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Maintainability Analysis of a Wheel Loader Engine in the Construction Industry

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Abstract

The maintainability analyses of a repairable mobile earth-moving equipment was undertaken. Using the analytical research approach, the Reliability, Availability and Maintainability models of the system were established through tedious computations to reveal the most pertinent candidate theoretical distributions that best modelled each quantity. Data was taken from a typical example of a Wheel loader Engine used in Crushed Rock Industries (NIG) Limited, located in Ebonyi State Nigeria. The results show that the equipment can retain up to 0.9 Reliability after 12o hours of operation. The results also show that the Engine system can be available for over 98% when operated under the stipulated design conditions, while about 17.38hours is the mean period required for the engine to be restored to its normal operating condition after a particular failure, when maintenance is carried out according to the designers prescription. The work further shows that mathematical modeling can be a good means of establishing actionable maintenance policies.

Keywords

Reliability, Availability, Maintainability, Wheel loader, Engine.

1. Introduction

Reliability, availability, and maintainability (RAM) are crucial system characteristics that determine product utility and life cycle cost. According to (Baboria & Devi, 2022)), they originated during World War II, when Germans built chained armor machines that could operate in any environment. RAM analysis has been developed to minimize operational costs and increase system reliability. Reliability refers to the capacity of an equipment to execute its function within a specified time frame (Agrawal et al., 2019), while availability is the likelihood of an item being ready to use when needed (Bizuayehu, 2022). Maintainability is the likelihood of a component being repaired to a healthy state within a specified time (Ebeling, 1997) and higher maintainability leads to shorter repair (ASQ, 2011). RAM analysis is essential for improving equipment efficiency, reducing operational costs, and extending the overall life span of a system. Wheel loaders are mobile earth-moving equipment used in production operations, capable of loading bulk soil or rock (Achelpohl, 2018) with a bucket capacity of less than 70 cm3. They can transport materials within 500–600 feet and have a lifespan of 12–20 years (Alegre, 2019; Xiao & Watson, 2019). They are crucial in developing countries like Nigeria for efficient production. The engine system is critical for a wheel loader combusting fuel to generate power. It comprises pistons, valves, heads, bearings, hardware, timing parts, ignition, injection, fuel filters, radiators, and more, working in series for maximum combustion. However, abrupt failures can occur due to climatic conditions and working environments, leading to catastrophic consequences. RAM analysis helps identify areas for improvement, establish maintenance intervals, and plan maintenance based on availability. Corrective maintenance is crucial for ensuring wheel loader availability and reliability, but it can result in increased operational costs, unpredictable failures, and extra labor time.

1.1 **Aim and Objectives**

The study aims to evaluate the maintainability of the engine, by specifying a repair time probability distribution for the system. The objective is to establish an operational condition of the system as well as estimate the remaining useful life under which maintenance is to be performed.

2. **Literature Review**

The use of RAM in studies of system maintenance has gained popularity among scholars and researchers in specifying reliability and maintainability of various systems. For instance, Wang and Zang (2021) evaluates heavy-duty diesel engine reliability using after- sale maintenance information. Baliwangi, (1999) studied the RAM of a shuttle tanker propulsion system, while Rizqika and Mahbubah (2022) evaluated heavy-duty equipment breakdowns using a wheel loader. Studies on the crankshaft failure of wheel loader diesel engine as well as overloading effects on wheel loader buckets reliability are available (Aliakbari et al. 2018; Achelpohl 2018). Rajaprasad, (2018) evaluated the RAM of a paper machine. The authors concluded that finding wire parts were more critical to failures requiring 4% and 1.5% improvement in maintainability and availability. Ahluwalia et al. (2022) proposed suitable performance and cost functions for off-road heavy-duty vehicles, while Carazas and De Souza, (2007) analyzed gas turbine availability in power plants. There is no particular report on the maintainability of Wheel loader engine known to the authors. Also, the environment of operation of an earth-moving equipment can significantly affect the repair process. In particular, the studied system is used to move crushed rocks (granite) which can differ from a similar engine for moving sandy soil. Hence, this work is seen as a very important investigation to focus on the maintainability of the named wheel loader engine. The research results can aid investors decision on the best repair distribution and acceptable operational condition of engine systems employed in quarry industries.

3. **Methodology**

This study employ the repair time distribution in analyzing the maintainability of the studied system. The most suitable measure due to data availability and proper estimation was the mean time to repair (MTTR). Other measures, just for the mention are the median-time-to-repair, the mode, and the most-likely-repair-time. In execution, historical repair data of the wheel loader engine was extracted from the documents of the case study company. The authors took advantage of the six-Months training at the company to ensure that the data collected actually represented the true situation. As a result, no further confirmation was required. However, the performance data of the engine system was collected with other information, which include time of failure, cause of failure, failing part, time to repair and time of recommissioning. This makes further processing of the data to fish out the inherent repair time mandatory. The inherent repair time may be seen as the integral of other time dependent maintenance activities. These include access time, diagnosis, actual repair or replacement, validation and alignment.

3.1 **Failure and repair time analysis**

The empirical methods are still popular in analyzing repair times because they easily extracts reliability information from real-world failure data, while obtaining key metrics like failure times, candidate distributions, reliability functions, and hazard rate functions, especially when theoretical distributions don't accurately represent observed data.

The mean time to failure and mean time to repair obtainable from the sample mean are given as in Ebeling (1997):

$$\widehat{MTTF} = \sum_{i=1}^{n} \frac{t_i}{n} \tag{1}$$

$$\widehat{MTTR} = \sum_{i=1}^{n} \frac{t_i}{n} \tag{2}$$

3.2 Estimation of candidate distribution

An important exercise in obtaining accurate repair distribution is normally the determination of the best candidate theoretical probability distribution where the data is most suited. For this study, a preliminary statistical analysis of the repair times based on histogram, probability distribution and relationship of the mean with the median indicated a strong affinity of the data with the lognormal and exponential distribution. Therefore, further analysis in this presentation were based on the two most favoured distributions.

3.2.1 Lognormal distribution

In a lognormal distribution, a random variable, T, has a logarithm with a normal distribution. It has boundaries for positive values of t and can take on various shapes. The mean, variance and, reliability of a lognormal distribution are given.

$$MTTF = t_{med}\, exp\left({s^2}/{2}\right) \tag{3}$$

$$\sigma^2 = t_{med}\, exp(s^2)[exp(s^2) - 1] \tag{4}$$

$$R(t) = 1 - \Phi\left\{\frac{1}{s} ln \frac{t}{t_{med}}\right\} \tag{5}$$

3.2.4 Exponential reliability distribution

The exponential distribution is a significant reliability distribution with constant failure rates, indicating that random or changing failures conform to this distribution. The mean, variance and, reliability of an exponential distribution are given by Ebeling as:

$$MTTF = \frac{1}{\lambda} \tag{6}$$

$$\sigma^2 = \frac{1}{\lambda^2} \tag{7}$$

$$R(t) = 1 - F(t) = e^{-\lambda t} \tag{8}$$

3.3 Repair-Time distribution

The repair-time distribution is crucial for establishing maintainability, as recurring repair activities can lead to new failures and vary in maintenance personnel's skills. The time needed to diagnose problems can vary depending on luck and problem-solving speed. The likelihood of a repair being completed within time can be determined using model (9):

$$MTTR = \int_0^\infty th(t)dt = \int_0^\infty (1 - H(t))dt \tag{9}$$

For an exponential case;

$$H(t) = \int_0^t \frac{e^{-t/_{MTTR}}}{MTTR} dt = 1 - e^{-t/_{MTTR}} \tag{10}$$

Where the mean time to repair $(MTTR)$ is the parameter of the distribution

If the repair process were to be a log-normal distribution, the reliability is given as:

$$H(t) = \Phi\left\{\frac{1}{s} ln \frac{t}{t_{med}}\right\} \tag{11}$$

The median time to repair is directly proportional to the mean time to repair, which is the mean of the lognormal distribution.

$$MTTR = t_{med} e^{s^2/2} \tag{12}$$

3.4 Identification of theoretical failure and repair distributions

A statistical test using essential system data is normally an option for determining if measured times deviate from a distribution. This involves creating a histogram, dividing failure times, and calculating the sample mean, median time to failure, as well as the standard deviation. The failure process information can be used to model the fitting distribution. However, the dominant characteristics of a particular distribution in quite an early stage can be a pointer to the most likely distribution. In which case, reducing the analysis further by estimating the parameters of the benefiting distribution and implementing a goodness of fit test thereafter. This was actually the case adopted for this research.

3.5 Estimation of Dominant Distribution parameters

Maximum likelihood estimation (MLE) is a statistical technique that optimizes the likelihood function with observed data, particularly for discrete random variables, to accurately characterize the resulting distribution. According to Ebeling (1997), MLE of the lognormal and exponential distributions parameters can be obtained using equation (13) and equation (14) respectively.

$$\hat{t}_{med} = e^{\hat{\mu}} \tag{13}$$

Where $\hat{\mu} = \sum_{i=1}^{n} \frac{lnt_i}{n}$ $and\ \hat{s} = \sqrt{\frac{\sum_{i=1}^{n}(lnt_i-\hat{\mu})^2}{n}}$

$$\hat{\lambda} = \frac{r}{T} \tag{14}$$

Where r denotes the number of failures while T represents the total time of the test given as:

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

Hence, r = n, for a complete data.

3.6 Goodness-of-fit test

A goodness-of-fit test compares a sample's fit to a theoretical probability distribution function, calculating a statistic based on failure rates and comparing it to a crucial value, with acceptance based on significance level and sample size. Specific tests models were adopted for this research rather than general test, in order to tactically tailor the data to the particular distribution or entirely reject the distribution if it fails the test.

3.6.1 Kolmogorov-Smirnov test for lognormal distributions:

The hypothesis for this test is given as:
H_0: $failure\ rates\ are\ lognormal$; H_1: The failure rates are not lognormal.

For a log-normal failure and repair, Ebeling (1997) gave the test statistic equation as:

$$D_1 = max_{1\le i\le n}\left\{\Phi\left(\frac{lnt_i - \bar{t}}{s}\right) - \frac{(i-1)}{n}\right\} \tag{15}$$

$$D_2 = max_{1\le i\le n}\left\{\frac{i}{n} - \Phi\left(\frac{lnt_i - \bar{t}}{s}\right)\right\} \tag{16}$$

If $D_{critical}$ > D_1, H_0 is accepted; if $D_{critical}$ is less than or equal to D_n, H_1 is accepted.

3.7. Bartlett's Test Exponential Distribution

Bartlett's test statistics for the exponential distribution is presented in equation (17). It has two hypothesis given as:
H_0 = exponential failure times; H_1 = non-exponential failure times.

$$B = \frac{\left[ln\left(\left(1/_{r}\right)\sum_{i=1}^{r} t_i\right) - \left(1/_{r}\right)\sum_{i=1}^{r} lnt_i\right]}{1 + (r+1)/_{6r}} \tag{17}$$

The test statistic B has a chi-square distribution with a degree of flexibility of r - 1 as presented in equation (18).

$$X^2_{1-\frac{a}{2}\ ,r-1} < B < X_{\frac{a}{2}\ .r-1} \tag{18}$$

The level of significance $(\boldsymbol{\alpha})$ is the probability of rejecting the null hypothesis and accepting the alternative hypothesis, typically ranging from 5% to 1%. A statistical significance test helps to analyze the accuracy of a study's findings. Equation (19) can be applied in elucidating the maximum likelihood estimate of this parameter.

$$\hat{\lambda} = \frac{r}{T} \tag{19}$$

4. Data Collection

This study utilized the historical data from Crushed Rock Industries Nigeria Limited's Mechanical Workshop Unit to quantify the maintainability of the Wheel loader 980G engine system. The data covered the period between March 2021 and February 2023. Table 1 presents the original data, which were further processed to obtain the inherent data in only two subtitles of time-to-failure and time-to-repair for the purpose of space.

Table 1: Wheel Loader 980G TTF and TTR data for engine system

S/N	MONTH (YEAR)	TTF (hrs)	TTR (hrs)
0	MAR (2021)		0.75
1	MAR (2021)	171.00	22.75
2	MAY (2021)	759.50	14.05
3	AUG (2021)	2294.22	52.30
4	DEC (2021)	3042.92	6
5	DEC (2021)	171.83	0.83
6	FEB (2022)	1530.33	19.83
7	JUNE (2022)	2889	0.83
8	JUNE (2022)	116.58	17.92
9	JULY (2022)	479.08	1
10	SEPT (2022)	1300	49.42
11	OCT (2022)	1076.8	5.15
12	NOV (2022)	652.5	0.833
13	FEB (2023)	1915.17	1.583

5. Result and Discussion

Using the set of data for time-to-failure from Table 1 with a class interval of 5, decided upon application of Sturge's rule, the following set of results were obtained: $\widehat{MTTF} = 1261.46hrs$, the median time is $\hat{t}_{med} = 1076.8$. For the standard deviation $\widehat{S},\ Where\ S^2 = \sum_{i=1}^{n=13} \left(t_i - \widehat{MTTF}\right)^2 /_{n-1}$; $\hat{S} = 1014.33hrs$. The sample mean is higher than the median, suggesting a right-skewed failure process. Therefore the lognormal or exponential distribution were most suspect. Testing for the two distributions became necessary. From equation (13), the maximum likelihood for the lognormal distribution was obtained to be: $\hat{\mu} = 6.700165$hrs. The variance and median were computed respectively to give $\hat{s} = 1.067361$hrs and $\hat{t}_{med} = 812.5397$hrs. Applying the Kolmogorov-Smirnov's test, which is specific to the lognormal distribution, with a significant level of α = 0.10, the statistical test were obtained by Equation (15) through equation (16) as: $D_1 = 0.091607 \quad and \quad D_2 = 0.79673$. Therefore, $D_n = \max\{D_1, D_2\} = 0.79673$.

From standardized normal distribution Table, the value of $D_{critical,\alpha}$ was obtained for $\alpha = 0.1 \; and \; sample \; size \; of \; n = 13$, i.e., $D_{critical,\;0.1} = 0.234$.
Since $D_n = \max\{D_1, D_2\} = 0.79673 > D_{critical,\;0.1} = 0.234$, the null hypothesis is rejected. Thus, the failure process was not from the lognormal distribution. The results of the investigation for the exponential distribution are presented in what follows.
The maximum likelihood for an exponential distribution is given equation (19). Where r denotes the number of failures and T represents the total time of test given as .$\sum_{i=1}^{n=13} t_i$ =16398.98, Hence $\hat{\lambda} = \;0.000793$. This study uses Bartlett's statistical test specific to the exponential distribution, with a significant level of α = 0.10, to examine the relationship between the variables. From equation (17) and (18), $B \; = 9.70$; and the null hypothesis is accepted if $X^2_{1-\frac{\alpha}{2}\;,r-1} < B = 9.70 < X_{\frac{\alpha}{2}\;.r-1}$. For α = 0.10, $\frac{\alpha}{2} = 0.05, 1 - \frac{\alpha}{2} = 0.95$, with $r - 1$ as the degree of freedom, and from Chi-square significance Table; $X^2_{0.95,12} = 5.23$ and $X^2_{0.05,12} = 21.0$. Since $X^2_{0.95,12} = 5.23 < B = 9.70 < X^2_{0.05,12} = 21.0$. The null hypothesis Ho was accepted, indicating that the Failure times of the wheel loader's engine system came from the exponential distribution.

5.1. Repair data analysis for the engine system

Table 1 presents the set of repair data. A class interval of 5 was decided upon following Sturge's rule presented in Ebeling (1997). From equation (2), the mean time to repair is given as 13.807hrs while the median time-to-failure is $5.575hrs$, The standard deviation $\widehat{S}$, $Where \; S^2 = \sum_{i=1}^{n=14} {\left(t_i - \widehat{MTTR}\right)^2}\Big/_{n-1}$, and for n = 14, was found to be $17.559hrs$.

The relationship of the mean to the median can help characterize the nature of the matching repair distribution. For instance, the two quantities are nearly or approximately equal for symmetrical distributions, such as the Weibull or Normal distributions. The sample mean and the standard deviation are most often equal for an exponential distribution, but the difference between them is clear for the engine repair data under analysis. In this case, the sample mean is significantly far from the median, suggesting a right-skewed repair process, potentially associated with lognormal or exponential distributions. Additional to this, Rajpal et al (2006) had already reported that repair times most often follows a lognormal distribution. On the basis of the above premise, the parameters of the two closest distributions were estimated and tested in turn, to tailor the repair data to the appropriate model.

5.1.2 Compatibility test for exponential distribution

The maximum likelihood for an exponential distribution was deduced from equation (19).
Where r denotes the number of repair points and T represents the total time of repair given as $\sum_{i=1}^{n=14} t_i$. Therefore, the maximum likelihood of the parameter estimate was found to be $\hat{\lambda} = \;0.07245hr$. The specific Goodness-of-fit-test Recommended for the Exponential distribution is the Bartlett's statistical test. Applying equation (17) through (19) with a significant level of α = 0.10, $B \; = 24.1$. The null hypothesis is accepted if $X^2_{1-\frac{\alpha}{2}\;,r-1} < B = 24.1 < X_{\frac{\alpha}{2}\;.r-1}$, at $r - 1$ as 13 which is the degree of freedom. From Chi-square significance table; $X^2_{0.95,13} = 22.4$, and $X^2_{0.05,13} = 5.89$. Since $X^2_{0.95,13} = 22.4 < B = 24.1 > X^2_{0.05,13} = 5.89$, the null hypothesis is rejected, indicating that the repair times of the wheel loader's engine system did not come from the exponential distribution.

5.1.3 Compatibility test for the lognormal distribution;

The maximum likelihood parameters of the Lognormal distribution are based on the sample mean, $\hat{\mu}$, and variance, $\hat{s}$. Interested readers that may be concerned with the derivations can refer to any standard statistical textbook, (see for example Ross, 1987). Accordingly, $\hat{\mu} = \;$ 1.6100hrs and $\hat{s}$ =1.5782 while $\hat{t}_{med} = e^{\hat{\mu}} =$ 5.002hrs. Kolmogorov-Smirnov's test is ideal for the lognormal distribution. Hence, from equation (15) through (16), and using a significant level of α = 0.10, the statistical tests are found to be $D_1 = 0.164221$ and $D_2 = 0.193603$. Recall that; $D_n = \max\{D_1, D_2\} = 0.193603$. From standardized normal distribution Table, the value of $D_{critical,\alpha}$ was obtained for $\alpha = 0.1 \; and \; sample \; size \; of \; n = 14T$ and found to be 0.207.
Since $D_n = \max\{D_1, D_2\} = 0.193603 < D_{critical,\;0.01} = 0.207$, the null hypothesis is accepted. Thus, the failure process came from a lognormal distribution.

5.2 Reliability assessment

For the engine system, the failure process was found to be an exponential distribution with shape parameter $\lambda = 0.000793$. Equation (20) presents the reliability model for the Wheel loader engine system after a given operational time.

$$R(t) = e^{-0.000793t} \tag{20}$$

With model (20), it will be possible to obtain the reliability level of the system at any given period, while the maintenance Engineer is expected to integrate other maintenance resources in deciding the exact level of operational Reliability for the Engine system. For example, assuming an operational time of 120 hours (5 days) of operation, model (20) can be applied to ascertain the Reliability level of the Engine System, which is 0.90923.

5.3. Maintainability assessment

The engine system repair time model follows from the analysis defining the log-normal distribution as the candidate for further analysis. Equation (11) presents the general cumulative distribution function H(t). From equation (11) t_{med} *and* s are distribution parameters found to be 5.002 and 1.5782 respectively, and Φ is the standardized normal variate. Hence, the repair function was established as shown in equation (21).

$$H(t) = \Phi\left\{\frac{1}{1.5782} ln \frac{t}{5.002}\right\} \tag{21}$$

Employing equation (11), the MTTR was obtained to be $MTTR = 17.38hrs$.

5.4. Availability assessment

Analytical modeling of wheel loaders primarily relies on failure and repair data, making inherent availability the most suitable fit for determining system availability. Engine system availability can be calculated as

$$\boldsymbol{A_{inh(ENG)}} = \frac{\boldsymbol{MTTF}}{\boldsymbol{MTTF+MTTR}} \tag{22}$$

The inherent availability of the wheel loader Engine gave $\boldsymbol{A_{inh(ENG)} = 0.989}$

Thus; wheel loader engine can be available for over 98% of its operating time when operated under the stipulated conditions and under the normal design environment.

6. Conclusion

This research work has fulfilled its cleavage to presenting a logical evaluation of data required to improve wheel loader maintenance in Nigeria, especially in quarry or construction industries, by evaluating the RAM quantities. The study used two years of failure and repair data from the crushed rock industries (NIG) to perform analytical and RAM analysis. The project improved knowledge of RAM behavior in heavy-duty machinery, established a RAM analysis model, and created a framework for monitoring heavy-duty equipment performance.

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Biographies

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