Availability Analysis of Repairable Pumping System in Oil Refinery Gas Plant

P. A. Ozor, C. Mbohwa

ABSTRACT: This paper presents a constructive technique that can be used in analysing the availability of service producing repairable systems. The main focus is to provide an alternative approach that can be applied by a wider range of maintenance practitioners, especially in situations where mathematical complexities of existing models impose significant practical application difficulty in assessment of system availability measures. The procedure used involve careful combination of simpler aspects of selected existing models and empirical methods to assess most of the availability variables of a repairable system. In particular, a case of a pumping system in a gas power plant in Nigeria which is addressed as G4 Company for confidentiality was undertaken. The information on the operation and maintenance of the system were used to identify the best life time distribution for modelling the system availability. The results reveals that important system availability parameters like the mean time to failure, repair rate and remaining useful life, among others can accurately be estimated with the procedure described in the study.

Keywords: Repairable system, availability, existing models, empirical methods, practical application

I INTROCUCTION

Industrial repairable systems can be categorized as those systems that can be restored to a functional operable state by maintenance actions upon failure. Regardless of the maintenance policy adopted, a maintained system can be placed between two extremes of post maintenance states: perfect state, which are often referred to “as good as new” [1] or minimal change “as bad as old” [2-3]. A vast majority of other maintenance policies outside the post repair state assumptions are partly admixtures or intermediates of the two extremes. The emphasis of formulating most of the maintenance policies has been to increase system availability, which in turn reduces idle time, maintenance resource costs and increase product quality and throughput. High system availability must be born in mind right from the product design stage, such that adequate provisions are made to ensure that the product continues to operate at its installed capacity. The most efficient method of ensuring high system availability is through provision of identical system replicas that can immediately replace the operating system in case of any malfunction or failure. While this option is less time consuming and inevitable for non-repairable systems, it comes with prohibitive costs for many repairable systems and will less often be considered where investment capital impose a limitation to efficient plant operation. The alternative is full dependence on maintenance actions for achieving and retaining expected system availability. Researchers have toiled on the concept of system availability for almost one half of a century, during which period, numerous policies have been suggested for different categories of the performance measure. The definitions of various aspects of availability of maintainable systems are found in literatures [4-5]. Understanding system behaviour and detecting the time of failure incipience as well as the best period of maintenance can offer some benefit to availability upkeep effort. Some authors have made significant attempt to prescribe availability improvement and maintenance policies for systems subjected to intermittent checking and rechecking. Sobreal and Ferreira [6] describe how inspection can be used to detect hidden failures. Qiu et al [7] is another example of a formulation in the category. The authors utilize analytical results to derive the optimal inspection period that minimizes long term cost rate or maximizes steady-state availability. Dynamic analysis can be conducted for software and other critical systems to understand system behaviour and explore availability stabilization strategies that conforms to the availability requirements of such systems [8-11]. Upon detection of failure, the necessary maintenance actions can forestall the occurrence of the failure. Attempts have been made to develop maintenance models that prolong the next time of repair actions on a given system under imperfect repair policies. Imperfect repairs are more realistic to achieve because of hidden defects that might have been incurred by a component, subsystem or the system as a whole since its installation. Microstructural defects, environmental and weather effects can all affect the system during mission accomplishment, such that a perfect repair outside full replacement will be elusive. Repairable systems are normally subjected to series of imperfect repairs before replacement and scraping. There exist availability models suggested for systems undergoing series of imperfect repairs [12], as well as others dedicated to optimizing system availability [13-14]. Cykyay and Ozekici [15] analyse some system performance measures, namely; mean time to failure, system reliability and steady-state availability and adequately characterize the mathematical structure of each. The quantities were expressed as a function of the failure rate of the component. Despite the presence of vast literature on system availability measures and improvement models, there are still wide gaps in application of the models in the industry, especially in developing economies. This can be traced to the mathematical complexities associated with most of the models, without exemption of the ones mentioned in this paper. The analysis underlying the derivations as well as some of the assumptions frighten the maintenance

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practitioners to the extent that attempting to apply them in the industry continues to pose great challenge. The fire brigade result is that no particular availability model finds the desired application intended by its formulators. The maintenance personnel frequently relies upon no particular availability strategy, which has a lot of negative consequences. In particular, failures can be induced to the system by zealous technicians on irregular inspection, in an attempt to forestall stoppage of a system thought to fail soon. To address this trend, an availability model or group of literature models with relative ease of understanding and application, especially to the level of majority of a given maintenance crew can be explored to present a means of estimating availability of systems within the purview of such workers. The final model, though simplified, should be able to consider most of the terms frequently encountered by the intended users in practice, short of notations that can end up scaring any little desire to attempt application of the model.

In this paper, an attempt is made to combine availability models postulated independently in literature [4-5, 16], and use the result to explore the analysis of a pumping system in the gas plant of an Energy company. The company is located in Nigeria, but will be identified in this paper as G4 Company for the sake of confidentiality.

II MATERIALS AND METHODS

Alzghoul and Lofstrand [8] maintains that *"The most common way to detect, predict and avoid failures is to collect and analyse the information produced during the time of operation and maintenance".* Accordingly, qualitative and quantitative research design approaches were utilized in the work. The primary data collected through robust interviews and opinion surveys with the maintenance personnel of G4 Company on the thrust of the work form part of qualitative research. During organised visits, the type of availability improvement strategy in place and the capability of the maintenance crew to practically apply existing mathematical models in maintenance routines were inquired. The historical information on failure and repair of the studied system were abstracted from company archival documents as well as from opinion surveys of staff with over 10 years of experience. There were some intentional lengthy visits targeted at observing operation and maintenance proceedings to further consolidate the authenticity of the collected data. The secondary data used were mainly sourced from extensive survey of literature documents pertaining to system availability and suggested models for enhancement and stabilization. Through the reviews, the simplest model that seemed to have great Industrial applicability appeal to the maintenance crew in the studied stretch were selected for use in modelling the availability. The data as collected were not subjected to further confirmatory test since there were no known method of doing so. The first assumption that the data was correct and represents the information on the failure and repair of the system has to be made. The selected models were applied religiously to analyse the data. The methodological steps followed in the analysis were elaborated and displayed graphically. Effort was made to satisfy the cleavage of the study, which was to present an easy to apply technique of elucidating system availability in areas where complex mathematical formulations on the topic finds very little usage, if it is applied at al.

III ANALYSIS

From Lie et al [4], Inherent availability, A_i, is defined by

$$A_i = \frac{MTBF}{MTBF+MTTR} \quad (1)$$

Where $MTBF$ is the mean time between failures and $MTTR$ is the mean time to repair. It is based solely on failure distribution and repair time distribution. The achieved availability, A_g, includes preventive and unscheduled maintenance and is given by

$$A_g = \frac{MTBM}{MTBM+\overline{M}} \quad (2)$$

Where

$MTBM$ is the mean time between maintenance and $\overline{M}$ is the mean maintenance downtime resulting from both corrective and preventive maintenance actions. Operational availability, A_o, includes ready time, logistics time and waiting or administrative downtime and is expressed by Ebeling [5]**:**

$$A_o = \frac{MTBM+ready\ time}{(MTBM+ready\ time)+MDT} \quad (3)$$

Where

$$ready\ time = operational\ cycle - (MTBM + MDT)$$
$$MDT = \overline{M} + delay\ time$$

MODIFIED OPERATIONAL AVAILABILITY [16]**:**

$$A_{m_i} = \frac{A_{O_i} t_{d_i} T_{pm_i} + A_{O_i}(OC_i - MTBM_i + \overline{M}_i + DT_i)[T_{pm_i} m(t_d)_i + t_{d_i}]}{t_{d_i} T_{pm_i} + A_{O_i}(OC_i - MTBM_i + \overline{M}_i + DT_i)[T_{pm_i} m(t_d)_i + t_{d_i}]} \quad (4)$$

Where:

T_{pm} = mean time between performances of preventive maintenance, t_d = system design or economic life and $m(t_d)$ = expected number of failures in the interval (0, t_d)

Table 1: Sample Failure and Repair data

i	TTF	TTR	$\lambda(t)$	H(t)
1	-	4	0.125	0.037037
2	63.17	4.25	0.001613	0.074074
3	68.92	24.25	0.001324	0.111111
4	198	49.42	0.084104	0.148148
5	221.5	49.83	0.006389	0.185185
6	286.83	55.42	0.004317	0.222222
7	328.5	64	0.008801	0.259259
8	357.5	68.37	0.005242	0.296296
9	388.18	76	0.064103	0.333333
10	413.08	76.65	0.434783	0.37037
11	528.13	76.75	0.00209	0.407407
12	596.75	98.5	0.010197	0.444444
13	642.62	103.17	0.004082	0.481481
14	715.33	115.42	0.010569	0.518519
15	716.42	120.4	0.034722	0.555556
16	733.33	122	0.025246	0.592593
17	918.5	124.33	0.003333	0.62963
18	961.92	143.08	0.0163	0.666667
19	1099.75	147.17	0.002829	0.703704
20	1100.8	172.42	0.013785	0.740741
21	1160.52	178	0.010352	0.777778
22	1177.25	186.05	0.011993	0.814815
23	1281.58	193.63	0.001385	0.851852
24	1460.87	265.82	0.004882	0.888889
25	1580.85	288.58	0.001279	0.925926
26	3379.67	386.33	-0.00037	0.962963

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IDENTIFICATION OF A CANDIDATE DISTRIBUTION

When the data collection stage is completed, the data is sorted and empirical maintenance quantities computed. The next very important aspect of the analysis is selection of the most suitable theoretical distribution that each of the failure or repair data came from. Histogram of the observed times can be plotted as a preliminary investigation into the distribution of choice. Use of too few or too many class intervals can result in incorrect analysis of the data and inability to discern the shape of the distribution. Matters can be simplified by using the Sturge's model in equation (5) to determine the number of intervals. Figure 1 presents the histogram of the time to failure data. The theoretical distributions chosen for the pumping device are Weibull, Exponential. Normal and Lognormal.

$$K = [1 + 3.3log_{10}n] \quad (5)$$

where K is the number of classes, n is sample size and $\lfloor x \rfloor$ is integer part of x

HISTOGRAM

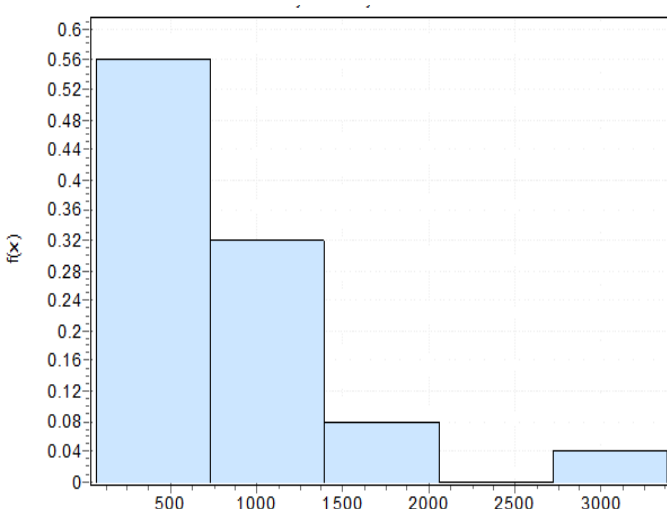

Fig 1: Histogram of TTF

Table 2: Descriptive Statistics

Statistic	Value	Percentile	Value
Sample Size	25	Min	63.17
Range	3316.5	5%	64.895
Mean	815.2	10%	146.37
Variance	4.738E+5	25% (Q1)	343
Std. Deviation	687.81	50% (Med)	715.33
Coef. of Varia tion	0.84373	75% (Q3)	1130.7
Std. Error	137.56	90%	1508.9
Skewness	2.2263	95%	2840.0
Exces Kurtosi s	7.3486	Max	3379.7

OBSERVATIONS

The statistical parametric behaviour supports the Weibul and Lognormal distributions. The mean is considerably larger than the median times to failure, so the data are skewed to the right and the exponential, lognormal or Weibull will provide better fit. Additionally, the exponential distribution may be ruled out since the sample mean and standard deviation are not approximately equal. Overall, further analysis involving the least square plots (LSP) was deemed necessary to identify the best candidate distribution. The initial values of the parameters of the selected distribution can be estimated from the LSP.

LEAST SQUARES FITTING

Figure (2-5) shows the least square plots for the various distributions; while the coefficient of determination R-square. The value indicates how accurate a distribution fits a data set. The closer the value gets to 1, the better the fitting accuracy.

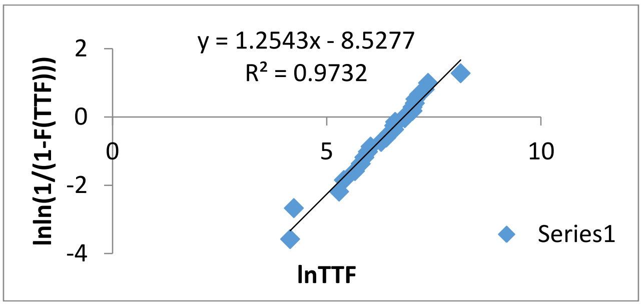

Fig. 2: Weibull Least-Square Plot of TTF

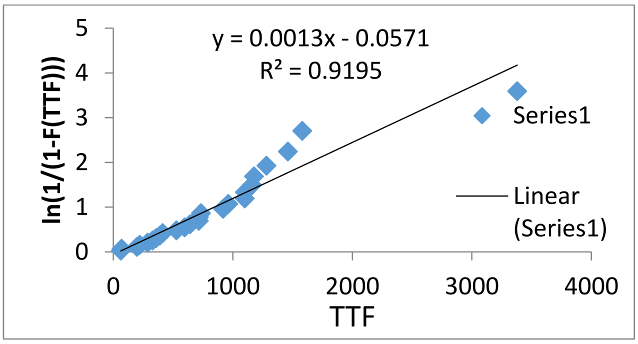

Fig. 3: Exponential Least-Square Plot of TTF

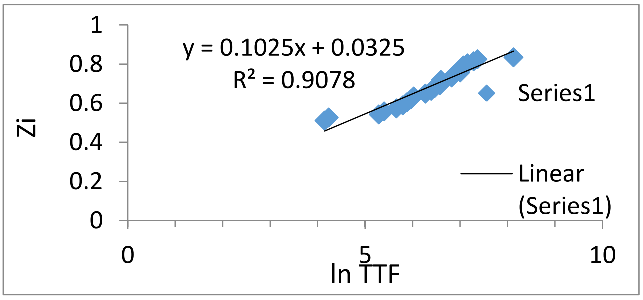

Fig. 4: Lognormal Least-Square Plot of TTF

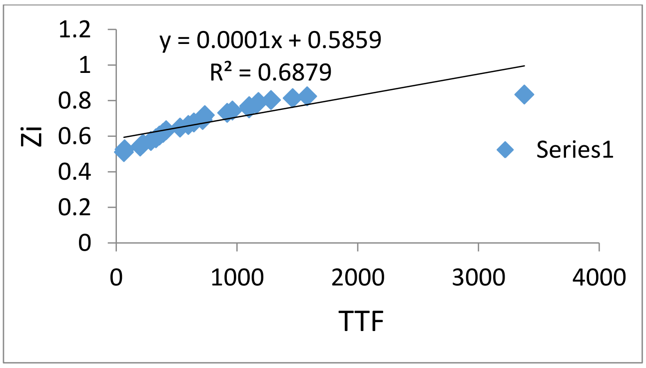

Fig. 5: Normal Least-Square Plot of TTF

The Weibull distribution was hypothesized for the data since it had the highest index of fit.

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PARAMETER ESTIMATION FOR THE WEIBULL DISTRIBUTION

Initial estimates of the parameters could be obtained from the least square fit, $\beta = 1.2543$, $\theta = 896.7456$. The Maximum likelihood estimates for β and θ can be obtained by solving equations (6) and (7). For the full solution of equation (6) and (7), see literature [16].

$$g(\hat{\beta}) = \frac{\sum_{i=1}^{r} t_i^{\hat{\beta}} \ln t_i + (n-r) t_s^{\hat{\beta}} \ln t_s}{\sum_{i=1}^{r} t_i^{\hat{\beta}} + (n-r) t_s^{\hat{\beta}}} - \frac{1}{\beta} - \frac{1}{r}\sum_{i=1}^{r} \ln t_i = 0 \quad (6)$$

$$\theta = \left\{\frac{1}{r}\left[\sum_{i=1}^{r} t_i^{\hat{\beta}} + (n-r) t_s^{\hat{\beta}}\right]\right\}^{\frac{1}{\hat{\beta}}} \quad (7)$$

MANN's PARAMETRIC TEST FOR THE WEIBUL DISTRIBUTION

Equations (8) due to [17] can be employed as a final confirmatory test that the data of TTF came from the Weibull distribution. The model can compare the empirical cumulative distribution function with the normal counterpart. The test statistic is given by:

$$D_n = max\{D_1, D_2\} \quad (8)$$

Where

$$D_1 = \max_{1 \le i \le n}\left\{\emptyset\left(\frac{t_i - \bar{t}}{s}\right) - \frac{i-1}{n}\right\}$$
(9)

$$D_2 = \max_{1 \le i \le n}\left\{\frac{i}{n} - \emptyset\left(\frac{t_i - \bar{t}}{s}\right)\right\}$$
(10)

$$\bar{t} = \sum_{i=1}^{n} \frac{t_i}{n} \quad (11)$$

$$S^2 = \frac{\sum_{i=1}^{n}(t_i - t)^2}{n-1} \quad (12)$$

If $D_n < D_{crit}$, H_o is accepted, otherwise, H_1 is accepted. The test statistic is given by equation (13) while the values for D_{crit} can be found in table of critical values of D.

$$M = \frac{K_1 \sum_{i=16}^{29}[(lnTTF1_{i+1} - lnTTF1_i)/M_i]}{K_2 \sum_{i=1}^{15}[(lnTTF1_{i+1} - lnTTF1_i)/M_i]} \quad (13)$$

Where $K_1 = \left\lfloor\frac{r}{2}\right\rfloor$, $K_2 = \left\lfloor\frac{r-1}{2}\right\rfloor$

REPAIR DATA ANALYSIS

The repair data was analysed with same procedure used for the failure data. The best estimate of the distribution parameters came from the least square plotting while the exponential distribution finished as best candidate.

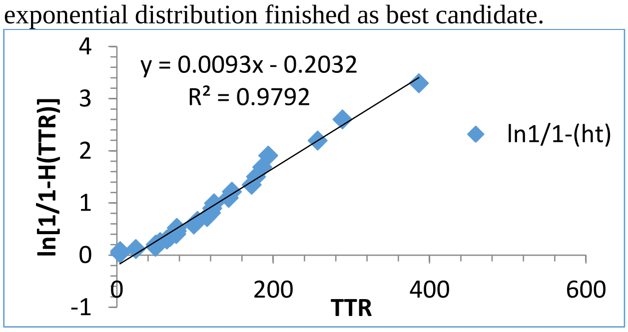

Fig. 6: Exponential Plot of TTR

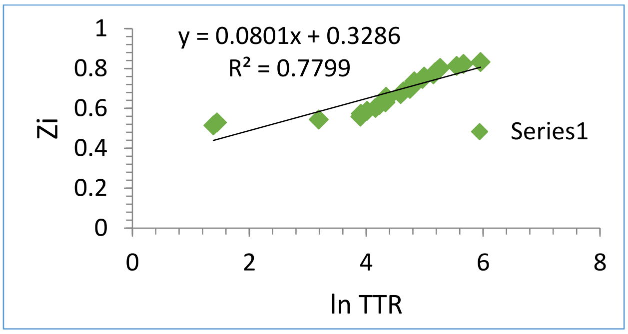

Fig. 7: Lognormal Plot of TTR

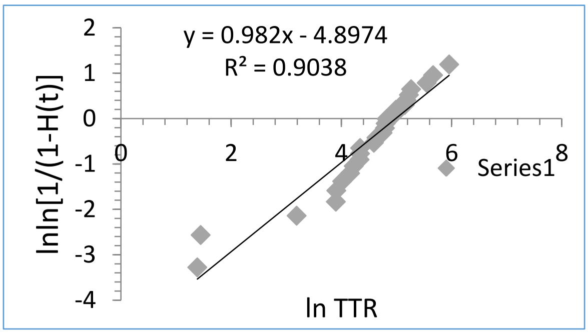

Fig. 8: Weibull Plot of TTR

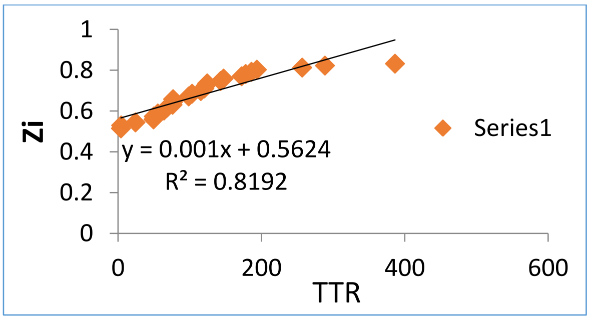

Fig. 9: Normal plot of TTR

The Exponential distribution had the highest index of fit and is therefore hypothesized for further analysis.

PARAMETER ESTIMATION FOR THE EXPONENTIAL DISTRIBUTION

The maximum likelihood estimator for the parameter λ is given by equation (14).

$$\hat{\lambda} = \frac{r}{T} \quad (14)$$

Where r is the sample size

$\hat{\lambda} = 0.008141$

The specific goodness of fit test for the parameter of exponential distribution (Bartlett's test) confirm the adequacy or otherwise of modelling TTR with exponential distribution.

BARTLETT'S TEST FOR THE EXPONENTIAL DISTRIBUTION

The computation of the test statistic, B of the specific test for this distribution can be implemented using equation (15), with the null hypotheses:

H_0 : Repair times are exponential with $\lambda = 0.008141$

H_1 : Repair times are not exponential with $\lambda = 0.008141$

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$$B = \frac{2r\left[\ln\left(\left(\frac{1}{r}\right)\sum_{i=1}^{r} t_i\right) - \left(\frac{1}{r}\right)\sum_{i=1}^{r} \ln t_i\right]}{1 + \frac{(r+1)}{(6r)}} \quad (15)$$

However, a complete solution of the test statistic can be found in relevant literatures [5, 16]. H_0 Satisfies the condition for acceptance. Further analysis is made with the exponential distribution, to obtain the best value for the parameter.

IV RESULTS AND DISCUSSION

There are useful deductions that can be inferred from the analysis of the failure and repair data of the pumping device studied in this paper. If a system has generated the type of data utilized in this study over time, then it will be possible to follow the procedure described above. The method is realistic if the method of data collection is strictly monitored to ensure that it represents the actual historic life of the system under study. When this is satisfied, most of the availability measures can easily be computed by evaluating a set of suitable theoretical distributions that the data came from. When the candidate distribution is identified and the parameters computed, though with a high level of care, the particular availability identities follows from the specified distribution. This does not preclude the use of other simpler models that are not covered within the ambit of theoretical lifetime distributions. The models in equation (16) through equation (20) are prescribed for assessing the specified availability parameters of the pumping device. The parameters of equations (19) to (20) have all been estimated. The Weibull and exponential distributions are respectively recommended for modelling the failure and repair variables of the system. As presented in the literatures for this particular eventuality [16,18], the models for evaluating the probability density function $f(t)$, MTTF, median time to failure, t_{med}, reliable life or system design life, t_d as well as failure rate for the studied system, can be obtained by substituting the values of the estimated parameters into equations (16) through (20).

$$f(t) = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1} e^{-\left(\frac{t}{\theta}\right)^{\beta}} \quad (16)$$

The mean or MTTF can be computed by:

$$\text{MTTF} = \theta\Gamma\left(\frac{1}{\beta}+1\right) \quad (17)$$

Where

$\Gamma\left(\frac{1}{\beta}+1\right)$ is the gamma function, evaluated at the value of $\left(\frac{1}{\beta}+1\right)$

The median of the distribution is given by:

$$t_{med} = \theta(ln2)^{1/\beta} \quad (18)$$

When the system mission is started at age zero, the reliable life t_d, for a specified reliability, R, can be deduced by:

$$t_d = \theta\{-ln(R)\}^{\frac{1}{\beta}} \quad (19)$$

Equation (19) can also measure the time which the system will perform well, under its stated conditions, from the date of the last maintenance. The failure rate function can be computed using equation (20) when accurate values of the parameters are deduced from operation and maintenance information of the system.

$$\lambda(t) = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1} \quad (20)$$

From equation (19), the model for the system design life can be written as:

$t_d = 884.5206\{-ln(R)\}^{0.77294}$ $t_d = 448.6305\text{h}$

As hinted earlier, all other measures of the system performance (equations 16-20) can be given a similar treatment to obtain easy to apply models of the studied pumping device.

V. AVAILABILITY ESTIMATION

Table 4 shows other values of availability parameters measured in the work. The computations are based on the selected and developed models for the pumping device. Some of the values are from the results of extensive opinion surveys with the maintenance personnel to articulate the most accurate values of affected parameters. The operational availabilities at all intervals were determined directly from equation (3) and displayed in Table (4).

Table 3: Values of Parameters of Equation (4)

A_0	O_C	T_{pm}
Table 3	$2160h$	$168h$
$m(t_d)$	D_T	A_m
30	72h	Table 3

TABLE 4: OPERATIONAL AND MODIFIED AVAILABILITY VALUES

TTF	A_o	A_m
63.17	0.94045	0.999535
68.92	0.941916	0.999547
198	0.890889	0.999109
221.5	0.817585	0.998397
286.83	0.851987	0.998751
328.5	0.855647	0.998791
357.5	0.848161	0.998722
388.18	0.850246	0.998745
413.08	0.844606	0.998694
528.13	0.87326	0.998969
596.75	0.886043	0.999087
642.62	0.867093	0.998922
715.33	0.873952	0.998988
716.42	0.861247	0.998876
733.33	0.858972	0.998857
18.5	0.882749	0.999076
961.92	0.885542	0.999102
1099.75	0.884876	0.999103
1100.8	0.882072	0.99908
1145.8	0.879204	0.99909
1160.52	0.870647	0.998989
1177.25	0.868659	0.998974
1281.58	0.873231	0.999018
1460.87	0.882968	0.999106
1580.85	0.856054	0.998901
3379.67	0.92133	0.999447

VI. CONCLUSION

In this paper, a method that can reduce the dilemma encountered in applying complicated mathematical availability formulations in industrial repairable systems has

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been described. The necessary assumption that the data on failure and repair of a case study unit, namely; pumping device in the gas plant of G4 Company located in Nigeria was made. The models formulated by the approach can find easy application among many maintenance personnel. In particular, those with limited knowledge of applied mathematics and statistics frequently used in formulating availability and maintenance models. The modelling procedure can be a means of bridging the widening gap between maintenance mathematical models and their consumption by maintenance practitioners or field technicians in the industry.

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