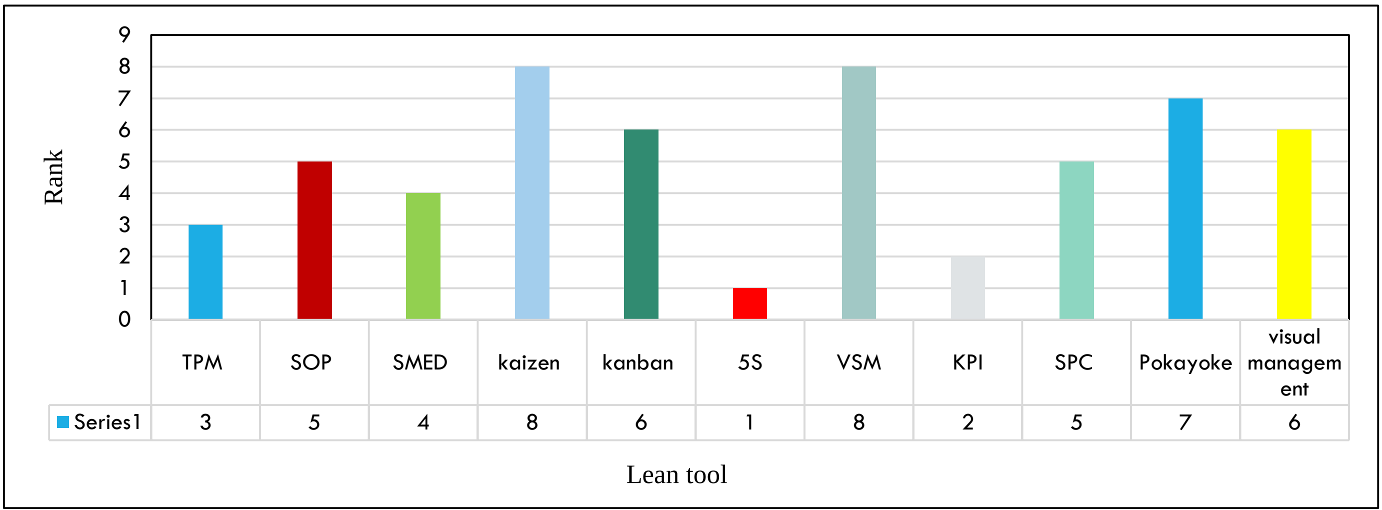


Fig. 4 Rank vs. Lean tool

Table 6 Results of the NHPP analysis

Machine no	Machine name	β	Prediction of next failure(day)	Time to failure (historical data)
1	Overhead crane machine	1.46	1210.17	1128
2	500-ton press machine	1.43	328.30	343
3	Air compressor machine	1.77	598.45	628
4	VDF lathe machine	1.59	588.32	615
5	Roller machine	1.194	638.95	740

Table 7 Results of the Weibull analysis

Machine no.	Machine name	β	λ/day	Reliability (%)
1	Overhead crane machine	1.35	0.012	41.1
2	500-ton press machine	1.21	0.039	35.8
3	Air compressor machine	1.39	0.020	36.81
4	VDF lathe machine	3.16	0.037	35.6
5	Roller machine	2.18	0.027	25.9

Table 8 Maintenance strategy of each machine

Machine name	MTBF(days)	MMTR(days)	Criticality score (%)	Maintenance strategy
Overhead crane machine	102.78	81.5	80	MOH
500-ton press machine	41.29	83.5	65	MOH
Air compressor machine	69.36	88.7	71.67	MOH
VDF lathe machine	86.23	60.5	33.33	FTM
Roller machine	81.27	50	33.33	FTM

Table 9 Importance of weighting of the ME

Importance weighting (c)	0.046	0.031	0.078	0.118	0.387	0.119	0.126	0.024	0.07

6.1 Discussion

The combined QFD –AHP was used to rank the lean maintenance tool. A survey was conducted based on ME. These survey results were used to compare the two ME and develop a pairwise comparison matrix. The important weighting of ME is listed in Table 9. Consistency ratio was calculated and from the Saaty table, m is equal to 11 for nine 9 ME criteria. The result of the consistency ratio is 0.023 which was less than 0.1. So, it was indicated that the result of the QFD –AHP approach was quite acceptable. The rank obtained from the QFD –AHP analysis shown in Fig. 4 will guide the way to which lean tool is useful for the shipyard and what tool was used to enhance the performance of the asset.

The historical failure date of the machine was collected from the maintenance logbook of the SIGMA shipyard. The machine was under a breakdown maintenance strategy and these machine data were collected from the logbook for analyzing the reliability study. The machines selected were the overhead crane machine, air compressor machine, 500-ton press machine, VDF lathe machine, and roller machine. After collecting the failure data, the time to failure was calculated. Then the cumulative time and cumulative MTBF were determined. Then NHPP modeling by Microsoft excel was used for calculating the slope (β) and failure rate (λ) of each machine. The instantaneous failure and the instantaneous failure rate were determined. The value of beta (β) and lambda (λ) from NHPP and Weibull analysis are listed in Table 6 and Table 7 respectively. Cumulative no of failure vs. cumulative failure time was plotted in Fig. 5. From this plotting, it could be easily shown that the failure rate was increasing. Moreover, it might be easily understood by the value of slope (β). The plot was drawn using historical data and predicted data for the next failure obtained from NHPP in Microsoft excel. Another plot was drawn by using the failure data of this machine. The amount of failure data was used for overhead crane m/c, 500-ton press machine, air compressor m/c, VDF lathe m/c, and roller m/c which were 11, 10, 9, 8, 10 accordingly. The result that got from the reliability model is correct or not, this may be verified by the historical data. The next failure event for the overhead crane machine was expected 1210 days later by the calculation of the historical data. In reality, the failure occurred 1128 days later which indicated that the error was minor. Whereas the value of β was larger than 1, which confirms that the failure rate of the machine was increasing.

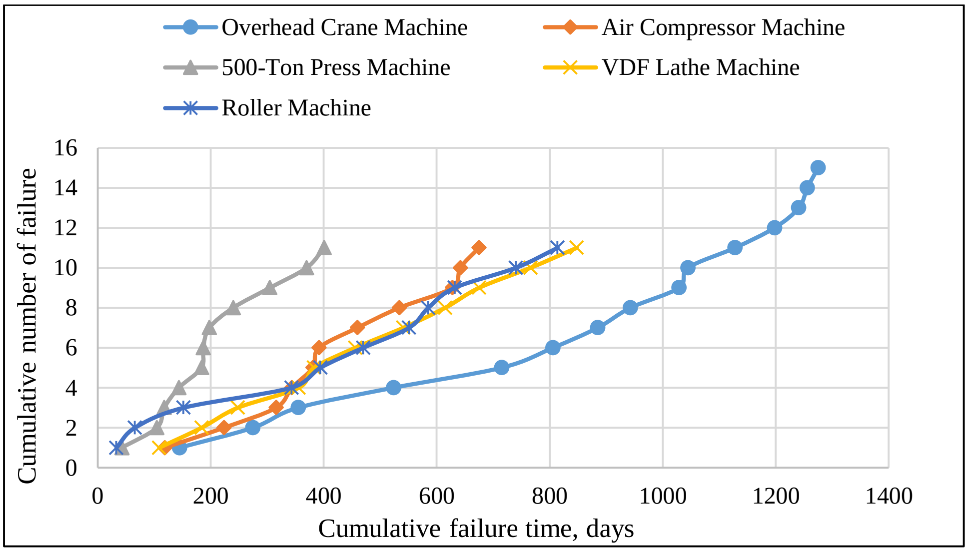


Fig. 5 Cumulative failure time vs. Cumulative no of failure

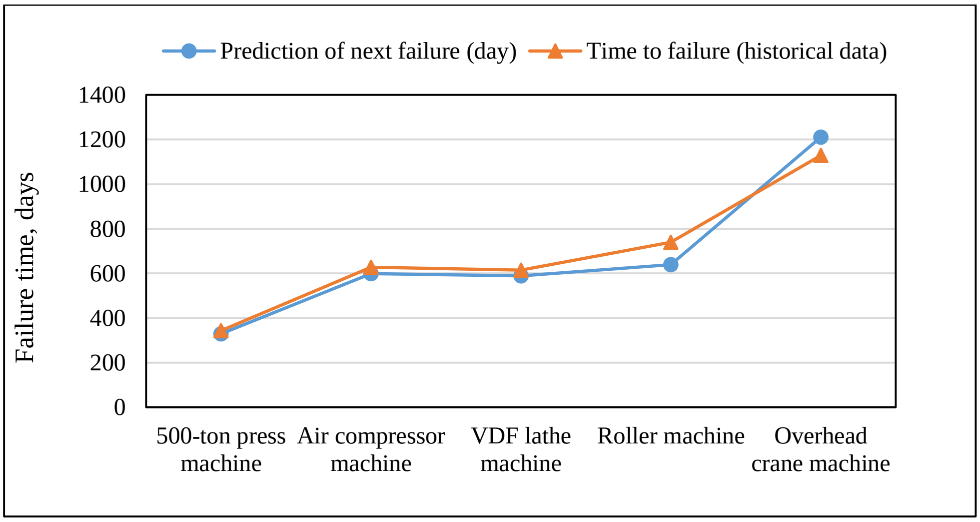
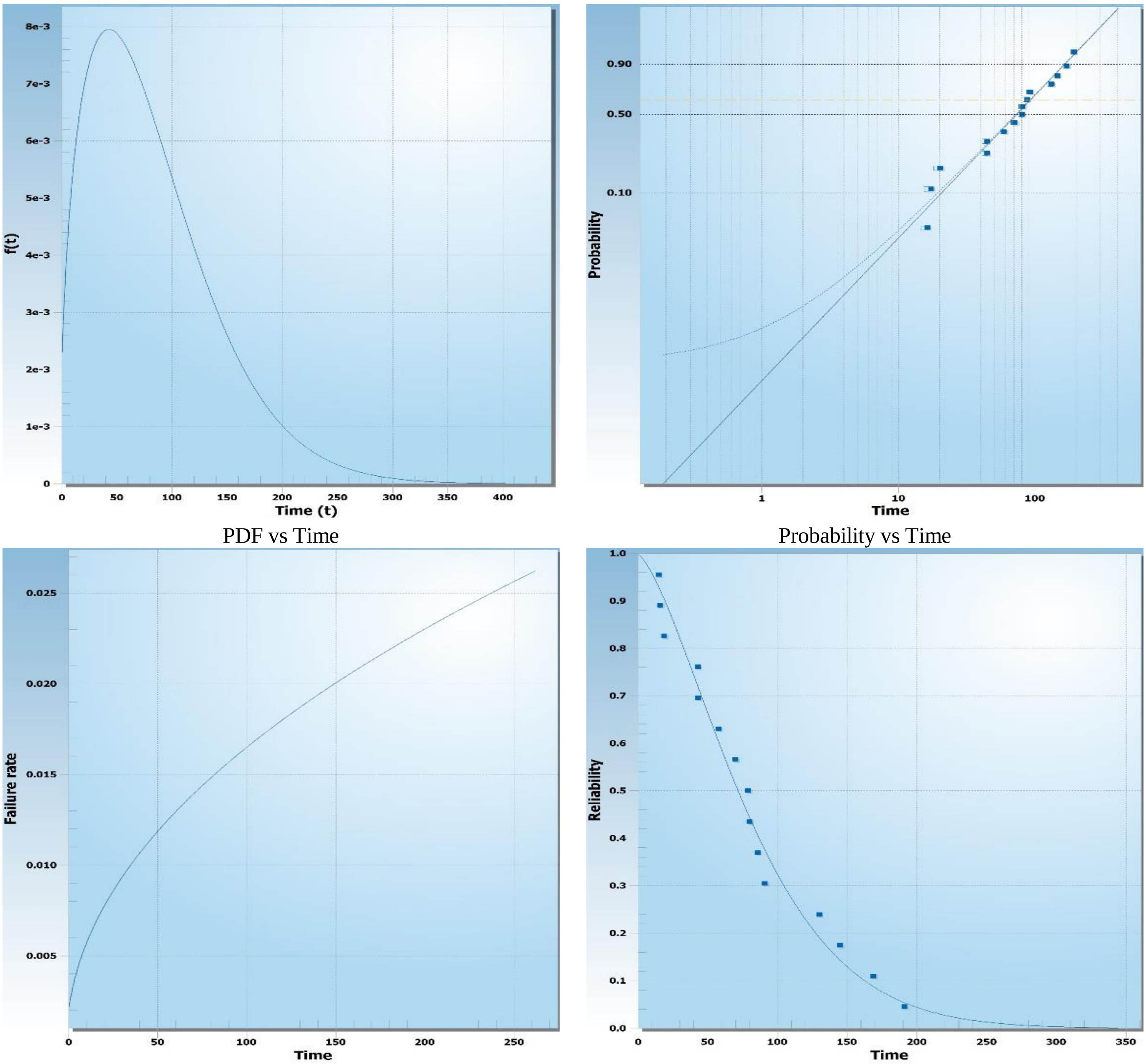


Fig. 6 Machine vs. predicted failure data

Another plot was drawn in Fig. 6 by using historical failure data and predicted failure data. If the prediction line is analyzed thoroughly in Fig. 6, it can be seen that the prediction data point were very close to the actual data points of the failure events. In the same way, the next failure air compressor machine was expected 598.45 days later and the actual failure happened 401 days later. Hence, the value of beta was larger than 1 so the rate of degradation was increased. The next failure events for the 500-ton lathe machine, VDF lathe machine, and roller machine were expected at 328, 588, and 638 days later accordingly and the actual time to failure of this machine was 343, 615, and 740 days later respectively. For the 500-ton press machine, the deviation between the prediction of failure and actual failure was more. This might be occurred due to missing data. Because the collected data of SIGMA shipyard are not computerized. This data was collected from the maintenance logbook so it was possible to miss out on recording any failure data. The graph shown in Fig. 7 was obtained using the "PTC Wind-chill Quality Solutions 11.0 Tryout" for an overhead crane. For Weibull results for the overhead crane machine shown in Fig. 7, the slope of the shape parameter is 1.35 which represents the wear-out hazard rate and it followed the Rayleigh distribution. Replacement of schedules would be effective for the overhead crane machine. The reliability curve decreases moderately and this assent was entering the wear-out phase. The variation of data was less as shown in the figure of the CDF plot so it asserts the low variation of the failure time. The characteristics of life and mean time to failure is 102.78 days.



PDF vs Time — Probability vs Time

Failure Rate vs Time — Reliability vs Time

Fig. 7 Weibull result for overhead crane machine (β = 1.4848; η = 93.4681; γ = -1.3293; ρ = 0.9762; ρ^2 = 0.9529).

Weibull results for the 500-ton press machine and air compressor machine are shown in Fig. B1 and Fig. B2 in Appendix B accordingly. The value of the slope was 1.21 and 1.39 respectively. As β>1, the hazard rate was increased and it followed the Rayleigh distribution also. From the CDF plot, it was concluded that the variation of failure time was more than the overhead crane machine. The characteristics of the life of the machine were 41.29 and 69.36 days respectively. The percentage of failure at the end of the observation time is 64.2% and 63.9% accordingly.

Weibull results for the VDF machine are shown in Fig. B3 in Appendix B. The value of the slope is 3.16. As β>1, the hazard rate was increasing and the graph of the PDF looked like a normal distribution. The variation of data was moderate. The reliability with time was decreasing slowly. The mean lifetime of the machine and cumulative density function was 87.12 days and 64.4% accordingly.

Weibull results for the Roller machine are shown in Fig. B4 in Appendix B. The value of the slope was 2.18. As β>1, the hazard rate was increasing and the equipment's entered the early wear phase and the graph of the PDF followed the Rayleigh distribution. The failure data were more scattered than other equipment. The reliability with time was decreasing slowly. The mean lifetime of the machine was 82.16 days and the cumulative density function was 64.1%. The goodness of data fit was 89%.

Reliability parameter (β) from the Weibull analysis and availability and machine criticality were considered to select the appropriate maintenance strategy. Hence, the value of β obtained from the Weibull analysis was greater than 1 so it was high time to replace the old one with the new one. It was also considered that the cost for repair was greater than the equipment preventive cost. As a result, a major overhaul was selected for all the assets. But according to the equipment criticality, a major overhaul was selected for the overhead crane machine 500-ton press machine, and air compressor machine but FTM was selected for the VDF lathe machine and roller machine.

7 Conclusion

The implementation of lean tools and the selection of an effective maintenance strategy can make the maintenance function dynamic and effective. The study proposed appropriate lean tools to be implemented among ten (10) lean tools in the maintenance department of the SIGMA shipyard. 5S and KPI are the two lean tools having the maximum importance degree of 5.5 and 2.33 respectively. According to NHPP analysis and Weibull analyses, predicted next failure events (11th) were estimated after 76.16 days, 23.30 days, 38.45 days, 47.32 days, and 53.95 days respectively and the failure rate (β) was 1.35, 1.21, 1.39, 3.16, and 2.81 for Overhead crane machine, 500-ton press machine, Air compressor machine, VDF lathe machine, Roller machine accordingly. Based on the reliability analysis, a major overhaul was selected for the overhead crane machine 500-ton press machine, and air compressor machine. As equipment criticality and the cost of fixed maintenance were less, FTM was the best maintenance strategy for the VDF lathe machine and roller machine. The method employed in the study was used as a generalized method for various forms of repairable assets. The QFD-AHP approach employed in this study helps maintenance practitioners to prioritize the lean tool to achieve lean maintenance. NHPP modeling created by using excel can be used as a template for identifying upcoming failure events. A decision diagram is applied for choosing the best strategy that may be used as a decision model for any repairable asset. The decision conceptual model might be improved by adding maintenance costs. Reliability analysis can be investigated for the entire maintenance department as a whole.

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Appendix A

Maintenance excellence criteria survey for AHP Analysis

1. Spare parts availability:

Are the materials and parts ordered and delivered on time so as to avoid stock out during planned outs and during planned maintenance activities and emergency breakdowns?

2. Key performance indicator:

Do all key performance processes have KPIs and are these KPIs regularly reviewed for decision-making process?

3. Policy and strategy:

Are the current maintenance policies and strategies are well understood by all maintenance workers?

4. Comprehensive work order:

Are work orders and job cards containing clear comments that can be used for future reference?

5. Organization cleaning, tiding of work areas:

To what extent is the organization in ongoing efforts for cleaning and tiding work areas?

6. Reduction in intervention number:

To what extent is the organization engaged in ongoing effort to reduce breakdown of a machine?

6. Reduction in process variability:

To what extent are the current SAP systems helping the organization do its work more effectively?

7. Preventive maintenance implemented in the organization:

Is maintenance work generally complemented according to schedule?

8. Continuous monitoring of procedure and increasing efficiency:

To what extent is the organization engaged in ongoing effort to improve maintenance efficiency?

Five options for each questionnaire

- Excellent
- Good
- Average
- Poor
- Bad

Appendix B

Table B1 Data required for reliability analysis

Equipment no.	Equipment name	Failure date	Repair time (months)	Failure date	Repair time (months)
1.	Overhead crane machine	24.9.14	6	15.10.17	7
		02.05.15	7	1.11.17	3
		12.8.15	8.5	3.8.18	5
		02.11.15	8	24.3.18	6
		17.02.16	6	4.5.18	3
		21.05.16	5	17.5.18	4
		02.12.16	5	2.5.18	4
		03.02.17	4	12.6.18	4
		19.7.17	4		
2	500 ton press machine	30.1.17	7	14.08.17	5
		13.3.17	2	13.10.17	4
		11.5.17	12	5.12.17	8
		24.5.17	7	13.3.18	4
		20.6.17	5	15.4.18	5
		30.7.17	3	16.5.18	3
		03.08.17	6		
3	Air compressor machine	25.04.16	8.5	18.7.17	6
		24.10.16	8.5	06.10.17	8.2
		11.02.17	8.5	20.12.17	8.5
		13.05.17	16	24.03.18	8.5
		11.06.17	4	07.0618	6
		17.7.17	6	10.07.18	8.5
5	VDF lathe machine	29.02.16	5	25.04.17	4
		18.06.16	4	19.07.17	5.5
		03.08.16	6	3.10.17	7
		07.10.16	7	3.1.18	6
		15.01.17	4	4.4.18	6
		12.02.17	6	26.6.18	4
6	Roller machine	25.3.16	3	24.03.17	6
		28.04.16	4.5	15.06.17	3
		11.06.16	6	19.07.17	4.5
		07.09.16	6	05.09.17	3
		18.11.16	4.5	23.12.17	4.50
		08.01.17	5	07.03.18	4.50

Table B2 Data input section and result table for an air compressor machine

Air Compressor Machine

Result Section

Input data		
No. of failure (n)		8
End of observation time (T)		560 days
Availability		0.8839
Sum ln(Cum. failure time)		46.11
Estimated parameters		
Slope (β)		1.77
Lamda (λ)		0.000107/day
Calculations		
Failure rate (instantaneous)	1200 days	0.0267
Instantaneous MTBF, 1/u(t)		37.42
Cumulative failure N (t)	1200 days	9.041
Cum. failure rate		0.0151
Cum MTBF		66.362
Prediction to next failure		
Next failure occurrence (t)	n=11	598.45 days
Time to next failure (t)		38.45 days

Data Input Section

No of failures	Time between failure	Cum. Failure time	Cum. MTBF	ln (Cum. Failure Time)	MTTR
1	119	119	119.00	4.78	8.5
2	105	224	112.00	5.41	8.5
3	92	316	105.33	5.76	16.0
4	28	344	86.00	5.84	4.0
5	37	381	76.00	5.94	6.0
6	11	392	65.33	5.97	6.0
7	68	460	65.71	6.13	8.2
8	74	534	66.75	6.28	8.5
9	94	628	69.78	6.44	8.5
10	14	642	64.20	6.46	6.0
11	33	675	61.36	6.71	8.5
			Sum	65.53	88.7

Table B3 Data input section and result table for 500-ton press machine

500-Ton Press Machine

Result Section		
Input data		
No. of failure (n)		9
End of observation time (T)		305 days
Availability		0.8188687
Sum ln(Cum. failure time)		45.19
Estimated parameters		
Slope (β)		1.431036
Lamda (λ)		0.0025/day
Calculations		
Failure rate (instantaneous)	1200 days	0.0522545
Instantaneous MTBF, 1/u(t)		19.137111
Cumulative failure N (t)	1200 days	18.257578
Cum. failure rate		0.0365152
Cum MTBF		27.385888
Prediction to next failure		
Next failure occurrence (t)	n=11	328.30 days
Time to next failure (t)		23.30 days

Data Input Section						
No of failures	Time between failure	Cum. Failure time	Cum. MTBF	ln (Cum. Failure Time)	MTTR
1	43.00	43.00	43.00	3.76	7.00
2	62.00	105.00	52.50	4.65	2.00
3	13.00	118.00	39.33	4.77	12.00
4	26.00	144.00	36.00	4.97	7.00
5	40.00	184.00	36.80	5.21	5.00
6	3.00	187.00	31.17	5.23	3.00
7	11.00	198.00	28.29	5.29	6.00
8	42.00	240.00	30.00	5.48	5.00
9	65.00	305.00	33.89	5.72	4.00
10	65.00	370.00	37.00	5.91	8.00
11	31.00	401.00	36.45	5.99	4.00
			Sum	57.00	63.00

Table B4 Data input section and result table for VDF lathe machine

VDF Lathe Machine

Result Section		
Input data		
No. of failure (n)		7
End of observation time (T)		541 days
Availability		0.9334067
Sum ln(Cum. failure time)		39.66
Estimated parameters		
Slope (β)		1.59
Lamda (λ)		0.00031/day
Calculations		
Failure rate (instantaneous)	1200 days	0.0219
Instantaneous MTBF, 1/u(t)		45.64
Cumulative failure N (t)	1200 days	8.255
Cum. failure rate		0.0138
Cum MTBF		72.688
Prediction to next failure		
Next failure occurrence (t)	n=11	588.32 days
Time to next failure (t)		47.32 days

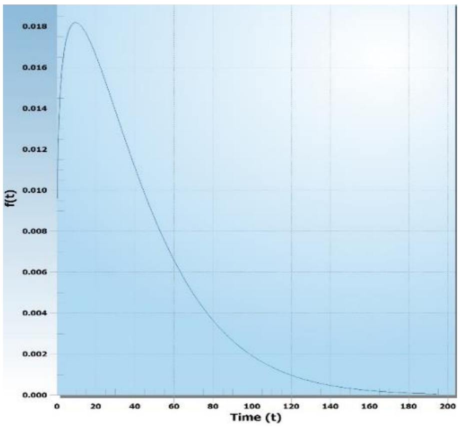
Data Input Section					
No of failures	Time between failure	Cum. Failure time	Cum MTBF	ln (Cum. Failure Time)	MTTR
1	109.00	109.00	109.00	4.69	5.00
2	75.00	184.00	92.00	5.21	4.00
3	64.00	248.00	82.67	5.51	6.00
4	108.00	356.00	89.00	5.87	7.00
5	27.00	383.00	76.60	5.95	4.00
6	73.00	456.00	76.00	6.12	6.00
7	85.00	541.00	77.29	6.29	4.00
8	74.00	615.00	76.88	6.42	5.50
9	60.00	675.00	75.00	6.51	7.00
10	91.00	766.00	76.60	6.64	6.00
11	82.00	848.00	77.09	6.74	6.00
Sum				65.98	60.50

Table B5 Data input section and result table for roller machine

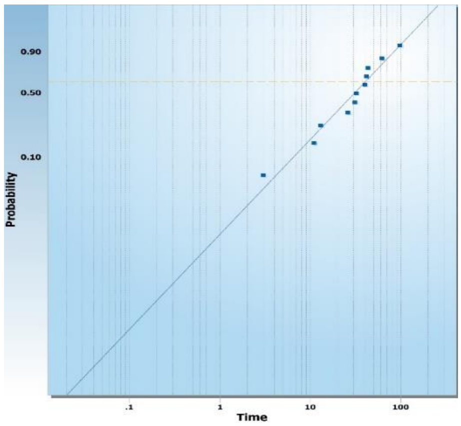
Roller Machine

Result Section		
Input data		
No. of failure (n)		8
End of observation time (T)		585 days
Availability		0.9421296
Sum ln(Cum. failure time)		49.81
Estimated parameters		
Slope (β)		1.19436
Lamda (λ)		0.004459/day
Calculations		
Failure rate (instantaneous)	1200 days	0.0195273
Instantaneous MTBF, 1/u(t)		51.210349
Cumulative failure N (t),	1200 days	13.079672
Cum. failure rate		0.0163496
Cum MTBF		61.163614
Prediction to next failure		
Next failure occurrence (t)	n=11	638.95 days
Time to next failure (t)		53.95days

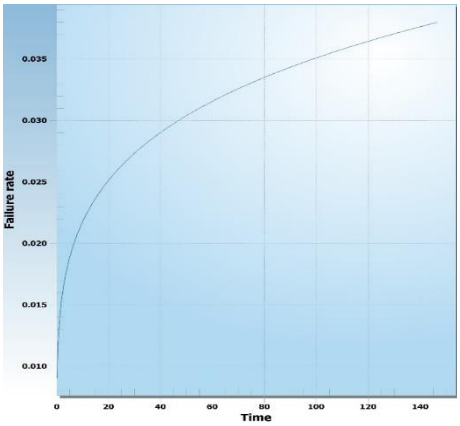
Data Input Section					
No of failures	Time between failure	Cum. Failure time	Cum MTBF	ln (Cum. Failure Time)	MTTR
1	33.00	33.00	33.00	3.50	3.00
2	33.00	66.00	33.00	4.19	4.50
3	86.00	152.00	50.67	5.02	6.00
4	191.00	343.00	85.75	5.84	6.00
5	51.00	394.00	78.80	5.98	4.50
6	76.00	470.00	78.33	6.15	5.00
7	81.00	551.00	78.71	6.31	6.00
8	34.00	585.00	73.13	6.37	3.00
9	47.00	632.00	70.22	6.45	4.50
10	108.00	740.00	74.00	6.61	3.00
11	74.00	814.00	74.00	6.70	4.50
			Sum	63.12	50.00



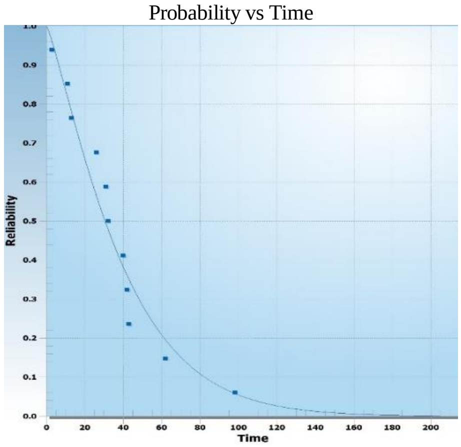
PDF vs Time



Probability vs Time

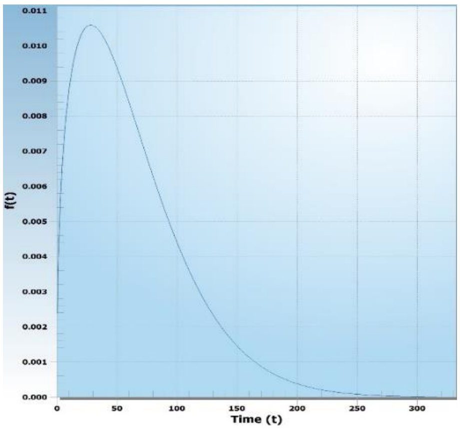


Failure Rate vs Time

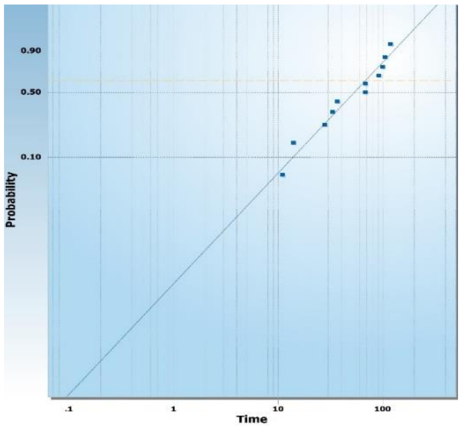


Reliability vs Time

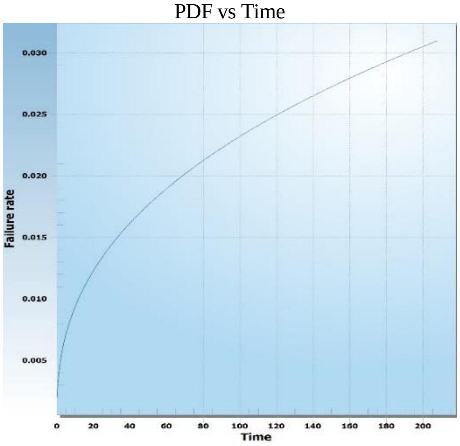
Fig. B1 Weibull result for 500-ton press machine (β = 1.2072; η = 41.2906; ρ = 0.9774; ρ^2 = 0.9552).



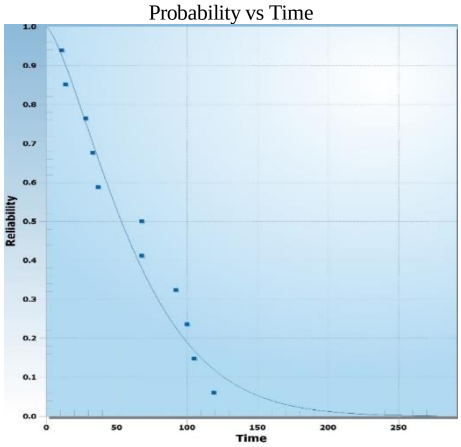
PDF vs Time



Probability vs Time

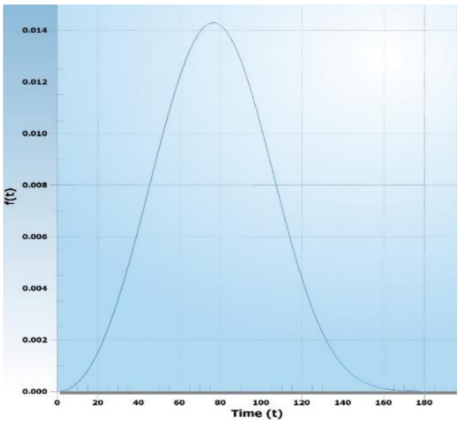


Failure Rate vs Time

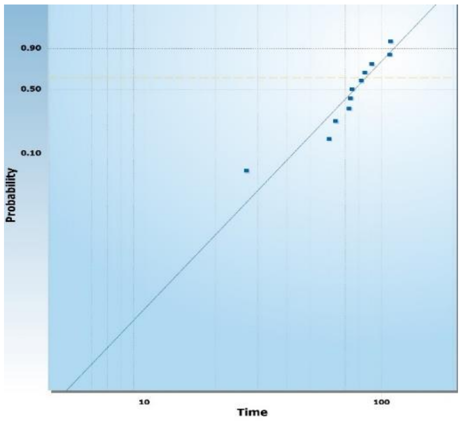


Reliability vs Time

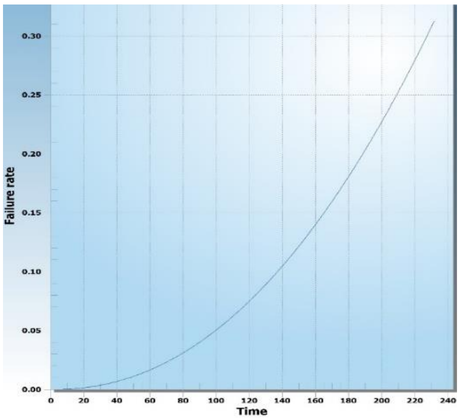
Fig. B2 Weibull result for an air compressor machine (β = 1.3949; η = 69.3860; ρ = 0.9784; ρ^2 = 0.9572).



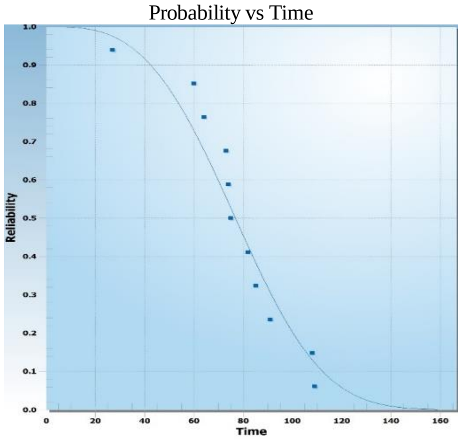
PDF vs Time



Probability vs Time

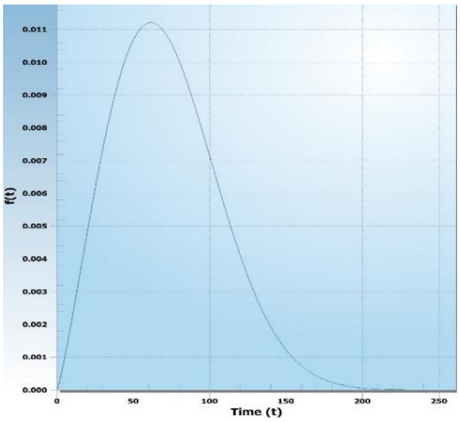


Failure Rate vs Time

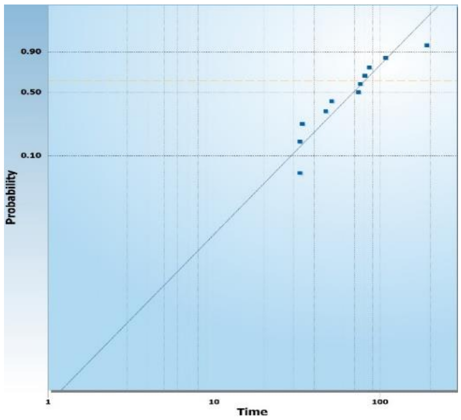


Reliability vs Time

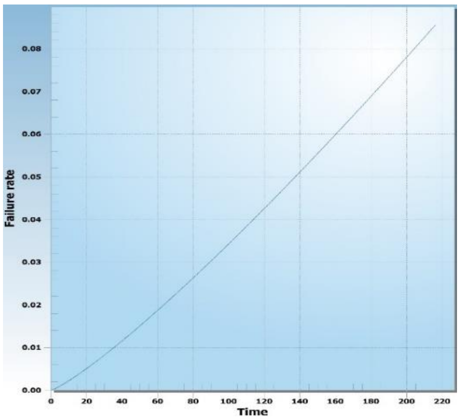
Fig. B3 Weibull result for VDF machine (β = 3.1679; η = 86.2276; ρ = 0.9363; ρ^2 = 0.8767).



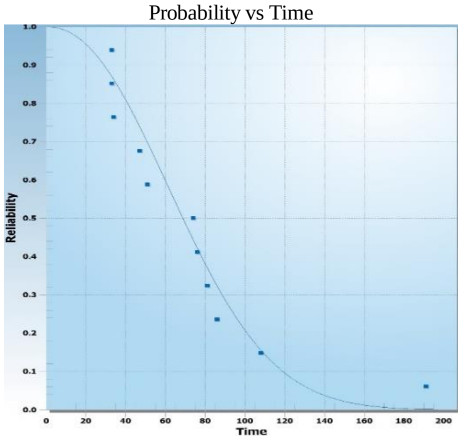
PDF vs Time



Probability vs Time



Failure Rate vs Time



Reliability vs Time

Fig. B4 Weibull result for Roller machine (β = 2.1850; η = 81.2703; ρ = 0.9289; ρ^2 = 0.8628).

Appendix C

Table C1 Abbreviation of ME

SP	Spare sparts and material availability
KPI	Key performance indicators
PS	Policy and strategy
CWO	Comprehensive work order
OCT	Organization cleaning and tiding of work areas
RIN	Reduction in intervention number
RPV	Reduction in process variability
PM	Preventive maintenance
CMPANDIE	Continuous monitoring of procedure and increasing efficiency

Table C2 Pairwise Comparison matrix developed by experts

	SP	KPI	PS	CWO	OCT	RIN	RPV	PM	CMPANDIE
SP	1	1/3	1/3	1	1/7	1	1	3	1
KPI	3	1	1	1/3	1/7	1/3	1/3	3	1/3
PS	3	1	1	1/3	1/7	1/3	1/3	3	3
CWO	1	3	3	1	1/3	1	1	3	1
OCT	7	7	7	3	1	5	3	7	3
RIN	1	3	3	1	1/5	1	1	5	1
RPV	1	3	3	1	1/3	1	1	5	1
PM	1/3	1/3	1/3	1/3	1/7	1/5	1/5	1	1/5
CMPANDIE	1	3	1/3	1	1/3	1	1	5	1

Table C3 Fuzzification matrix

	SPMA			KPI			PS			CWO			OCT			RIN			RPV			PM			CMPANDIE		
	L	M	U	L	M	U	L	M	U	L	M	U	L	M	U	L	M	U	L	M	U	L	M	U	L	M	U
SP	1	1	1	1/5	1/3	1/2	1	1/3	1	1	1	1	1/8	1/7	1/6	1	1	1	1	1	1	2	3	4	1	1	1
KPI	2	3	4	1	1	1	1	1	1	1/5	1/3	1/2	1/8	1/7	1/6	1/5	1/3	1/2	1/5	1/3	1/2	2	3	4		1/3	
PS	2	3	4	1	1	1	1	1	1	1/5	1/3	1/2	1/8	1/7	1/6	1/5	1/3	1/2	1/5	1/3	1/2	2	3	4	2	3	4
CWO	1	1	1	2	3	4	2	3	4	1	1	1	1/5	1/3	1/2	1	1	1	1	1	1	2	3	4		1	
OCT	6	7	8	6	7	8	6	7	8	2	3	4	1	1	1	4	5	6	2	3	4	6	7	8	2	3	4
RIN	1	1	1	2	3	4	2	3	4	1	1	1	1/6	1/5	1/4	1	1	1	1	1	1	4	5	6	1	1	1
RPV	1	1	1	2	3	4	2	3	4	1	1	1	1/5	1/3	1/4	1	1	1	1	1	1	4	5	6	1	1	1
PM	1/5	1/3	1/2	1/5	1/3	1/2	1/5	1/3	1/2	1/5	1/3	1/2	1/6	1/7	1/4	1/6	1/5	1/4	1/6	1/5	1/7	1	1	1		1/5	
CMPANDIE	1	1	1	2	3	4		1/3		1	1	1	1/5	1/3	1/2	1	1	1	1	1	1	4	5	6	1	1	1
	15.20	18.33	21.50	16.40	21.67	27.00	15.20	19.00	23.50	7.60	9.00	10.50	2.31	2.77	3.25	9.57	10.87	12.25	7.57	8.87	10.14	27.00	35.00	43.00	8.00	11.53	12.00

Table C4 Geometric Mean Value of Each ME

	Geometric mean value		
	Lower value	Middle value	Upper value
SPMA	0.526	0.557	0.65
KPI	0.5	0.63	0.88
PS	0.629	0.885	1.032
CWO	1.08	1.27	1.46
OCT	3.25	4.01	4.88
RIN	1.11	1.27	1.42
RPV	1.16	1.35	1.53
PM	0.23	0.28	0.37
CMPANDIE	0.65	0.74	0.45
TOTAL	**9.135**	**10.992**	**12.672**
INVERSE	**0.077**	**0.09**	**0.1094**

Table C5 Weight of Each ME

	Weight of each value		
	Lower value	Middle value	Upper value
SPMA	0.04	0.05	0.07
KPI	0.0385	0.0567	0.096
PS	0.0484	0.072	0.112
CWO	0.083	0.114	0.1531
OCT	0.25	0.3601	0.5338
RIN	0.085	0.1143	0.1553
RPV	0.089	0.1215	0.1673
PM	0.018	0.0252	0.029
CMPANDIE	0.05005	0.0666	0.092

Table C6 Normalized Weight of Each ME

	Defuzzied weight	Normalized weight
SPMA	0.05	0.050
KPI	0.031	0.031
PS	0.077	0.077
CWO	0.1167	0.117
OCT	0.3839	0.386
RIN	0.1182	0.119
RPV	0.125	0.126
PM	0.024	0.024
CMPANDIE	0.0693	0.070
Total	0.9951	1.000