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Maintainability Evaluation of Steam and Gas Turbine Components in a Thermal Power Station

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Abstract: Maintenance costs have risen steadily over recent years in proportion to total investment in thermal power stations, however lack of regular maintenance can result in serious equipment failure with catastrophic consequences. In general, the Nigerian power generation capability has nosedived to an abysmal level, particularly at the generation stations due to poor maintenance culture. This paper evaluated maintainability of steam and gas turbines components in a thermal power station. Data were obtained from a thermal power station in Nigeria; these raw data were extracted from the operation department, which represents records of plant generation capabilities as well as other inherent daily conditions that will enhance the success of this study. Various maintainability measures were used in analyzing the data, the study implemented log normal distribution considering that most turbines fails due to fatigue and other phenomenon that are caused by ageing or wear resulting in failure rates that increase with time. The estimated mean time to failure of turbine 2 reduced from 35744.5 hours to 33643.8 hours after the use of a condition based preventive maintenance policy. Mean Preventive Maintenance Time (MPMT) for Economizer Inlet non Return Valve and its effect on steam turbine 1 ranges from 77144hrs to 4296hrs for gas turbine 2. The station overall mean maintenance time showed that steam turbine 1 has a maximum hours (77144hrs), while its is minimum for gas turbine2 (4296 hrs). MPMT of sub-equipment is maximum up to 48717 hrs on Gear defect/Hood diaphragm for steam turbine 2; also maximum for the Economizer Inlet non Return Valve, while this was minimum about 48708 hrs for the water pump. For gas turbine 2 MPMT hours for seal leakages and air filters have a maximum value of about 4295.5 hrs, while it is very low on other equipment. The equipment maximum corrective maintenance time (MCMT) of various turbines is higher for steam turbine 2 (10.04 hrs), while minimum for gas turbine 2 (10.00 hrs). Conclusively, planned maintenance tasks can reduce the number of unplanned or emergency trips of these turbines.

Keywords: Maintainability, Steam Turbine, Gas Turbine, Power Station, Lognormal Distribution

1. Introduction

In the past, the maintenance practices of Nigerian industries has been learned through experience and rarely examined analytically. However, increased performance requirements have led to complex maintenance needs which necessitates adoption of more engineered decision support for maintenance of equipments. A lot of investment has been channelled to power generation process and automation to enhance the reliability of this systems, this requires adequate maintenance. Maintenance of process instruments and equipment play a major role in the smooth running of such process [1; 2]. Effective maintenance of turbines are obviously one of the most important aspects of modern thermal power station. Since the dawn of industrialization, people who were experts in maintenance, repairing, and diagnosing machines were entirely invaluable. Maintainability is defined as the probability of performing a successful repair action within a given time. In other words, maintainability measures the ease and speed with which a system can be restored to operational status after a failure occurs. The repair rate is a random variable since it is dependent on the nature of failure, ability to analyze the root cause of failure and expert human resources to carry out the repair procedure [3]. Maintainability is the ability of an item to be maintained, whereas maintenance constitutes a series of actions to be taken to restore or retain an item in an effective operational state [4].

The objectives of maintainability components is to isolate and correct defects, identify and repair damaged components without replacing other still working parts, prevent unexpected breakdowns, improve components useful life, enhance components efficiency and reliability. In most cases, maintainability involves learning from the past in order to improve the reliability of systems based on maintenance experience [5].

Zahir [6] developed reliability Models of adequately maintained systems incorporating measures used in maintainability analysis. Desai and Mital [7] evaluated strategies for improving maintainability of products through the adoption of a comprehensive design for maintainability measures. Teodor and Adina [8] studied reliability and maintainability of electric cable machinery utilizing Weibull ++9 software for characterization of functional safety and maintainability. Ding [9] examined product maintainability design method and support tool based on feature model. Sulaiman [10] evaluated the effect of planned preventive maintenance application on the performance of Egbin thermal power station, they used the overall equipment effectiveness model (OEE) approach which comprises of availability rate, performance rate, and quality rate to carry out the work. Adeoye and Bamisaye [11] carried out performance evaluation and analysis of Omotoso pwer plant in Nigeria, Bezerra et al [12] analyzed the feature models maintainability over their evolution process, Jha [13] studied the reliability and maintainability of electrical drives with particular reference to capital intensive heavy coal mining machineries, Zdravko et al [14] examined the evaluation and monitoring of condition of turbo generator on the example of thermal power plant Ugljevik 1x300 MW. Lu [15] undertook maintainability fuzzy evaluation based on maintenance task virtual simulation for aircraft system. Mohamed [16] carried out performance and maintainability evaluation of anti-spyware system, Isono [17] studied maintainability and repairability for Japan Sodium-Cooled Fast Reactor (JSFR), they identified a number of parts which have difficulty in maintenance and repair in main components of the reactor structure and the primary/secondary main coolant system. Hoffner et al [18] made efforts in creating a balance of cost, reliability, and maintainability for utility-scale PV power plants. Mohebbi [19] proposed maximum maintainability of complex systems via modulation based on DSM and module layout, Tian and Liao [20] examined condition based maintenance optimization for multi-component systems using proportional hazards model,

Kumar [21] reviewed reliability, availability and maintainability analysis of a process industry. Peng and Vayenas [22] in a case studies with an LHD Vehicle carried out maintainability analysis of underground mining Equipment using genetic algorithms. Atikpakpa, [23] employed the exponential and Weibull density models to evaluate the failure and reliability of six turbines as an individual component in a Nigerian thermal plant. Corvaro et al [24] X-rayed the reliability, availability, maintainability of reciprocating compressors API 618. Wu et al [25] carried out risk-based inspection and maintenance in process plants and their practices in Taiwan, they addressed various content of risk-based assessment and maintenance employed in process plants

Obviously, recent research has implemented various models of maintainability for different process equipments, but little research has focused on the steam and gas turbine components in a thermal power station. Studies that have examined maintenance problems in industries have focused almost exclusively on comprehensive design for maintainability measures. However the current study specifically reviewed various distributions for maintainability analysis and adopted log normal distribution considering that most turbines fails due to fatigue and other phenomenon that are caused by ageing or wear resulting in failure rates that increase with time.

2. Applicable Statistical Distributions in Maintainability Evaluation

Some of the applicable distributions for maintainability analysis include the normal, lognormal, and exponential distributions [6]. The exponential distribution applies to maintenance tasks and maintenance actions whose completion times are independent of previous maintenance experience [6, 26, 27].

Lognormal distribution applies to most maintenance and repair actions involving subsidiary tasks of unequal frequency and time duration [6, 28, 29]. The normal distribution is mostly useful in relatively straightforward maintenance tasks and repair actions which consistently require a fixed amount of time for its completion [30]. Weibull and gamma distributions are applicable in maintainability analysis depending upon the analysis of the data and the use of "goodness of fit" tests [31. 28].

The possibility that the turbine will be repaired in a specified period of time is characterized by maintainability and represented by a lognormal distribution; hence lognormal distribution is commonly used to model the lives of units whose failure modes are of a fatigue-stress nature [6, 32]. This paper will concentrate on the use of the lognormal distribution, and its use in maintainability analysis.

3. Materials and Methods

Data were obtained from a thermal power station in Nigeria. These raw data were extracted from the operation department, which represents records of plant generation capabilities as well as other inherent daily conditions that will enhance the success of this study. From the records obtained, daily, monthly and yearly data of power generated were computed. In addition, during the process of gathering data on this research work, both junior and senior staffs of the technical department of the plant operation unit of the thermal power station were interviewed to get some other relevant information which was of a great assistance to the success of this work. The prescribed procedure include not only the certain manner of actions but it also include availability of maintenance resources (spare parts, tools, manuals and labors), scheduling of maintenance, skilled personnel and number of peoples assign for the maintenance. Various researchers including Kusiak and Lee [33]; Dhillon [34] and Ding [9] has previously established the following measures used in maintainability analysis.

A. Mean time to repair (MTTR)

Mean Time To Repair, MTTR, is the actual time it takes to perform corrective maintenance. It is thus a maintenance activity that takes place after a function failure has been discovered. The MTTR is the mean of the distribution of turbine repair time and is estimated from the following equation [34; 33].

$$MTTR = \frac{\sum_{i=1}^{n} \lambda_i M_i}{\sum_{i=1}^{n} \lambda_i} \quad (1)$$

Where

M_i=The time needed to repair the turbine when component *i* fail. It also means the maintenance time for preventive maintenance activity *i.*

n=Number of repaired components in the system

λ_i=Failure rate of the i^{th} repairable component in the system

B. Maintenance Function ($M_{(t)}$)

In addition to these measures, maintainability functions are used to predict the probability that a turbine repair, starting at time t=0, will be completed in a time t. Mathematical expression of maintainability according to Gupta [35] is

$$M_{(t)} = 1 - e^{-(t/_{MTTR})} \quad (2)$$

The maintainability density functions of a lognormal random variable Tr whose logarithm is normally distributed has been proposed by Muralidharan and Syamsundar [36] as follows:

$$M(t) = \frac{1}{t\sigma\sqrt{2\pi}} exp\left[-\frac{1}{2}\left(\frac{\ln(t) - \mu}{\sigma}\right)^2\right]. t > 0, \sigma > 0 \quad (3)$$

The corresponding maintainability function is given by

$$M(t) = \int_{-\infty}^{t} \frac{1}{x\sigma\sqrt{2\pi}} exp\left[-\frac{1}{2}\left(\frac{\ln(x) - \mu}{\sigma}\right)^2\right] dx$$

$$M(t) = \Phi\left(\frac{\ln(x) - \mu}{\sigma}\right), t > 0, \sigma > 0 \quad (4)$$

Where,

M (t)=Maintainability at time t,

Φ=Standard normal distribution cumulative function

μ=Lognormal distribution mean value

σ=Lognormal distribution standard deviation

C. The Standard Deviation (SD)

The standard deviation of the lognormal distribution ($\boldsymbol{\sigma_T}$), as discussed in Kececioglu [37] is expressed as

$$\sigma_T = \sqrt{\left(e^{2\mu' + \sigma'^2}\right)\left(e^{\sigma'^2} - 1\right)} \quad (5)$$

D. Mean Preventive Maintenance Time (MPMT)

According to Dhillon [34] the objective of the preventive maintenance program is to postpone the point at which the equipment or any of its components wears out or breaks down.

$$\text{MPMT} = \frac{\sum_i^n T_{mpi} F_{pti}}{\sum_i^n F_{pti}} \quad (6)$$

T_{mpi} is the elapsed time for preventive maintenance task i for i=1, 2, 3.....n. F_{pti} is the frequency of preventive maintenance task i, for i=1, 2, 3,...n. n is the number of preventive maintenance tasks.

E. Overall Mean Maintenance Time (OMMT)

To calculate the Mean Maintenance Time all in all, that is to say the total time of maintenance considering both corrective and preventive maintenance task, f is the frequency of maintenance.

$$\text{OMMT} = \frac{\lambda.MTTR + f.\text{MPMT}}{\lambda + f} \quad (7)$$

F. Maximum corrective maintenance time (MCMT)

According to Ding [9], MCMT for lognormal distribution measures the time required to complete all potential repair activities up to a given percentage, often 90th or 95th percentiles.

$$\text{MCMT} = anilog(T_m + k\sigma) \quad (8)$$

Where

T_{mcm}=maximum corrective maintenance time.

T_m=mean of the logarithms of the repair times.

σ=standard deviation of the logarithms of repair times.

k=1.28-1.64 for 90th and 95th percentiles.

G. Mean Maintenance Down Time (MMDT)

This is the total time needed either to restore equipment to a specified performance level to maintain it at that level of performance. Thus, it includes active corrective and preventive maintenance times, administrative and logistic delay times.

$$\text{MMDT} = \text{OMMT} + T_{ad} + T_{ld} \quad (9)$$

T_{ad} is the admnistrative delay time. Asssumed to be 600hrs and T_{ld} is the logistic delay time assumed to be 500hrs.

H. Mean time to failure (MTTF):

The mean of the lognormal distribution (μ), is discussed in Kececioglu [37].

$$\mu = e^{\mu' + \frac{1}{2}\sigma'^2} \quad (10)$$

Where,

$$\mu' = \frac{\sum \lambda}{n} \sigma'^2 = \sqrt{\frac{\sum(x - \bar{x})^2}{n}}$$

4. Results and Discussion

The thermal station has a very low maintenance structured for most of the units assessed in this study and as such these cannot guarantee maximum and efficient equipment performance. Gas turbine 01 and 02 was most affected while for the steam turbines maintenance is also very low for this station. For the gas turbines, equipment utilization remains nil for most of the turbines, which indicates the slower pace in maintenance culture in the station. Table 1 and 2 showed the lognormal distribution parameters for maintainability of steam and gas turbines. These were computed using equation 4-10.

Table 1. *Lognormal distribution parameters for maintainability of steam and gas turbines.*

System	**Lognormal Distribution Parameters**	
	Mean Value (μ)	**Standard Deviation (δ)**
Steam turbine 01	1.0003	0.00013
Steam turbine 02	1.0002	0.00016
Steam turbine 06	1.0005	0.00011
Gas turbine 01	1.0001	0.00047
Gas turbine 02	1.00006	0.000084

Table 2. *Lognormal distribution for maintainability of steam and gas turbines.*

Year			**2003**	**2004**	**2005**	**2006**	**2007**
Maintainability M (t)& β_t	ST01	M (t)	0.16	0.16	0.15	0.18	0.16
		β_t	7920	7776	8544	8616	1824
	ST02	M (t)	0.17	0.15	0.15	0.18	0.18
		β_t	7440	8016	8424	7800	8448
	ST06	M (t)	0.24	0.21	0.22	0.25	0.24
		β_t	1872	1560	1150	1368	528
	GT01	M (t)	0.17	0.15	-	-	-
		β_t	1320	2500	-	-	-
	GT02	M (t)	0.27	0.19	-	-	
		β_t	336	3072	-	-	-
Year			2008	2009	2010	2011	2012
Maintainability M (t)& β_t	ST01	M (t)	0.16	0.16	0.18	0.16	0.16
		β_t	8112	8424	8400	8328	8400
	ST02	M (t)	--	--	--	0.15	--
		β_t	--	--	--	8592	--
	ST06	M (t)	0.32	0.24	0.28	--	0.23
		β_t	72	768	768	-	840
	GT01	M (t)	-	-	-	-	-
		β_t	-	-	-	-	-
	GT02	M (t)	0.24	-	-	-	-
		β_t	888	-	-	-	-

Table 3-7 highlight the analysis of the turbines using some equipment maintainability parameters, such as equipment Mean Preventive Maintenance Time (MPMT), Mean Maintenance Down Time (MMDT), Maximum corrective maintenance time (MCMT), Overall Mean Maintenance Time (OMMT), the mean and standard deviation on the repair status for Maintainability of equipment. Based on analysis, MPMT for steam turbine 1 is as high as 77144hrs and as low as 4296hrs in gas turbine 2. The overall mean maintenance time for steam turbine 1 is maximum about 77141hrs in Economizer Inlet non Return Valve and air filters, while its is minimum 77123 hrs for seal leakages. For steam turbine 2 MPMT is maximum to about 48717 in Gear/Hood diaphragm and Economizer Inlet non Return Valve, while its is minimum 48708 in Water Pump. For gas turbine 2 Mean Preventive Maintenance Time is maximum about 4295.5 in seal leakages and air filters, while it's is minimum on other equipments. The standard deviation of mean repair time of equipment is higher in steam turbine 2 and lower in gas turbine 2. The equipment maximum corrective maintenance time MCMT is higher to about 10.04, for steam turbine 2 but and minimum value of 10.00 for gas turbine 2.

Table 3. *Repair time of steam turbines 01 (hrs).*

Components / **system**	**Field breaker**	**Boiler Field pump**	**Gear/Hood diaphragm**	**Water Pump**	**Econo. Inlet non Return Valve**	**Leakage seal**	**Air Filters**
ST01	2	2	2	-	1	7	1
MTTR	252	64.8	120		120	113.14	24
Actual time for repair (T)	504	648	240		120	792	24
T/MTTR	2	1.13	2	-	1	7	1
M (t) at MTTR (hrs)	0.865	0.675	0.865	-	0.632	0.999	0.632
M (t) at TTR (min)	51.88	40.52		-	37.93	59.94	37.94
OMMT	77137.5	77140.8	77138	-	77141	77123	77141
MMDT	78237.5	78240.8	78238	-	78241	78223	78241
MTTF	3942	799.2	4200	-	8520	1218.1	8616

Table 4. *Repair Time of Steam Turbines 02 (Hrs).*

Components / system	Field breaker	Boiler Field pump	Gear/Hood diaphragm	Water Pump	Econo. Inlet non Return Valve	Leakage seal	Air Filters
ST02	-	3	1	4	1	4	-
MTTR	-	336	957	234	336	144	-
Actual time for repair (T)	-	336	957	936	336	576	-
T/MTTR	-	1	1	4	1	4	-
M (t) at MTTR (hrs)	-	0.865	0.632	0.982	0.632	0.982	-
M (t) at TTR (min)	-	51.88	37.92	58.9	37.92	58.9	-
OMMT	-	48710	48717	48708	48717	48709	-
MMDT	-	49817	49817	49808	49817	49809	-
MTTF	-	2824	7683	2101.5	8304	2124	-

Table 5. *Repair time of steam turbines 06 (hrs).*

Components / system	Field breaker	Boiler Field pump	Gear/Hood diaphragm	Water Pump	Econo. Inlet non Return Valve	Leakage seal	Air Filters
ST06	-	5	4	3	-	14	4
MTTR	-	2976	132	112	-	183.4	354
Actual time for repair (T)	-	1488	528	336	-	2568	1416
T/MTTR	-	0.5	4	3	-	14	4
M (t) at MTTR (hrs)	-	0.394	0.982	0.950	-	0.999	0.982
M (t) at TTR (min)	-	23.6	58.9	57.01	-	60	58.9
OMMT	-	8924.8	8922.6	8925	-	8919.2	8924.6
MMDT	-	10024.8	10022.6	10025	-	10019.2	10024.6
MTTF	-	1668.5	2127	2843	-	604	2071.5

Table 6. *Repair Time Of Gas Turbines 01 (Hrs).*

Components / system	Field breaker	Boiler Field pump	Gear/Hood diaphragm	Water Pump	Econo. Inlet non Return Valve	Leakage seal	Air Filters
GT01	-	-	-	-	-	-	9
MTTR	-	-	-	-	-	-	413.7
Actual time for repair (T)	-	-	-	-	-	-	3724
T/MTTR	-	-	-	-	-	-	9
M (t) at MTTR (hrs)	-	-	-	-	-	-	0.999
M (t) at TTR (min)	-	-	-	-	-	-	60
OMMT	-	-	-	-	-	-	5676.2
MMDT	-	-	-	-	-	-	6776.2
MTTF	-	-	-	-	-	-	914.02

Table 7. *Repair Time Of Gas Turbines 02 (Hrs).*

Components / system	Field breaker	Boiler Field pump	Gear/Hood diaphragm	Water Pump	Econo. Inlet non Return Valve	Leakage seal	Air Filters
GT02	-	-	-	-	-	1	2
MTTR	-	-	-	-	-	96	1944
Actual time for repair (T)	-	-	-	-	-	96	3888
T/MTTR	-	-	-	-	-	1	2
M (t) at MTTR (hrs)	-	-	-	-	-	0.632	0.865
M (t) at TTR (min)	-	-	-	-	-	37.93	51.88
OMMT	-	-	-	-	-	4295.5	4295.3
MMDT	-	-	-	-	-	5395.5	5395.3
MTTF	-	-	-	-	-	8448	1404

Table 8. *Mean Preventive Maintenance Time (Mpmt) And Maximum Corrective Maintenance Time (Mcmt) For Gas And Steam Turbines.*

SYSTEM	ST01	ST02	ST06	GT01	GT02
MPMT (hrs)	77144	48720	8926	5682	4296
MCMT (hrs)	10.1	10.01	10.04	10.01	10.00

The lognormal distribution of equipment maintainability on figure 1 and 2 showed that maintainability of equipment on steam turbine 2 has improved efficient plant performance due to conditional maintenance, which indicates that the failure of the steam turbine 2 is reduced. The planned maintenance tasks have reduced the number of unplanned or emergency trips of this turbine. The availability of steam turbine 2 has increased in one operational year which is very close to the turbine 1.

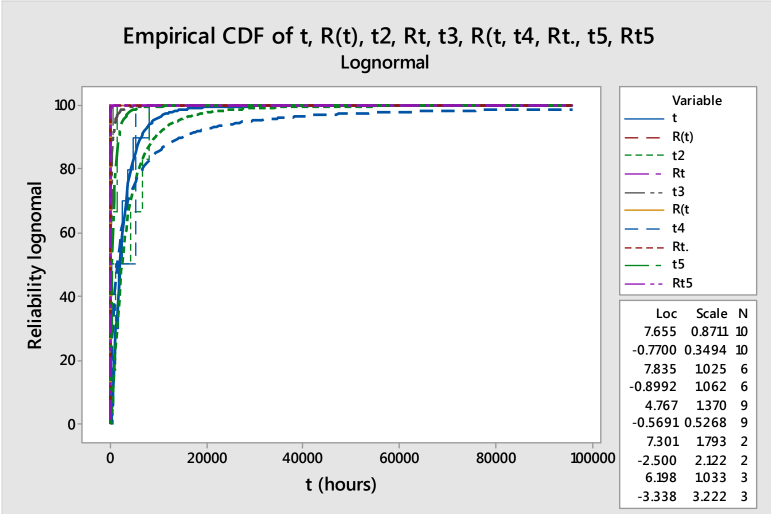

Figure 1. *Lognormal Reliability of gas and steam turbines.*

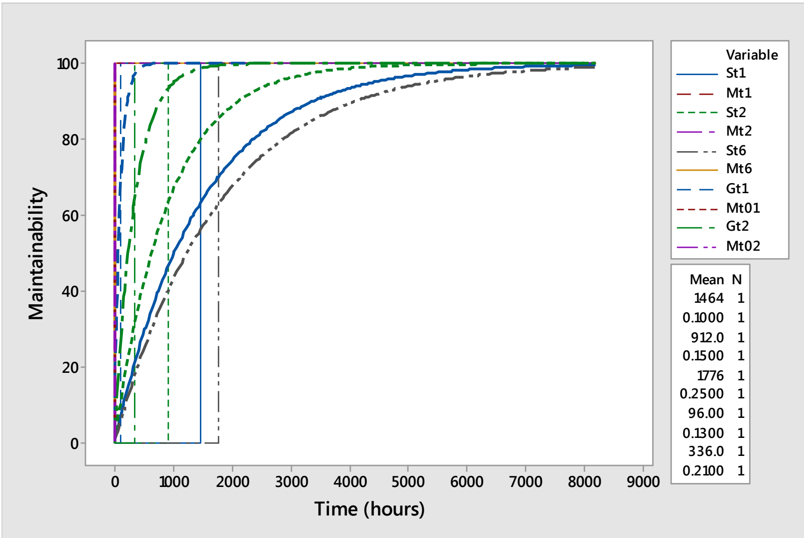

Figure 2. *Lognormal Maintainability of gas and steam turbines.*

From figure 3-7, each curve compressed on both axes. The vertical axis showed the density of stretchiness of the reliability of both turbines while the horizontal axis showed the minimum life of turbine or the aging condition in hours. The total time of maintenance considering both corrective and preventive maintenance task is in the range of 4295.3-77141 hrs.

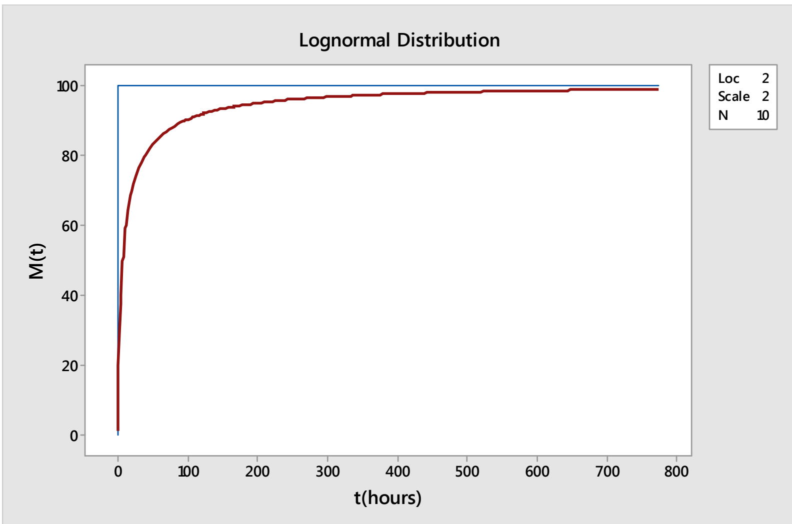

Figure 3. *Lognormal Maintainability of ST01 turbines.*

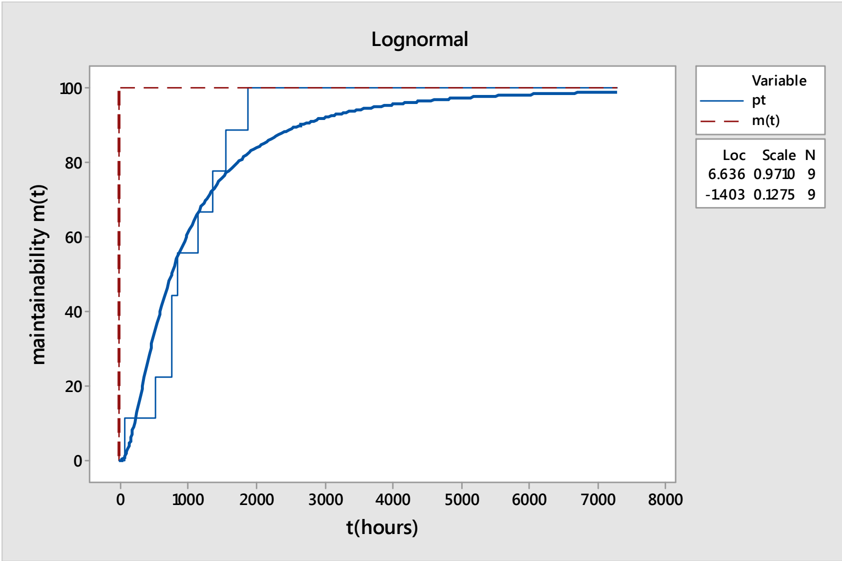

Figure 4. *Lognormal Maintainability of ST02 turbines.*

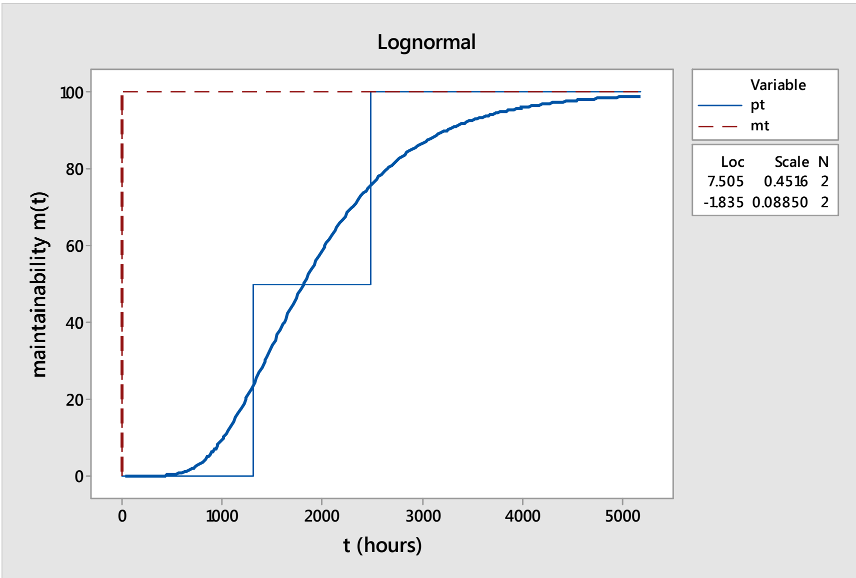

Figure 5. *Maintainability of GT01 turbines.*

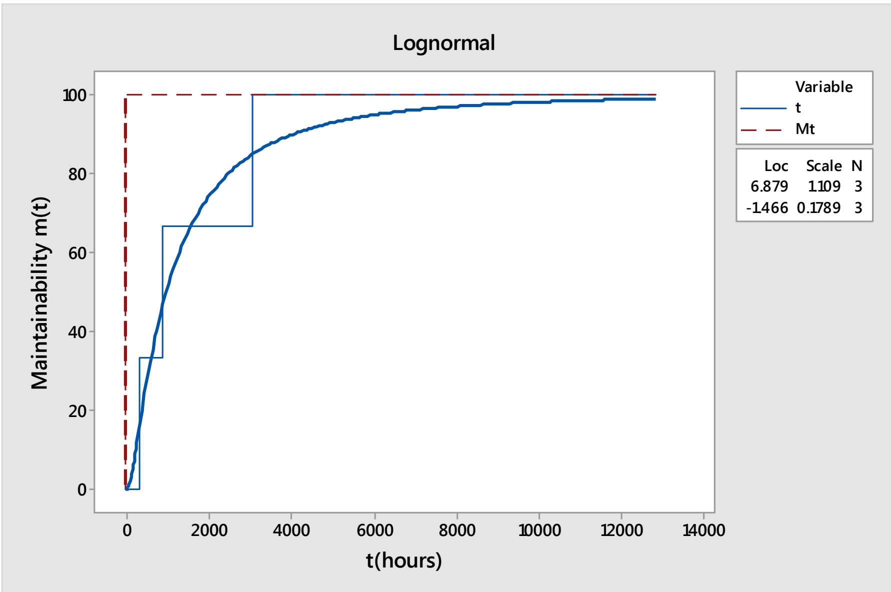

Figure 6. *Maintainability of GT02 turbines.*

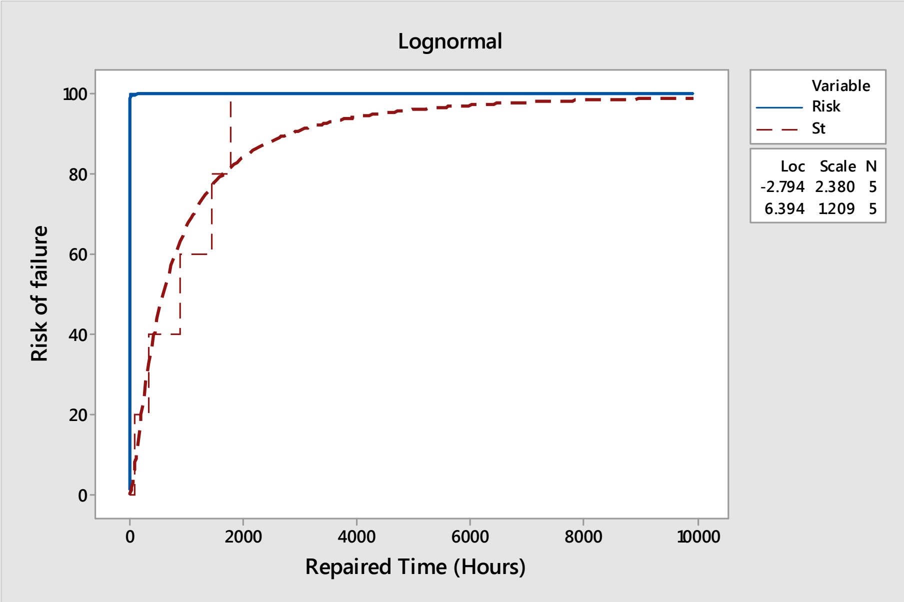

Figure 7. *Risk of failure of gas and steam turbines.*

The effect of failure caused by leakages along the gas supply line and the failure of boiler feed pump on steam turbine 01 and 02 was high and this subsequently affects their efficiency in power generation. Other inherent problems was the issue of cracked; caused by gear defect & hood diaphragm and blockage incurred by as a result of dirt on the air filter.

5. Conclusion

In this study, various measures used in maintainability analysis were adopted in evaluation of steam and gas turbines components in a thermal power station. It became obvious that reliability of equipment depends on prompt maintenance of equipment; however, when the interval between first maintenance and sub-time of system maintenance becomes farther the reliability figure dropped from unity to zero. Therefore, one of the important factor that is very relevant in the performance of thermal power station is maintainability.

Out of all the sub systems studied, ST01 has the highest preventive maintenance time of 77144 hrs which represents the point at which the turbine or any of its components wears out or breaks down. The total time of maintenance considering both corrective and preventive maintenance task is in the range of 4295.3-77141 hrs. However, average of 10hrs is required to complete all potential repair activities in the turbine subsystems up to 95th percentiles. On the whole, the total time needed either to restore the turbines to a specified performance level or to maintain it at that level of performance ranges from 78241 - 5395.3 hrs. Conclusively, Mean time to repair (MTTR), Mean Preventive Maintenance Time (MPMT), Median Corrective Maintenance Time (MCMT), Overall Mean Maintenance Time (OMMT), Maximum corrective maintenance time (MCMT), Mean Maintenance Down Time (MMDT) and Mean time to failure (MTTF) has been effectively applied in maintainability analysis.

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