Original Research Article

MAINTAINABILITY MODELLING OF TOTAL POWER OUTAGE 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. The data was subjected to both descriptive and inferential analysis. 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, $M(t) = \emptyset\left(\frac{1}{0.6374}\ln\left({t}/{e^{0.28256}}\right)\right)$. Furthermore, it was observed that the lognormal distribution was the best distribution to model the maintainability of the electric power supply in Uyo.

KEYWORDS: Maintainability, Power Outage, Time To Restore, Lognormal 2-Parameter Distribution, Exponential Distribution, Maximum Likelihood Estimation.

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. Furthermore, Nigeria's population is growing, which suggests that the number of electric power users is growing as well, necessitating a higher level of power supply for Nigeria's economic operations. According to Blischke and Murthy (2003), "the repercussions of system failure are numerous and diverse, yet almost every failure has an economic impact. A power outage causes not only a loss of productivity, but also a loss of quality and timely services to consumers, as well as safety and environmental issues".

Nonetheless, electricity is critical, and man cannot live without it. It plays an important part in the industrial growth and development of the world's countries. Because of its significance, homes, commercial and governmental enterprises, as well as multiple institutions and research centers, have taken various steps to ensure the provision of consistent electric power in their domains, including the use of private fuel generators or solar generators. Nigeria, for her part, is investing heavily to ensure that the country has a consistent power supply (Nnanna et al 2011). In order for Nigeria to be among the best economies in the world, she needs to guarantee that epileptic power supplies and power outages are a thing of the past. An in-depth investigation and evaluation of power outages needs to be handled seriously in order to solve the problem of power outages.

Maintainability is a well-known performance indicator in system analysis, and it is regarded as a useful starting point for system improvement (Saraswat and Yadava, 2008; Danjuma et al., 2022). Several firms and industries have boosted their specifications in response to the rapid rise in the development of scientific and technological systems, as well as increased competition among providers of services to implement sufficient and appropriate management techniques for the systems in order to improve their availability and compliance with acceptable guidelines (Aly et al., 2018). The key argument in this scenario is that a system or services may not be effectively improved until the system's maintainability is fully understood. As a result, understanding maintainability is essential for improving electric power availability. In this paper, we examine the maintainability models for the epileptic electricity power supply in some parts of Nigeria, using Uyo as a case study. The rest of the papers are as follows, section 2 looks at some literature review, section 3 examines the materials and methods, section 4 shows the results and discussion, while section 5 concludes the paper.

2. LITERATURE REVIEW

In this section, we look at some works carried out on the usefulness and applications of maintainability. Gupta et al. (2011) proposed “certain aspects of maintainability in bulk material handling system design and performance measures in the design and selection of bulk material handling equipment and systems in their research. They discuss belt and pneumatic conveying design, excavator stacker and reclaimer exterior miners design selection and application, testing and examination of the primary causes of equipment damages, equipment-related injuries, and the maintainability of equipment aspect of ore degradation during handling and modeling in their research”.

“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).

Kajal et al. (2003) proposed “using the MATLAB Genetic Algorithm tool to optimize the steady-state availability of a load management system. The researchers reported the failure and repair rates from the historical maintenance sheet and optimized them from 96.20% to 98.87% utilizing a mathematical formulation and a probabilistic approach. They used the Markov birth-death process to construct the Chapman Kolmogorov difference differential and argued that in order to attain the highest level of availability, maintenance and failure rates of the subsystems must be maintained. The researchers concluded that higher repair rates can be achieved by employing more trained workers and utilizing better repair facilities, while lower failure rates can be achieved through good design, the use of reliable machines, the implementation of a proper preventive maintenance schedule, and the provision of 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".

Danjuma et al. (2022) evaluated the maintainability, time to failure, and mean time between failures of a series-parallel system with four subsystems. The units in each subsystems were assumed to have a failure and repair rates with exponential distribution. Their findings show that when the overall system failure rate is low and the supporting units have been activated, the ideal system reliability can then be achieved.

Tu et al. (2016) used "the digital enterprise lean manufacturing interactive application (DELMIA) to analyze and evaluate the maintainability of flexible cables. They suggested a flexible cable maintainability evaluation model that could be used in the DELMIA virtual maintenance environment to evaluate the cable maintainability design using 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

The data for this study was gathered from the record unit of the Port Harcourt Distribution Company (PhED) Uyo. The statistics included the uptime and downtime of electric power in Akwa Ibom State's Uyo local government area from January 2014 to December 2018.

Weibull 2 -Parameter Distribution:

The pdf for Weilbull 2 -parameter distribution is given by

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

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

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

Because it has a constant failure rate, λ, the exponential distribution is useful in the study of reliability engineering. The distribution has also been proven to be particularly beneficial in simulating the lifespan of mechanical and electrical system components.

Maintainability

Maintainability is defined as the likelihood that a particular active maintenance operation for an item under specified conditions of usage may be completed within a specified time interval when executed under specified conditions and utilizing specified process and resources (Dhillon 2008). A product's maintainability is a function of time t and may be represented 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

$$M(t) = \int_o^t f^1(t)\,dt \quad (6)$$

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 means that a specific probability distribution can be utilized to model the system. If the data set does not meet the iid requirements and probability distributions are employed for modeling, the results and conclusions of the analysis may be incorrect (Kumar and Klefsjo, 1992).The iid assumption will be graphically proved in this work using both the trend test and the serial correlation test.

The Trend Test

The cumulative time to restore (CTTR) is shown against the cumulative repair number when employing the trend test. “If a line formed through the data points resembles a concave upwards or concave downwards trend, the system is either improving or degrading. If the line formed between the data points is nearly straight, the data is free of the trend and the data set is identically distributed" (Kumar et al., 1989).

The Serial Correlation Test

The (i-1)th TTR is shown against the ith TTR in the serial correlation test. If the plotted data points are randomly distributed with no discernible pattern, it suggests that the data set is free of serial correlation, which implies that the data points in the data set are independent of one another (Kumar et al., 1989).

Models for Data Analysis

TTR data analysis is used to model the system. A goodness of fit test is used to identify the best-fit probability distributions, and the maximum likelihood estimation method is used to estimate the parameters for the best fit distribution.

TTR Data Analysis

The primary goal of TTR data analysis is to model the system's healing mechanisms. This is accomplished by estimating parameters to match the distributions to the data collection and fitting a probability distribution that best represents the restoration data. The following probability distributions are widely used for life and repair distributions: Exponential distribution, Normal distribution, lognormal distribution, and Weilbull distribution.

Goodness-Of-Fit-Test

The idea of goodness-of-fit testing is to see how closely the chosen distribution matches the real data set. The p-value test, chi-squared test, Anderson-Darling test, and Kolmogorov-Smirnov test are some of the most commonly utilized tests. The Kolmogorov-Smirnov test is the most commonly employed for maintainability analysis.

Modified K-S Test

Let F(t) be a continuous distribution that will be tested as the parent distribution of a 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 analyze the largest difference at points where the empirical distribution function EDF is bigger than F(t), and the largest difference at points where the EDF is less than F(t) as well

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

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

Then the K-S Statistic is given as

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

The probability distribution with the lowest K-S value is deemed to provide the greatest fit when using the K-S Statistic (Reliasoft, 2007; Mehrannia and Palegohar, 2014).

Anderson-Darling Test

Anderson-Darling Statistics are based on the empirical distribution function (EDF), which is denoted by F_n(t) and defined as;

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

The plot of $F_n(t)$ against t is a step function that gives the proportion of observations that are less than or equal to t. if H_O is true, the EDF should have the same shape as 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 used, which can yield a z-set that is uniformly distributed on the [0,1] interval if the value of the parameter θ is known. The formula for calculating the statistic using the z-set is given by;

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

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

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

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 K-1-Number of estimated parameters as Chi-Square distribution degrees of freedom. The probability distribution with the lowest x^2 value is deemed to be the best match when utilizing the Chi-Square Statistics (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. Because it is more resilient and has the qualities of unbiasedness, consistency, sufficiency, and minimum variance for large samples, the Maximum Likelihood Estimation (MLE) approach will be utilized to estimate the parameters in this work.

Maximum Likelihood Estimator (MLE)

In general, the maximum of the following likelihood functions with regard to the unknown parameters: θ_1 , θ_2 ,…, θ_k must be obtained when determining the MLE for any probability distribution with complete data.

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

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

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 λ is given by

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

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

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

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

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

When combined with the Newton Raphson technique, the maximum likelihood method can only be used to obtain parameter estimates for the Weibull distribution (Dibal et al., 2016). In addition, by solving the equations, the estimations can be obtained;

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

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

However, for this study, the "Easy-fit" reliability software was utilized to perform both the goodness-of-fit test and the MLE parameter estimate.

Maintainability Models

Let T be a continuous random variable indicating the time required to repair a system with 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 ≤ 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. Furthermore, between January 2014 and December 2018, Uyo L.G.A experienced 416 total power outages.

The trend test for this study was done graphically. Figure 1 depicts the trend test for TTR data.

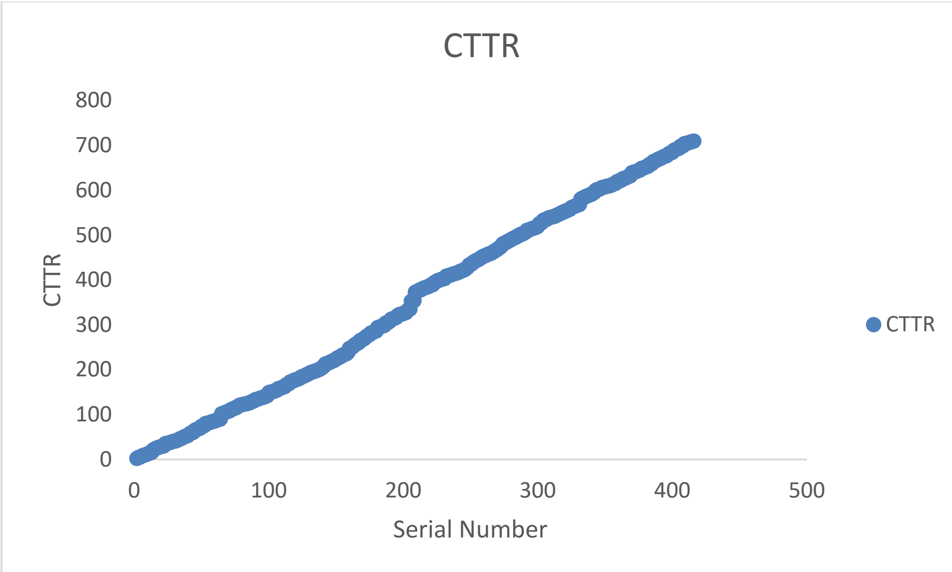

Figure 1. trend test of CTTR

To determine the relationship between the two variables ($TTR_{(i)} and\ TTR_{(i-1)}$), a serial correlation test was used. The test was carried out graphically, as illustrated in Figure 2.

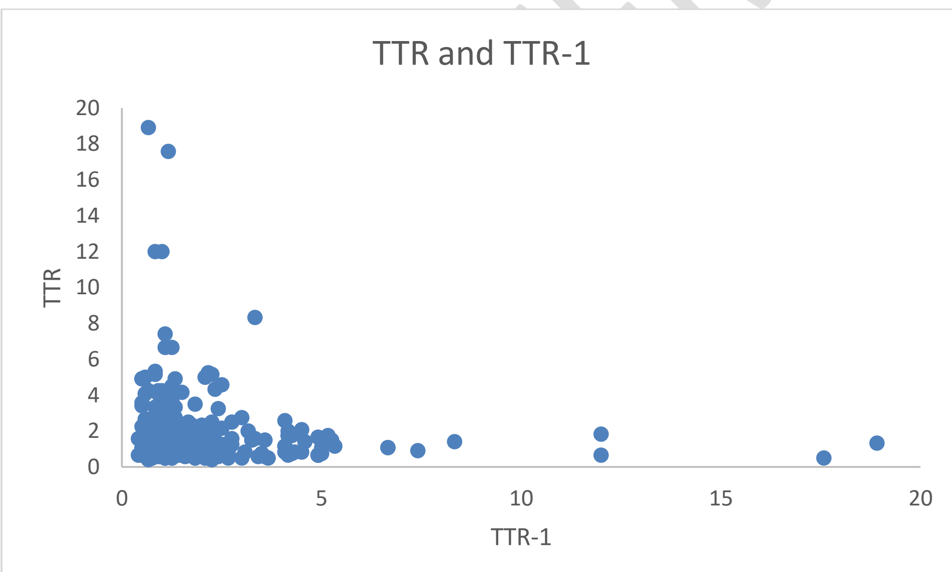

Figure 2: Correlation test for TTR

Serial Correlation and trend tests for TTR data

As previously indicated, the trend test for this study was done graphically. Before fitting the data, it is required to determine whether the data has a trend, that is, whether the system's restoration rate is increasing, decreasing, or constant. This was done by plotting the cumulative time to restore against the number of restorations. From the trend plot in Figure 1, the restoration rate showed an upward trend.

The scatter plot for TTR data is shown in Figure 2. The scatter plot between ($TTR_{(i)} and\ TTR_{(i-1)}$) demonstrates that the data were scattered, and hence there is no serial correlation between two subsequent restorations. This verifies the premise that TTR is distributed independently and identically.

The maximum likelihood estimation and goodness-of-fit test were carried out using the Easy-Fit reliability software program. Table 2 shows the outcome.

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	$\lambda = 0.58629$

The maximum likelihood estimates for the parameters of the four probability distributions utilizing TTR data are shown in Table 2. The Lognormal distribution's mean (μ) and standard deviation (σ) were found to be 0.28256 and 0.6374, respectively. The Weibull distribution's shape parameter (α) and scale parameter (β) were 1.83303 and 1.8012, respectively. The parameter (⋏) of the exponential distribution was estimated to be 0.58629, whilst the mean (μ) and standard deviation (σ) of the normal distribution were estimated to be 1.705 and 1.7878, respectively.

The values of the Kolmogorov-Smirnov test, Anderson Darling test, and Chi-Square test used to fit the four probability distributions on the TTR data are also shown in Table 2. The lognormal distribution was found to be the best suited distribution for TTR data because it produced the lowest values in all of the preceding tests.

5. CONCLUSION

This work examined the epileptic power supply data of uyo in Nigeria. The descriptive analysis of the data showed a trend indicating that the restoration rate has an upwards trend. In addition, there was no evidence of serial correlation between two consecutive restorations hence validating the iid assumption of the TTR. Furthermore, employing multiple competing distributions, maximum likelihood estimates and goodness of fit tests were performed. According to our findings, the best model with the lowest K-S value was the Lognormal distribution. This means that the TTR's maintainability model is given by the lognormal repair distribution's cumulative distribution function 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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