Original Research Article

MAINTAINABILITY MODELLING OF TOTAL POWER OUTAGE POWER DATA

Abstract

Sequel to the trend of the epileptic nature of electricity power supply in some part of the country, this paper provides a maintainability model for this problem in Uyo. Different statistical test were employed in the work. It was observed that the set of outage data used in the research were identically and independently distributed. Different distributions were tested to obtain the best fitted distribution. Hence the maintainability model for the total outage power data was proposed as, $M(t) = \emptyset \left(\frac{1}{0.6374} \ln \left({}^{t}/_{e^{0.28256}} \right)\right)$.

KEYWORDS: Maintainability, Power Outage, Time To Restore, Lognormal 2-Parameter Distribution.

1. INTRODUCTION

Power outage is very common in Nigeria and could be adjudged by many Nigerians to be a normal incident. Cities and even villages are not spared of this menace and sometimes it occurred without the benefit of prior notice or warming. Moreover, the population of Nigeria is increasing, which implies that the number of electric power users is equally increasing with time, and this demands a higher level of power supply for Nigeria's economical operations. According to Blischke and Murthy (2003), the consequences of failure of a system are many and varied, but nearly every failure has an economic impact. A failure in power supply results not only in the loss of productivity, but also loss in quality and timely services to customers and can even create safety and environmental problems.

Nevertheless, electricity is very important and man cannot do without it. It plays significant role in the industrial growth and development of the countries of the world. Due to its importance, households, private and governmental firms, several institutions and research centres has taken various steps to ensure the availability of constant electric power in their domains by using private fuel generators or solar generators. Nigeria on her part is putting in huge resources to ensure that there is steady power supply in the country (Nnanna et. al 2011). As Nigeria planned to be among the best world economies, she must ensure that epileptic power supply and power outage are things of the past. In order to solve the problem of power outage, an in depth study and analysis of power outages should be treated with seriousness.

Maintainability is a very notable performance metrics in system analysis, it is considered to be a good starting point for the improvement of a system (Saraswat and Yadava, 2008). Several firms and industries have increased its requirements, coupled with the rapid rise in scientific and technological systems, and increased competitions of service providers to implement adequate and acceptable management strategies for the systems to enhance their availability and to comply with acceptable standards (Aly et al., 2018). The important point in this case is that a system or service cannot be well improved unless the knowledge of maintainability of the system is well acquired. Therefore the knowledge of maintainability is a necessity for the improvement in availability of electric power.

2. LITERATURE REVIEW

The importance of maintainability cannot be over-emphasized. It is a necessary function in life-cycle costing, cost benefit analysis, operational capability studies, repair and facility resourcing.

It is also useful in inventory and spare parts requirements determinations, replacement decisions and the establishment of both corrective and preventive maintenance programs (Ebeling, 1997).

Gupta et. al. (2011) in their research, proposed some aspect of maintainability in bulk material handling system design and factors of performance measure in design and selection of bulk material handling equipment and system. In their research, they discuss some areas of belt and pneumatic conveying design, excavator stacker and reclaimer surface miners design selection and application, testing and examination of the major causes of equipment damages, equipment related injuries, and the maintainability of equipment aspect of ore degradation during handling and modelling.

Kajal et. al. (2003) suggested a steady state availability optimization of load handling system by making use of the MATLAB Genetic Algorithm tool. The researchers presented the values of failure and repair rates taken from history maintenance sheet and optimized it from 96.20% to 98.87% through mathematical formulation and was carried out using probabilistic approach. They employed Markov birth-death process to develop the Chapman Kolmogorov difference differential and stated that to achieve the optimum availability level, the corresponding repair and failure rates of the subsystems must be maintained. The researchers concluded that the repair rates can be achieved by employing more trained workers and utilizing better repair facilities while the corresponding failure rates can be minimized or maintained through good design, using reliable machine, adopting proper preventive maintenance schedule,, and providing standby components.

Szkoda (2004) in his research presented selected results of maintainability analysis for the SM48 diesel locomotive. The results showed that the first failure of the SM48 locomotive after a revision repair occurs after 816 hours (i.e approximately 34 days) of operation on average, and the next unplanned failures occur every 386 hours (i.e. approximately 16 days) of operation on average. The mean renewal time (i.e planned maintenance) for the Sm48 locomotive is 5.7 hours on average. The result also revealed that the locomotive is out of operation due to planned repairs and preventive maintenances for 139 hours in a year on average, while it is out of operation due corrective maintenance for 1046 hours on average in one year.

Peng et.al. (2013) studied a probabilistic model checking approach to analysing maintainability of a single satellite system. They performed maintainability analysis using PRISM, a popular tool for the formal modelling and verification of stochastic systems. The author's opined that maintainability analysis is indispensable in the design phase of satellites in order to achieve minimum failures and to increase mean time between failures (MTBF) and to plan maintainability strategies, optimise reliability and maximise availability.

Tu et al. (2016) studied maintainability analysis and evaluation of flexible cables based on the digital enterprise lean manufacturing interactive application (DELMIA). They proposed a flexible cable maintainability evaluation model applicable to the virtual maintenance environment of DELMIA to sevaluate the cable maintainability design with the help of maintenance simulation.

Wolde and Ghobbar (2013) studied the problem of relation between the availability and maintainability of means of rail transport, and the cost of planned vehicle downtimes and maintenance. They proposed a model for optimum inspection and periodical restoration from the viewpoint of costs, taking into consideration the current data on vehicle failures.

Kolawole et al. (2019) emphasized that the consequence of power outage goes beyond the frustration experienced by the users. The researchers stated clearly that electric power outage could lead to injuries and deaths especially when it has to do with the elements of daily utility like powered elevators in skyscrapers and life-saving equipment in the hospitals.

El-Bassiouny et al. (2019) highlighted five major categories of outage causes namely; transformer related outage, power system related outages, environment related outages, human factors related outage and the unclassified outages usually referred to as no flag. They revealed that about 70% of power outage are environment related and are caused by bad weather phenomena such as lightening, rain, wind and even dust, and that animals and large birds which comes into contact with power lines are environment agents that caused power outages.

3. MATERIALS AND METHODS

Data for this research is a secondary data obtained from the record unit of the Port Harcourt Distribution Company (PhED) Uyo. The data consisted of the up-time and down-time of electric power in Uyo local government area in Akwa Ibom State from January 2014 to December 2018.

Weibull 2 -Parameter Distribution:

The pdf for Weilbull 2 -parameter distribution is given by

$$f(t) = \frac{\alpha}{\beta}\left(\frac{t}{\beta}\right)^{\alpha-1} e^{-\left(\frac{t}{\beta}\right)^{\alpha}} \quad (1)$$

Where t is the time parameter, β is the scale parameter and α is the shape parameter.

Lognormal 2-Parameter Distribution:

The pdf for lognormal 2-parameter distribution is given by

$$f(t) = \frac{1}{t\sigma\sqrt{2\pi}}\, e\{\frac{-(\ln(t)-\mu)^2}{2\sigma^2}\} \quad (2)$$

Where μ is the mean of natural logarithm of time to restore (TTR), σ is the standard deviation of the natural logarithm of TTR.

Normal Distribution:

The pdf of normal distribution is given by

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}}\, e^{\frac{-(t-\mu)^2}{2\sigma^2}} \quad (3)$$

Where μ is the mean time to restore (TTR) and σ is the standard deviation of TTR.

Exponential Distribution:

The pdf of exponential distribution is given by

$$f(t) = \lambda e^{-\lambda(t)} \quad (4)$$

The exponential distribution plays an essential role in the study of reliability engineering because it has a constant failure rate, λ. The distribution is also found to be extremely useful in modelling the lifespan of mechanical and electrical parts of a system.

Maintainability

Maintainability can be defined as the probability that a given active maintenance action, for an item under given conditions of use can be carried out within a stated time interval, when the maintenance is performed under stated conditions and using stated procedure and resources (Dhillon 2008). Maintainability of a product is a function of time t, and can be expressed as

$$M(t) = P(T^1 \leq t) = F^1(t) \quad (5)$$

Where F^1 (t) is the cdf of the time to repair and T^1 is the random time to repair variable. The pdf for the maintainability is denoted by f^1 (t), and then the maintainability function M (t) can be equally expressed as

$$M(t) = \int_o^t f^1(t)\,dt \tag{6}$$

Where f^1 (t) is the probability distribution for the repair time. (Dhillon 2008).

Identically and Independently Distribution (iid) Assumption

There is an assumption that when data sets are iid it implies that a particular probability distribution can be used to model the system. In a situation where the data set do not satisfy the iid requirements, and probability distributions are used for modelling, then the results and the conclusions of the analysis can be wrong (Kumar and Klefsjo, 1992).In this work, the iid assumption shall be verified graphically by using both the trend test and the serial correlation test.

The Trend Test

In using the trend test, the cumulative time to restore (CTTR) is plotted against the cumulative repair number. If a line drawn through the data points either resembles a concave upwards or concave down wards trend, then the system is an improving or a deteriorating system respectively. If the line drawn through the data points is approximately a straight line, then the data is free from the trend and this implies that the data set is identically distributed (Kumar el al., 1989).

The Serial Correlation Test

In the serial correlation test, the (i-1)th TTR is plotted against the ith TTR. If the plotted data points are scattered randomly and has no clear pattern, then it means that the data set is free from serial correlation, and this implies that the data points in the data set are independent of each other (Kumar et al., 1989).

Models for Data Analysis

The system is modelled by TTR data analysis. The best-fit probability distributions are identified by a goodness of-fit test and parameters for the best fit distribution are estimated by the maximum likelihood estimation method

TTR Data Analysis

The major target of TTR data analysis is to model the repair processes of the system. This is done by fitting a probability distribution that best represent the restoration data, and estimating parameters to fit the distributions to the data set. The probability distributions that are commonly used for life and repair distributions are Exponential distribution, Normal distribution, lognormal distribution and the Weilbull distribution.

Goodness-Of-Fit-Test

The principle behind the goodness-of-fit tests is to see how far the chosen distribution is matched with the actual data set. Some of the most used tests are p-value test, chi-squared test, Anderson-Darling test and Kolmogorov-Smirnov test. The test that is mostly used for Maintainability analysis is the Kolmogorov-Smirnov test.

Modified K-S Test

Let F(t) be a continuous distribution to be tested as the parent distribution of a given random sample $t_{1,}t_2 \ldots, t_n$. Also let $t_{(1),}t_{(2)} \ldots, t_{(n)}$ *to* be the order statistics (i=1,…, n) and consider the largest difference at the points where empirical distribution function EDF is greater than F(t), and the largest difference at the points where the EDF is smaller than F(t) as

$$D_{k-s}^{+} = \max_{i=1\ldots,n}\{\frac{i}{n} - F(t_{(i)})\}$$

$$D_{k-s}^{-} = \max_{i=1,\ldots,n}\{ F\,(t_{(i)}) - \frac{(i-1)}{n}\}$$

Then the K-S Statistic is given as

$$D_{k-s} = \max\{ D_{k-s}^{+}, D_{k-s}^{-}\} \quad (7)$$

Using the K-S Statistic, the probability distribution which has the least K-S value is considered to give the best fit (Reliasoft, 2007; Mehrannia and Palegohar, 2014).

Anderson-Darling Test

Anderson-Darling Statistic is one of the statistics based on empirical distribution function, (EDF) which is denoted by F_n(t) and defined as;

$$F_n\,(t) = \begin{cases} 0\ if\ t < T_{(1)} \\ \frac{i}{n}\ if\ T_i \le t < T_{(i+1),} i = 1, \ldots, n-1 \\ 1\ if\ t \ge\ T_{(n)} \end{cases}$$

The plot of $F_n\ (t)$ against t is a step function which gives the proportion of observation less than or equal to t. if H_O is true, the EDF should mirror the null distribution F (t;θ). The EDF statistics are based on

$$F_n(t) - F(t;\theta)$$

Anderson-Darling Statistic is given by

$$A^2 = n\int_{-\infty}^{\infty}[F_n(t) - F(t;\theta)]^2\ \varphi(t)dF(t;\theta)$$

where φ(t) =$[F\ (t;\theta)(1 - F\ (t;\theta))]^{-1}$

In practice, the probability integral transform (PIT), z_i =F (t_i;θ) is carried out, which if the parameter θ is known can produce a z-set which is uniformly distributed on [0,1] interval. The formula for computation of the statistic based on the z-set is given by;

$$A^2 = -n - {}^1/_n\{\sum(2i-1)\left[\ln z_{(i)} + \ln\left(1 - z_{(n+1-i)}\right)\right]\} \qquad (8)$$

A distribution with the least value of Anderson-Darling Statistic is considered to give the best fit (Reliasoft, 2007; Mehrannia and Pakgohar, 2014)

Chi-Square Test

The Chi-Square statistic is given by

$$x^2 = \sum_{i=1}^{k}\left[\frac{(O_i - E_i)^2}{E_i}\right] \qquad (9)$$

where K = number of classes or bars

O_i = observed number of failures or repairs in the ith class

$E_i = nP_i$=expected number of failures or repairs in the ith class

n= total number at risk or sample size.

P_i= probability of a failure occurring in the ith class if H_O is true

$= F(t_i)$-F (t_{i-1})

= $H(t_i) - H(t_{i-1})$ for fitting repair data

The Statistic (x^2) has a Chi-Square distribution whose degrees of freedom is K-1-Number of estimated parameters.When using the Chi-Square Statistics, the probability distribution which gives the least x^2 value is considered to give the best fit (Mehrannia and Pakgohar 2014).

In this work, the modified K-S test, the Anderson-Darling test and the Chi-Square test are used.

Parameter Estimation

Once a distribution has been identified, the next thing to do is to estimate the parameters of the distribution. It is only when the parameters are determined, that the distribution is considered to be completely specified. In this work, the Maximum Likelihood Estimation (MLE) method shall be used to estimate the parameters because it is more robust and possesses the properties of unbiasedness, consistency, sufficiency, and minimum variance for large samples.

Maximum Likelihood Estimator (MLE)

Generally, in finding the MLE for any probability distribution with complete data, the maximum of the following likelihood function with respect to the unknown parameters θ_1 , θ_2 ,…, θ_k must be found:

$$L(\theta_1, \theta_2, \ldots, \theta_k) = \prod_{i=1}^{n} f(t_i|\theta_1, \theta_2, \ldots, \theta_k) \quad (10)$$

This is aimed at finding the values of the estimations of θ_1 , θ_2 ,.., θ_k that makes the likelihood function to be as large as possible for given values of t_1 , t_2 ,.., t_n.

The necessary conditions for finding the MLEs are obtained by setting to zero, the first partial derivatives of the logarithm of the likelihood function with respect to θ_1, θ_2 ,…, θ_k.

i.e. $\frac{\partial \ln L\ (\theta_1,\theta_2\ ,\ldots,\theta_k)}{\partial\theta i} = 0$ i= 1, 2,…,k (11)

Moreover, the MLEs for some of the probability distributions are given as follows:

i. The exponential MLE

For complete data, the MLE for the parameter ⋋ is given by

$$\hat{⋋} = \frac{n}{T} = \frac{1}{\mu}$$

Where $n =$ the number of failures

$$T = \sum_{i=1}^{n} t_i$$

ii. The Normal MLE

The MLE for the population mean and population variance are given by

$$\hat{\mu} = \overline{t}$$

$$\hat{\sigma}^2 = \frac{(n-1)S^2}{n}$$

iii. The Lognormal MLE

The MLE for the lognormal parameters are given by

$\hat{\mu} = \sum_{i=1}^{n} \frac{\ln t_i}{n}$

and

$\hat{S} = \sqrt{\frac{\sum_{i=1}^{n}(\ln t_i - \hat{\mu})^2}{n}}$

iv. The Weibull MLE

The maximum likelihood method can only be used to get the parameter estimates for Weibull distribution when it is used jointly with Newton Raphson method. (Dibal et al., 2016). The estimates can be obtained by solving the equations;

$$\alpha = \left(\frac{\sum t_i^{\alpha}\, lnt_i}{\sum t_i^{\alpha}} - \frac{1}{n}\sum lnt_i\right)^{-1}$$

$$\beta = \left(\frac{1}{n}\sum t_i^{\alpha}\right)^{1/\alpha}$$

However, for this research, the reliability software, “Easy-fit” was used to carry out both the goodness-of-fit test and the MLE parameter estimation.

Maintainability Models

Let T be the continuous random variables representing the time to repair a system and having a Pdf, f (t). then the cumulative distribution function is

$$P(T \leq t) = F(t)$$

$$= \int_0^t f(t)dt$$

This is the probability that a repair will be made within time t.

The Lognormal Repair Distribution

For the lognormal distribution;

$$f(t) = \frac{1}{t\sigma\sqrt{2\pi}}\ exp\left\{-\frac{1}{2}\frac{\left[\ln\left({}^{t}/_{t_{med}}\right)\right]^2}{\sigma^2}\right\},\ t \geq 0 \qquad (12)$$

is the probability density function.

$\sigma$is the standard deviation (shape parameter),t_{med} is the median time to repair and is estimated by $\hat{t}_{med} = e^{\hat{\mu}}$

The probability of a repair being made in time t is found by using the relationship between the normal and lognormal distributions and is given by

Pr (T $\leq$ t) =F (t)

$$= \emptyset\left(\frac{1}{\sigma}\ln\left({}^{t}/_{t_{med}}\right)\right) \qquad (13)$$

Where $F(t)$ is the lognormal cumulative distribution function for repair which is equal to the standardized normal cumulative distribution. The mean time to repair is the mean of the lognormal distribution, which is related to the median time to repair as;

$$\text{MTTR} = t_{med}.exp\left\{\frac{\sigma^2}{2}\right\} \qquad (14)$$

4. RESULTS AND DISCUSSION

In order to obtain the mean time to restore (MTTR), the summary statistic is needed. This is shown in table 1:

Table 1: Summary Statistics

	TTR
Mean	1.705649
Standard Error	0.087653
Median	1.25
Mode	1.25
Standard Deviation	1.787768
Sample Variance	3.196114
Range	18.5
Minimum	0.41
Maximum	18.91
Sum	709.55
Count	416

Mean Time Analysis

Table 1 shows the summary statistics for the TTR data.

$$MTTR = \frac{CTTR}{Total\ number\ of\ restoration} = \frac{709.55}{416} = 1.705649 hours$$

The Mean Time To Restore (MTTR) was found to be 1.705649 hours which indicates the average time of each outage. Moreover it was observed that complete power outage occurred 416 times in Uyo L.G.A between January 2014 and December 2018.

The trend test for this work has been carried out graphically. The trend test for TTR data is shown in figure 1.

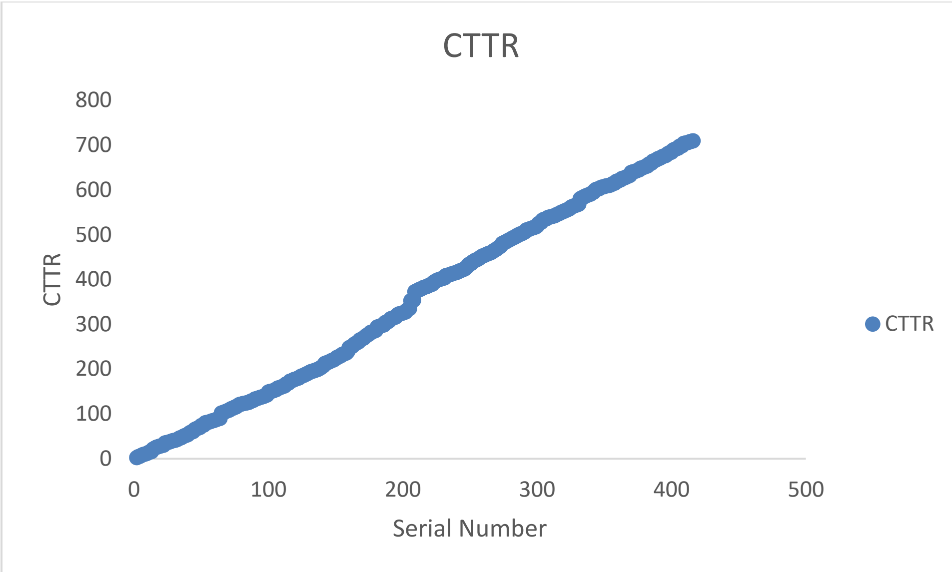

Figure 1. trend test of CTTR

A test for serial correlation was performed to find out the relationship between the two variables ($TTR_{(i)} and\ TTR_{(i-1)}$). The test was performed graphically as shown in figure 2.

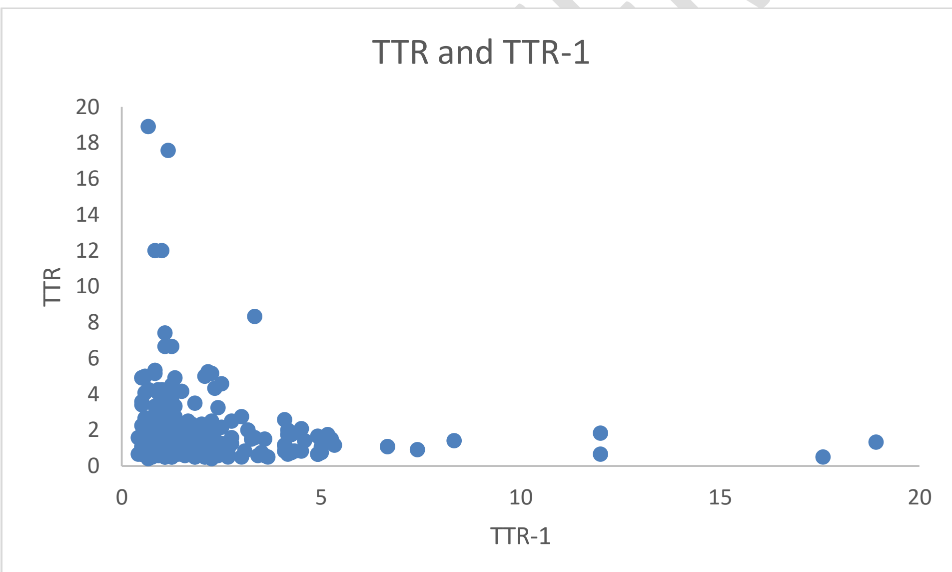

Figure 2: Correlation test for TTR

Serial Correlation and trend tests for TTR data

As earlier stated, the trend test for this work was performed graphically. Before the data is fitted, it is necessary to find out whether the data has a trend that is if the restoration rate for the system is increasing, decreasing or constant. This was done by plotting the cumulative time to restore against the number of restorations.

Figure 2 represents the scatter plot for TTR data. The scatter plot between $(TTR_{(i)} and\ TTR_{(i-1)})$ shows that the data were scattered, therefore there is no serial correlation between two consecutive restorations. This validates the assumption that TTR is independently and identically distributed.

The Easy-Fit reliability software package was used to perform the maximum likelihood estimation and the goodness-of-fit test. The result is shown in table 2

Table 2: parameters estimates and goodness of fit statistics of fitted distributions for TTR data.

Data	K-S	Anderson Darling	Chi Square	Best Fit	Parameter
TTR	0.09483	4.2667	22.151	Lognormal	$\sigma = 0.6374$
					$\mu = 0.28256$
	0.15701	22.154	68.767	Weibull	$\alpha = 1.8303$
					$\beta = 1.8012$
	0.24282	49.922	247.92	Normal	$\sigma = 1.7878$
					$\mu = 1.705$
	0.24687	32.296	222.43	Exponential	$\lambda = 0.58629$

Table 2 shows the maximum likelihood estimates for the parameters of the four probability distributions using the TTR data. The mean (μ) and standard deviation (σ) of the Lognormal distribution were found to be 0.28256 and 0.6374 respectively. The shape parameter (α) and scale parameter (β) of the Weibull distribution were 1.83303 and 1.8012 respectively. The estimate of the parameter (λ) of exponential distribution was found to be 0.58629 while the mean (μ) and standard deviation (σ) of the Normal distribution were found to be 1.705 and 1.7878 respectively.

Table 2 also shows the values of the Kolmogorov-Smirnov test, Anderson Darling test and Chi-Square test used for fitting the four probability distributions on the TTR data. The best fit distribution for TTR data was found to be the lognormal distribution because all the earlier mentioned tests give the least values when the lognormal is fitted.

5. CONCLUSION

Modelling the Power Outage Data

Based on the results of our analysis, the maintainability of electricity is the probability that electric power outage will be restored within time t, this is given by the cumulative distribution function of the lognormal repair distribution as

$$M(t) = P(T \leq t)$$

$$= F(t)$$

$$= \emptyset \left(\frac{1}{\sigma}\, ln\left({}^{t}/{}_{t_{med}}\right)\right)$$

$$= \emptyset \left(\frac{1}{0.6374}\, ln\left({}^{t}/{}_{t_{med}}\right)\right)$$

$$= \emptyset\ (1/0.6374\ \ ln(t\ /\ e^{\hat{\mu}}\ ))$$

$$= \emptyset\ (1/0.6374\ \ ln(t\ /\ e^{0.28256}\ ))$$

Therefore, electric power restoration follows the lognormal distribution and its maintainability for a given time t can be obtained by

$$M\ (t) = \emptyset\ \left[\frac{1}{0.6374}\ ln\ \left({}^{t}/_{e^{0.28256}}\right)\right]$$

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