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RELIABILITY, AVAILABILITY AND MAINTAINABILITY OF A BOILER IN THERMAL POWER PLANT– A CASE STUDY

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Abstract

Many countries face problems in electricity generation. Boilers play an important role in a power plant. Sudden failures of a power plant boiler components cause loss of production and high maintenance cost. Due to unplanned and irregular maintenance, which can ultimately increase the production cost of electricity. This is a common challenge faced by power plant operators worldwide. The present study aims to examine and analyze the failure times of a boiler at a thermal power plant and identify its critical failure expectancy and system reliability. The data was collected over a long period and was analyzed using statistical methods. In this study, the hypothesis has been proposed to choose the best analysis. Furthermore, reliability, availability, and maintainability analysis were carried out under discrete analysis. The analysis included identifying the probability distribution of the failure times, identifying critical failure expectancy, and determining system reliability.

Keywords: Boiler, mean time between failure (MTBF), mean time to repair (MTTR), reliability, availability, maintainability, log-normal distribution, Weibull distribution, hazard function, survival function.

1. Introduction

Uninterrupted power supply functioning be influenced by its equipment and components. The functioning of boiler tubes, super heaters, heat exchangers, turbines, etc., is important to maintain the power supply in fossil fuel-based power plants. A single component failure also leads to the shutdown of the entire power generation system. Boilers are designed to operate at high temperatures, pressure and they play a critical role in the efficient, reliable operation of a thermal power plant. Analysis of failures of a boiler in a power plant is important to continuous power generation. The boiler is a key component of a thermal power plant and is used to convert water into steam, which is then used to generate electricity. The steam is produced by heating water in the boiler through the combustion of fuel, such as coal or natural gas. The steam sent through a turbine, which powers a generator to produce electricity. The steam is then cooled and condensed back into water, which is then returned to the boiler to be heated again. Boiler components are mainly made of steel, cast irons stainless steel, and high-temperature alloys. The combustion, ignition, and fuel-feeding systems are also equally important in the reliability and availability study of the boiler also few authors focused on the failure analysis of these systems. The availability of the steam boiler is a key factor, as it affects the performance and productivity of the process industry. The availability of the steam boiler and its components depends on its reliability and maintainability and can be enhanced by avoiding the number of failures and decreasing the time required scheduled and unscheduled maintenance activities. System availability can be enhanced by identifying critical mechanical subsystems concerning failure frequency, reliability and maintainability.

For the system reliability analysis, it is necessary to classify the system into various levels such as assembly and sub assembly components. Reliability analysis can be done with the collection of failure data from a variety of sources. After collecting the failure data, criticality analysis is needed for the identification of critical parts, the next stage is to estimate the parameters of the distribution and finally, the reliability characteristics are found.

Failure of boiler tubes has often been reported in many such power plants [1]– [3]. Duarte et al. [4] studied failure analysis of water-tube boiler as case study and identified that the occurrence of failure of the water-tube boiler as stress corrosion cracking. Moghanlou and Pourgol-Mohammad [5] investigated on failures of boiler tubes in power plants by Failure Modes and Effect Analysis (FMEA) and stochastic technique. S. Chaudhari and R. Singh [6] focused on high temperature boiler tube failures specifically on preheater tube, carbon steel and superheater tubes. Barry and Hudson [7] suggested a probabilistic feedback scheme for the maintenance of fuel feeding system. By reviewing the literature on failures of boiler and its components, it is found that the data which was recorded is necessary to find boiler’s reliability and to enhance maintenance strategies for boiler system.

In this article, failure of boilers of the electricity power plant has been analyzed. Discrete and continuous analysis has been done by considering suitable distributions. Plotted probability and cumulative probability distribution functions and hazard rate curve

2. Methodology

2.1. Discrete Analysis

For performing discrete analysis, the failure data is studied on yearly basis, and outage frequency, forced outage hour, service hour, and period hour are calculated for each year. Further, the mean time between failure (MTBF), mean time to repair (MTTR), repair rate, failure rate, reliability, and availability are calculated and noted in different columns.

2.1.1 Reliability

If the failure rate remains constant for each year thus reliability is calculated using an exponential distribution.

$$Failure\ rate = \frac{Total\ no.of\ failures}{Total\ operating\ hours}$$

The reliability is given by

$$R(t) = e^{-\lambda t}, t > 0, \lambda > 0$$

where t is time

2.1.2 Availability

The availability is calculated using uptime and down time.

$$Availability = \frac{Up\ time}{Up\ time + Down\ time}$$

2.1.3 Maintainability

For calculating the maintainability, the mean time between failure (MTBF) and mean time to repair (MTTR) is calculated for each year.

$$MTBF = \frac{Total\ Operating\ Hours}{Total\ no.of\ failures}$$

$$MTTR = \frac{Total\ Forced\ Outage\ Hours}{Total\ no.of\ failures}$$

2.2 Continuous Analysis

2.2.1 Goodness of Fit

Goodness of fit is a statistical measure used to evaluate how well a given model fits a set of data. It measures the degree of agreement between the observed data and the expected values predicted by hypothesis. The goodness of fit can be calculated using various statistical tests, such as the Kolmogorov-Smirnov test, or Anderson Darling test, etc., which assess the statistical significance of the differences between the observed and expected values. A high value of goodness of fit indicates that the model or hypothesis is a good fit for the data, while a low value suggests that the model may not be appropriate or that there may be some underlying factors that the model does not account for.

2.2.2 Common Life Distribution

The reliability of any repairable system may be increased after its repair. So, finding the system's reliability is mandatory periodically. For this, a reliability analysis of the system is required to meet the desired reliability.

The following distributions may be included.

- Normal Distribution
- Gamma Distribution
- Log-normal Distribution
- Weibull Distribution
- 3-parameter Log-normal Distribution
- 3-parameter Weibull Distribution

2.2.3 3 -Parameter Log-normal Distribution

The 3-parameter lognormal distribution is a continuous probability distribution widely used to model positively skewed data in various fields, including finance, economics and engineering etc., It is called "lognormal" because its natural logarithm follows a normal distribution. This property is suitable for representing data that is the result of multiplicative processes, such as the product of random variables. It is characterized by three parameters, the shape parameter (μ), the scale parameter(σ) and the location (τ).

The probability density function of the 3-parameter lognormal distribution is given by

$$f(x:\mu,\sigma,\tau) = \begin{Bmatrix} \frac{1}{\sigma\sqrt{2\pi}} e^{\left(\frac{-(x-\mu)^2}{(2\sigma^2)}\right)} \; if\ x > \tau, \\ 0\ if x < \tau, \end{Bmatrix}, \sigma > 0$$

2.2.4 3 -Parameter Weibull Distribution

The 3-parameter Weibull distribution is a continuous probability distribution widely used in reliability engineering, survival analysis, and failure modeling. It is characterized by three parameters, the shape parameter (k), the scale parameter(λ) and the location (α). The probability density function (pdf) of the 3-parameter Weibull distribution is given by.

$$f(x:\lambda,k,\alpha) = \begin{Bmatrix} \frac{k}{\lambda}\left(\frac{x-\alpha}{\lambda}\right)^{k-1} exp\left[-\left(\frac{x-\alpha}{\lambda}\right)^{k}\right], if x \geq \alpha \\ 0\ , if\ x < \alpha \end{Bmatrix}$$

3. Case Study

The following data is collected from a thermal power plant, which is in Suryapet district, Telangana state, India. The power plant is functioning with two boilers to generate 15 MW/hour.

Tables 1 & 2 below provide an overview of the outage frequency of boiler_1 & boiler_2 respectively over a consecutive 10-year period, including forced outage hours and service hours.

Table 1: *Failures of Boiler_ 1*

SI No	Year	Outage frequency	Forced outage Hour(h)	Service Hour(h)	Period Hour(h)
1	2009	05	657.99	4982.01	5640
2	2010	11	1185.06	7574.94	8760
3	2011	05	2363.28	6396.72	8760
4	2012	02	202.10	8557.9	8760
5	2013	04	180.09	8579.91	8760
6	2014	04	412.22	8347.78	8760
7	2015	05	609.56	8150.44	8760
8	2016	09	1027	7733	8760
9	2017	07	3646.74	5113.26	8760
10	2018	05	380	8380	8760

Table 2: *Failures of Boiler_ 2*

SI No	Year	Outage frequency	Forced outage Hour(h)	Service Hour(h)	Period Hour(h)
1	2009	03	653.33	7170.33	7824
2	2010	04	712.50	8047.5	8760
3	2011	04	1844.18	6915.82	8760
4	2012	04	478.00	8282	8760
5	2013	03	198.9	8561.10	8760
6	2014	02	296.5	8463.5	8760
7	2015	06	756.92	8003.08	8760
8	2016	05	932.98	7827.02	8760
9	2017	04	2552.87	6207.13	8760
10	2018	04	170.61	8589.39	8760

Tables 3 & 4 below provide a detailed summary of the failure hours of boiler_1 & boiler_2 respectively and arranged chronologically from 2009 to 2018.

Table 3: *Failure Data of Boiler_ 1*

SI No	Failure Hours	SI No	Failure Hours	SI No	Failure Hours	SI No	Failure Hours	SI No	Failure Hours	SI No	Failure Hours
1	10.08	11	29.59	21	511.55	31	239.45	41	13.45	51	2518.25
2	459.30	12	6.05	22	146.00	32	284.58	42	29.45	52	305.45
3	49.40	13	50.48	23	56.10	33	5.02	43	40.45	53	27.50
4	59.21	14	9.16	24	37.14	34	236.56	44	116.50	54	11.35
5	80.00	15	88.50	25	21.55	35	83.40	45	511.12	55	12.15
6	63.20	16	553	26	7.20	36	18.16	46	49.30	56	23.55
7	47.40	17	278.32	27	114.20	37	9.50	47	264.37		
8	46.07	18	108.08	28	49.20	38	11.05	48	222.25		
9	286.24	19	302.13	29	49	39	7.29	49	9.45		
10	5.37	20	1163.20	30	74.57	40	781.15	50	72		

Table 4: *Failure Data of Boiler_ 2*

SI No	Failure Hours	SI No	Failure Hours	SI No	Failure Hours	SI No	Failure Hours
1	54	11	757.4	21	239.12	31	109
2	409.15	12	358.55	22	61.25	32	119.15
3	190.18	13	95.5	23	32.56	33	516.47
4	5	14	10.5	24	226.39	34	177.25
5	48.25	15	13.45	25	78.15	35	1740
6	118.10	16	92.10	26	119.25	36	10.11
7	541.15	17	7.35	27	18.16	37	7.15
8	183.19	18	99.45	28	24.07	38	140.20
9	502.42	19	201.10	29	21.20	39	13.15
10	401.17	20	95.4	30	760.55	40	209.30

Table 5 & 6 explain the identification of the distribution that best fits for boiler_1 & boiler_2, by using the Anderson-Darling test along with the correlation coefficient to determine the most appropriate fit.

Table 5: *Goodness of Fit of Boiler _1*

Distribution	Anderson-Darling Test	Correlation Coefficient
Weibull	2.463	0.948
Lognormal	0.631	0.989
Exponential	14.028	*
Normal	8.518	0.678
3-Parameter Weibull	0.605	0.994
3-Parameter Lognormal	0.530	0.994
2-ParameterExponential	6.831	*

Table 6: *Goodness of Fit of Boiler _2*

Distribution	Anderson-Darling Test	Correlation Coefficient
Weibull	0.809	0.977
Lognormal	0.761	0.987
Exponential	3.237	*
Normal	4.375	0.791
3-Parameter Weibull	0.539	0.994
3-Parameter Lognormal	0.667	0.988
2-ParameterExponential	2.658	*

4. Results and Discussions

The failure data of the boilers mentioned in the Table 3 and Table 4 has been organized into year-wise failures by sorting them in a chronological order. The sample data is then analyzed to determine the number of outages that occurred during each year, the mean time between two successive failures, the total number of hours that the system was operational and the total period of each year

Using these metrics, several important reliability and maintenance indicators are calculated, including MTTR, MTBF, failure rate, repair rate, reliability, availability. These measures provide important insights into the performance of the boiler system, helping to identify areas for improvement and optimize maintenance schedules.

4.1 Continuous Analysis

4.1.1 Probability Curve

Figure 1 provides the use of a 3-Parameter Lognormal distribution to model the failure hours of boiler_1. The plot shows a strong alignment of the data points with the line, indicating a good fit. This is further supported by a high correlation coefficient of (0.994) and a low Anderson-Darling statistic of (0.530). The analysis reveals key metrics, including a mean failure time of (256.8) hours and a median failure time of (55.35) hours. These values play a significant role in assessing the reliability of boiler_1. The close fit of the model highlights its effectiveness in capturing failure trends. This information is essential for evaluating the operational reliability of the system. Additionally, it aids in developing maintenance strategies to minimize downtime.

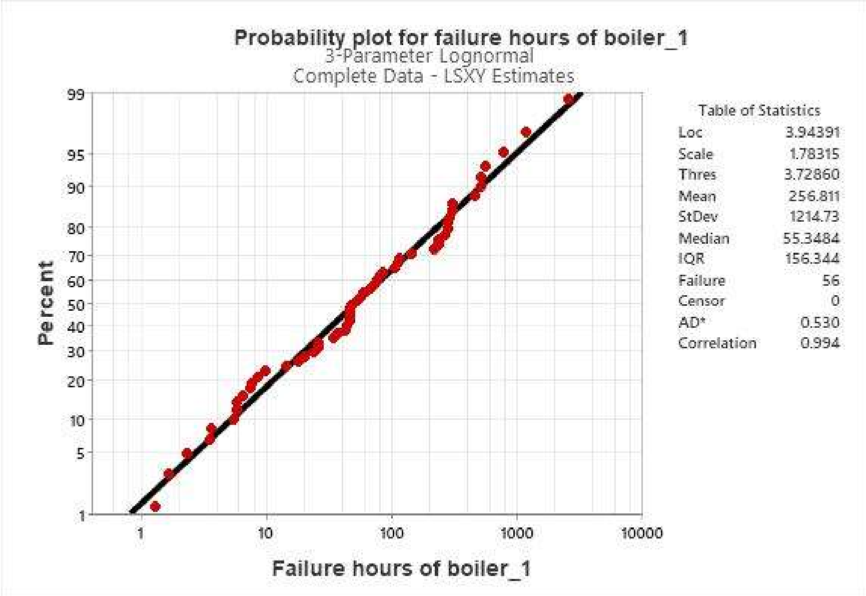


Figure 1: *Probability plot for failure hours of boiler_1*

From the below Figure 2, the plot utilizes a 3-Parameter Weibull distribution to model the failure hours of boiler_2. The data points closely align with the line, indicating a high correlation of (0.994) and a low Anderson-Darling statistic of (0.539) which suggests a strong fit. Notable values include a mean failure time of 232.4 hours and a median of 104.2 hours. This analysis is instrumental in evaluating reliability and informing maintenance strategies.

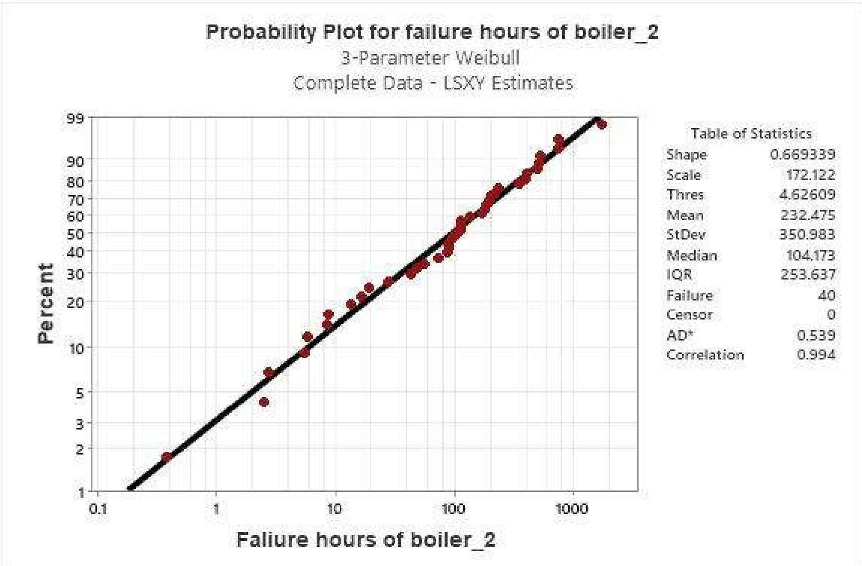
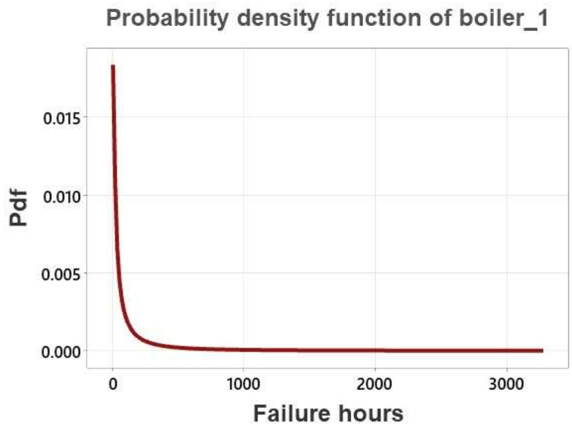


Figure 2: *Probability plot for failure hours of boiler_2*

4.1.2 Probability Density Curve

In figure 3, the curves are steep at the beginning, indicating a higher likelihood of failure shortly after operation begins. As the curves flattens out, the probability of failure decreases for longer operation hours. This distribution helps to identify the most likely failure periods and informs maintenance schedules or risk assessments to reduce unexpected downtime for boiler_1 & boiler_2.



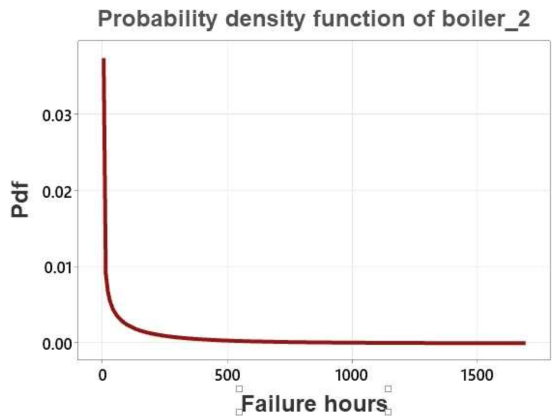
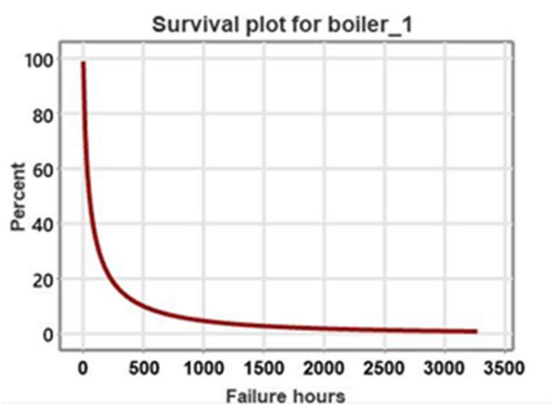


Figure 3: *Probability density function of plot for boiler_1 and boiler_2*

4.1.3 Survival Function

From Figure 4, the survival plots for both boilers start a 100%, indicating that all components are operational initially. For both, the curves show a sharp decline in the early hours, reflecting high failure rates during the initial phase. Over time, the slopes flatten, indicating fewer failures as the lifecycle progresses. Boiler_1 with survival probability nearing 0% by 3250 hours while boiler_2 reaches survival probability of nearly 0% by 1600 hours.



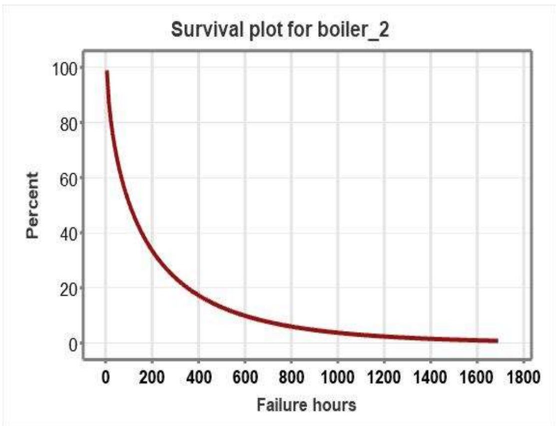


Figure 4: *Survival function plot for boiler_1 and boiler_2*

4.1.4 Hazard Function

From Figure 5, the hazard plots of boler_1 & boiler_2 reveals critical insights into the boiler's reliability. The high initial hazard rate indicates a need to address early-life failures through measures like better quality control, initial inspections, or burn-in testing. The decreasing hazard rate over time suggests that components become more stable as they age. This information is valuable for planning preventive maintenance and improving operational efficiency.

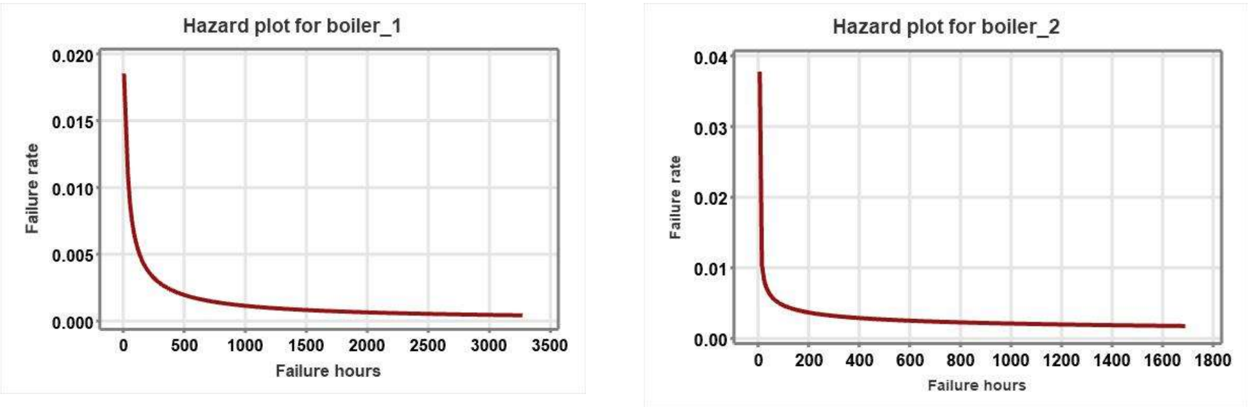


Figure 5: *Hazard function plot for boiler_1 and boiler_2*

4.2 Discrete Analysis

4.2.1 Reliability

In the Figure 6, the reliability of a boiler_1 starts low in 2008 and remains minimal through 2011 before sharply increasing in 2012, reaching its peak. It then declines steeply and stabilizes at lower levels, fluctuating minimally from 2014 to 2018 with no significant recovery. Similarly, the reliability of boiler_2 begins at a low level in 2009, declines further, and stabilizes minimally until 2013. In 2014, it peaks sharply but drops significantly in 2015 to its lowest point, followed by a gradual recovery with slight improvements through 2018.

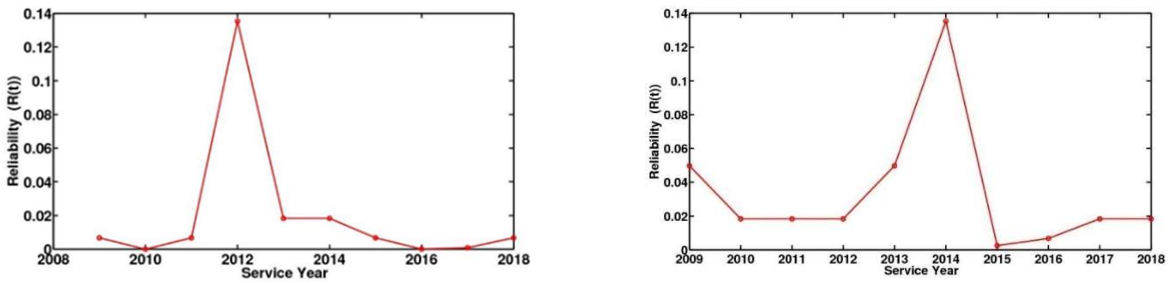


Figure 6: *Reliability plot for boiler_1 and boiler_2*

4.2.2 Availability

Figure 7 provides an overview of the availability rends for boiler_1 and boiler_2 over several years. Boiler_1 showed high availability in 2012, which remained consistent through 2013. From 2013 to

2016, its availability gradually declined, followed by a steep drop in 2017. Despite this downturn, 2018 marked a significant recovery, with availability increasing substantially. In comparison, boiler_2 experienced very low availability during 2017, indicating a challenging phase. However, 2018 brought a remarkable improvement in its performance, with availability rising sharply. These trends highlight contrasting patterns for the two boilers, with boiler_1 recovering from a decline and boiler_2 overcoming its earlier low performance. By 2018, both boilers exhibited significant improvement, underscoring their recovery and stability.

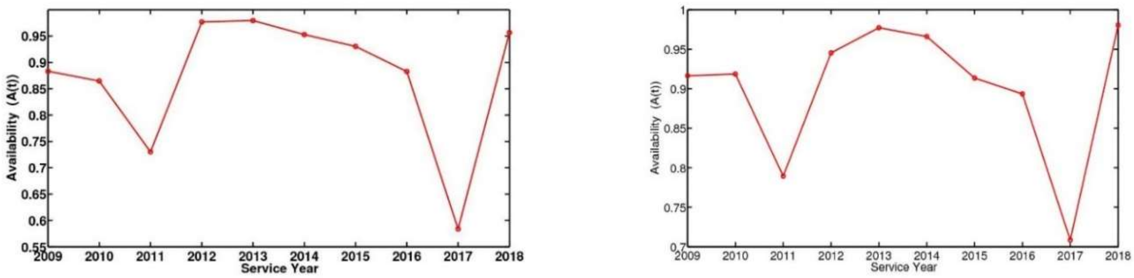


Figure 7: *Availability plot for boiler_1 and boiler_2*

4.2.3 Maintainability

From Figure 8, it shows that boiler_1 had a low MTTR in 2013, while a high MTTR was recorded in 2017. In contrast, boiler_2 experienced a low MTTR in 2018, but high MTTR was also recorded in the same year 2018.

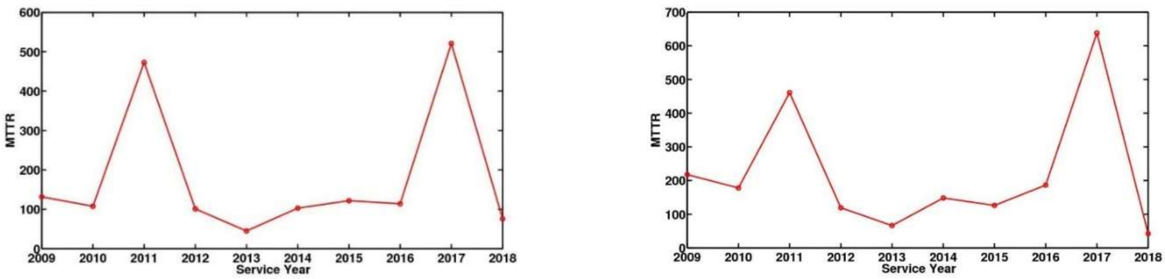


Figure 8: *Maintainability plot for boiler_1 and boiler_2*

5. Conclusion

In this paper, the work is based on discrete and continuous analysis using suitable distributions. The study involves analysis of failure times of a boiler system of a power generation plant. The data fits log-normal and Weibull distributions of boiler_1 and boiler_2 respectively, shape and scale parameters are determined. Using the sorted data, the probability density curve, cumulative probability curve and hazard rate curves are plotted. By these plots, it is easy to make possible predictions of the future tendency of failures of the boilers.

Discrete analysis is carried out to analyze failures of two boilers in the power plant over a period to identify patterns and trends in the frequency and nature of the failures. This analysis is conducted on a yearly basis, with the goal of identifying the effect of these failures on the overall performance of the boilers. In 2010 and 2016, the reliability of boiler_1 is very low whereas in 2015, the reliability of boiler_2 is very low. The availability of boiler_1 in 2012, 2013, and 2018 is very high. High availability suggests efficient operation, contributing to consistent power generation. Whereas in 2017, the availability of two boilers is less. For decreased availability, conducting root cause analysis to identify the underlying issues is mandatory. In 2017, the mean time to repair is very high for two boilers. It indicates some maintenance strategies must be planned. The information gathered from this analysis is used to create a plan that addresses the identified issues and implements actions to improve the reliability, availability and maintainability of the boiler. By doing so, the organization reduce downtime, improve performance and prevent future failures.

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