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Assessing Pump Reliability: a Case Study of Port Harcourt Refinery

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Abstract
The goal of the maintenance optimization process is to select the appropriate maintenance technique for each piece of equipment within a system and identifying the periodicity that the maintenance technique should be conducted to achieve regulatory requirements, maintenance targets concerning safety, equipment reliability, system availability and costs. This paper presents a predictive maintenance model for a deteriorating system in a manufacturing industry. In the deterioration process the important parameters of the system gradually worsen, and if left unattended, the process leads to deterioration failure of the whole system. In this study we considered discrete stage deterioration, where the first stage is a good stage and the last stage is the failed stage. During the life period of a machine the breakdown in the system can be rectified by immediate corrective maintenance programmes and the deterioration of the system can be solved by proper preventive maintenance schedule. The corrective and preventive maintenances bring the manufacturing system into a good and new stage of operation. Using Reliability models, this study presents closed-form analytical solutions for the performance measures of the model. The study also presents the optimal model parameters that maximize the system availability. An optimal design of the condition based models is essential for getting a closed form solution.. A modified FMEA approach has been used to identify the possible tests. The developed method is suitable for application in abroad range of industries. This study analyzes the maintainability of centrifugal pumps in a petrochemical refinery complex in Nigeria by analyzing the failure behaviours and downtime patterns. The data collected from the refinery cover a three year operation period of the high capacity, continuous operation pumps. This work aimed at improving the failure rates of pumps in chemical plants. Three pumps, 16 PO2,16 PO3 and 14 PO2, were assessed after collecting data on them from the plant record history for three years i.e. from 2017 through 2019. Proper reliability models were applied and results obtained showed the performance of each of them.. The results are analyzed in tables and figures. It was observed that 16 PO3 has the highest failure rate, the highest annual failure time, the highest labour and expense, the highest material per repair, the highest annual cost.

Keywords: Reliability, Availability, Maintainability, Mean Time Between Failures (MTBF), Pump, Refinery, business continuity plan, plant data, cost.

1.0 Introduction
Maintenance system is a complex configuration of people, machines and procedures. As the systems become more complex and strategic, efficiency and quality are heralded as important sources of competitive advantage[1]. Higher plant reliability reduces equipment failure costs. Failures decrease production and limit gross profits. Boosting reliability, by reducing the cost of unreliability, improves business performance. The clear reason for reducing unreliability is spelled money. The motivation for improving reliability is straight forward for a business plan: Improve reliability, reduce unreliability costs, generate more profit, and get more business. We talk about reliability (a good word), but we measure failures (a bad word). Failure demonstrates evidence of unreliability with unfavorable cost consequences for businesses. Failures in most continuous process industries are measured in process downtime. Cutbacks/slowdowns in output are also failures[2]. Failures require a clear definition for organizations making reliability improvements. Failures are loss of function when the function is needed—particularly for meeting financial goals. Everyone knows downtime stopping the production process measures unreliability and defines a failure.

Prediction procedures depended upon reliability data and experiences obtained from comparable system and components under similar conditions. The procedures depend on elemental activities of failure as the fundamental elements of down time[3]. Reliability tools showed their real value in the 1930s, 40s, and 50s when used on exotic military programs. Fortunately many reliability tools do not need a rocket scientist to use them cost effectively. Some simple reliability tools provide big gains quickly and defer the use of higher powered tools for squeezing out the remaining improvements. In all cases, scorecards for reliability improvements in business need measurements in naira. Use of reliability tools is evolutionary.

We built Monte Carlo models to simulate plant availability, reliability, maintainability, capability, and life cycle costs for deciding reliability strategies as seen in Excel.™ spreedsheets to provide ideas about how they function. Data acquisition has been a difficult task and a such cameras were used in this respect as recommended by Abernethy[4].

2.0 Literature Review

The review of past literature builds a theoretical foundation upon which the research is based by reviewing the literatures relevant to identifying research issues which are worth reaching. Based on these, literature on Basic failure data analysis, Reliability centered analysis, Reliability growth analysis technology and Maintenance decision analysis were reviewed.

A thoughtful plan to acquire a few pieces of carefully logged age-to-failure data for equipment is better than vast quantities of poorly planned data[5]. Notice the parallels between photography and failure data. People in many plants say they lack many data when in fact; data is all around them in various degrees of usefulness. Most industrial plants have been acquiring equipment of failure data for many years and seldom are the data analyzed in a scientific manner. Rarely do people acquiring the data see the data used to solve their problems. The net result is vast data banks of nearly useless information acquired haphazardly and annotated poorly. Today's task is to "mine" through piles of existing data while acquiring new age-to failure data in a carefully thought-out manner so that it can be used for an economic advantage[2]. The key phrase to remember is "age-to-failure" and of course that requires a consistent definition of failure. The field of reliability offers many technical guidelines for how data should be acquired, annotated, and used for analysis. In many cases, failures need a "death certificate" just as occurs with human failures. Death certificates for humans have been so productive in producing analyzable results, that it now illegal in the civilized world for a person to be buried without a death certificate listing age and cause of death. Substantial amounts of failure data exist in the literature awaiting knowledgeable use of the facts for improving the reliability of plants and equipment. New data acquisition initiatives by the Center For Chemical Process Safety (CCPS, 1989) using proven skills of data analysis experts at Det Nor Veratas, are underway for acquiring data from chemical plants and refineries[6]. We started with common sense data from the plants. Failure data works for solving personal and company problems in many plants now know their mean time between failure(MTBF) for pumps from special emphasis on reducing failures on rotating equipment. Because of redundancy, pumps (and other rotating equipment) today seldom shutdown plants. However, non rotating equipment often causes plant shutdowns—few plants know MTBF for heat exchangers columns, reactors, and so forth. It is important to use failure data to prevent failures and concentrate solutions on the vital few problems. For many plants the beachhead is secure in the rotating equipment area. It is time to reassign resources into non rotating equipment areas (while holding gains in rotating equipment areas) to reduce and prevent failures which cause plant outages. A reasonable time is taken to record all the failures. The number of failures occurring during the time interval is counted to calculate MTBF. The failure rate is the reciprocal of MTBF.
Unreliability is the turning point in life, history etc, and it is time of difficulty, danger or anxiety about the future. Unreliability is synonymous to crisis. In engineering, crisis is that state of emergency and/or uncertainty caused by either or all of the following:

a. Inability of machines to meet with demand due to failure of machines.
b. Lost time due to failures.
c. Mean Time Between Failures (MTBF).

Previous researchers applied the Crobbach's Alpha but this time I applied the Weibull distribution, the Crow/AMSAA Duane model and the Monte Carlo simulation.

To promote efficiency, unreliability arising in production projects must be pre-empted. Matsushita, Onho and Shingeo Shingo by 1990 were the three great Japanese crisis management experts that brought about the industrial revolution in Japan; this revolution brought crisis management to focus. Crisis impacts the organization's key holders, a business continuity plan is needed to minimize the disruption and financial damage.

Root Cause Analysis (RCA) works on defining problems into categories such as people procedures, or hardware. RCA solutions were demonstrated to problems so as to prevent recurrence meet the organizations goal, and be within an individuals control for preventing recurrence. Reliability Engineering Principles (REP) uses new tools to solve old nagging problems. The program is interested in solving the vital few problems that save/make the most money to reduce overall cost of unreliability. Many tools use bathtub concepts to match correct tools to cost effective strategies by applying science and engineering to Reliability-Centered Maintenance (RCM) efforts. Work-processes for reliability improvements start at ground level with a firm foundation and builds toward greater successes. Successful, on-going, reliability improvement programs don't just happen overnight—they are the results of well thought out programs which are carefully implemented. Generally, reliability work-process programs are driven by the need for improved profitability.

The cost of unreliability index is a simple and practical reliability tool for converting failure data into costs. When the entire organization can understand the problem on one side of a sheet of paper, effort focuses on solving important problems. Of course other reliability data could be converted into uncomplicated, figure-of-merit, performance indices useful for "getting a grip" on reliability by using mean times between failure.

Reliability is observed when Mean Time Between Failure (MTBF) is large compared to the mission time. Likewise, small values for mean time indices, compared to the mission time, reflect unreliability. Accuracy of these simple indices were improved when many data points were screened using well known statistical tools described in IEEE, OREDA, and RAC publications referenced above.

When only a small volume of data was available it was best analyzed using Weibull analysis techniques for component failures to arrive at better estimates of MTBF. Probability plots-Failure data is chaotic because of scatter in the data. Data scatter could be studied arithmetically for first, quick look results, or refined into statistical details providing richer descriptions when converted into straight line plots of time-to failure against cumulative chances for the failure.

Most engineers need graphical representation of data to fully understand problems. Without graphs, engineers are often overwhelmed by scatter as age to-failure data provides no traditional X-Y facts for making conventional plots. Probability tools are growing in importance with the use of personal computers which generate the curves with ease[8]. Weibull probability charts are the tool of choice for reliability problems because they often tell failure modes (how components die): infant mortality—uses a run to failure strategy, chance failures—use a run to failure strategy, or wear out failure modes—consider a timed replacement strategy based on costs. Data from Weibull plots support RCM decisions based on highly idealized bathtub curves[7].

Weibull charts are particularly valuable for pointing correct direction for finding root causes of problems using a few data points. Larger quantities of data add confidence to the decision making process, but at considerable greater expense for acquiring both failures and data. The motivation for using probability charts is to understand failure data and reduce costly failures by appropriate corrective.

Probability charts are easily interpreted, and simple plots of probabilities multiplied by costs can be plotted against time to quantify decisions and consider alternatives. In practice we seldom have too many data points for assessing risks. Weibull plots use few data and help the decision making process—some data is better than no data for making cost effective decisions. Monte Carlo models: The Monte Carlo demonstration models show end results for availability, reliability, and cost of unreliability[7].

Results from Monte Carlo models depend on good failure data (either actual or engineered data), good repair data, and accurate configuration by the modeler of how the plant physically operates. Of course models are only approximations of plants and making a model does not improve reliability— improvements must be converted into hardware.

Static spreadsheet model always produce the same results each time using arithmetic failure data. However equipment never fails at the same age-to failure or repair times in real life. Thus Monte Carlo models give different answers for availability, reliability, and costs each time the model is solved.

Now with today's fast PCs and Monte Carlo models, thousands of solutions are generated quickly at very low cost to model thousands of years of operation. From the multitude of answers produced by the model come trends, plant characteristics, and often alternatives for correcting deficiencies without incurring expense and delay of building hardware. Monte Carlo reliability models realistically assess plant conditions when combined with costs, repair times, and statistical events. Monte Carlo simulation models are very helpful for considering approximate operating conditions in a plant including cost effective sizing of tank age to provide protection for short duration equipment failures.

Good simulation models help determine maintenance strategies and turnaround timing for equipment renewal as simulation models are usually based on simple, heuristic rules. Heuristic rules are based on observed behavior of components or systems and heuristic rules are easy to construct using computer systems knowledge-based software.

Reliability models stimulate creative ideas for solving costly problems and prevent replication of old problems. Reliability models offer a scientific method for studying actions, responses, and costs in the virtual laboratory of the computer using actual failure data from existing plants. Monte Carlo models are never better than the data supplied. Monte Carlo models provide a way to search for lowest cost operating alternatives and conditions by predicting the outcome of conditions, events, and equipment. Monte Carlo models aid in finding the lowest long-term cost of ownership. The list of reliability tools is great[8]. The new reliability engineering tools require educating management and training engineers in their use to reduce risk, reduce costs, and improve operations.

2.5 Contribution to knowledge (knowledge gap):

Projects extending over a long period of time incurs more cost than those of shorter period. As a result, the most important reason for this work is to check unreliability and reduce down times. It was found out in the work, Assessing Reliability Indices using Cronbbach's Alpha that unreliability is a turning point in life or history because it was believed that unreliability results in hopelessness and this was reported in the work titled Solving Productivity Problems using Reliability Analysis[9.] It was found out that unreliability is crisis or a state of emergency but I, in this my study, view unreliability as a natural phenomenon which occurs when it shall occur except for some technical and/or logistic reasons and a such should be followed and observed closely recording all activities that could have played out in order to check a repeat occurrence.

My view conflicts with[9]. Solving reliability problems using reliability analysis and[5]. Assessing reliability indices using Crobbach's Alpha and agrees with other researchers' views[10]. In this study I first worked on the possible causes of unreliability and employed the probabilistic analysis, drawing statistical inferences and that reliability follows either/both exponential model or log normal model. In my assessment of pump failure proper I assessed pump reliability by mathematical model and not the Crobbach's alpha. I just wanted to draw the attention of all that at this level, several other indices could always be applied to solve reliability problems.

My work is in two parts: The first one is measuring the causes of pump failures; here, well structured questionnaires were administered and report analyzed using statistical inferences and statistical model was also employed[10]. The second part is the assessment of pump reliability proper. Here, three centrifugal pumps in a process plant were assessed. Their failure rates, meantime between failures and other relevant parameters were measured. The data was mathematically analyzed, and the model was by using the theory of mathematics and probability[11].

My statistical model employed in treating the first part of my work is entirely different from the model other researchers had used. From all the literatures I sighted, no one researcher was found to have adopted this inference. It was all use of theory of mathematics and probability. I employed questionnaires to get the best result. This agrees with the works of other researchers despite the applied theory and model. In the second part, that treated pump reliability assessment, past literatures were reviewed and results agreed with those of recognized best standards[12].

Theory and model of this research are in two parts, one was assessed using statistical inferences while the other part was by the use of mathematics and theory of probability. Depending solely on questionnaires for my life data looks so poor at this level, that was why assessing the reliability of the pumps were done using mathematical models . This is to add teeth to my research[13]. This work compared favourably with other recognized similar works[10].

The operating data is a foundation for statistical analysis regarding the reliability of the product. The goals of data analysis (focus: data uncertainty, reliability analytics, second-life-cycle aspects, Lessons-Learned issues) are the base of operations for the data requirements[14]. This forms my contribution to knowledge (knowledge gap). Data generated from the questionnaire source was subjected to descriptive methods such as cumulative distribution for the nominal data etc[15].

Prediction procedures depended on reliability data and experiences gotten from comparable systems and components under similar conditions. The procedures depend on elemental activities of failure as the functional elements of down time. Contingent on the findings therefore, specific questions were worded for a more systematic collection of data. This was for the root cause of pump failures.

For assessing pump reliability, availability and maintainability, a non parametric data was obtained from the operating downtime log from March 2017 through November 2019. The life data for pump reliability is reported. Most other researcher measured failure rates and downtime for a year and few measured for two years. In this research, three straight years were chosen for better convenience and result. More replicated data results in better Least Significant Difference(LSD)[15].

Example: an electric bulb does not fail because it is old or used for too long. It can fail at a flash which though could be caused by some technical reasons, but most times it flashes even when all parameters are correct and complete (failing exponentially). In this case unreliability comes into picture and this justifies this research work.

I think of a situation where the log normal model could be applied in assessing reliability where pumps fail due to fatigue or wear because I would want to observe and checkmate unreliability in pumps. I replicated my score cards for three years to record failure numbers so that a better plot could be achieved and ensuring the best least significant difference. This is not same as the other researcher's works. This forms part of my contribution to knowledge.

Assessing pump reliability, availability and maintainability was not enough, I went on to find out the possible causes of pump failures. This also forms part of my contribution to knowledge and proves originality of work[16]. In instances where failure is inevitable, the business continuity plan is needed to reduce the disruptions and financial damage. Many firms stipulate recovery requirements within their own internal security policies.

It is important to work on the timely issues of developing a risk decision-making culture and applying employee work teams and cost benefits analysis to evaluate risks[8]. The Crobbach's Alpha in assessing Reliability Indices and Reliability Indices were applied by most researchers while solving Reliability problems but this time I applied the Statistical analysis method in evaluating the possible causes of pump failure as I adopted the questionnaire method, Weibull distribution, the Crow/AMSAA Duane model and the Monte Carlo simulation in Assessing Pump Reliability proper[5].

The behaviour of a multi pump/pipeline system is hard to understand. As mentioned before, an infinite number of system configurations and soil conditions exist. Systems are usually configured, based on steady state calculations, while the dynamic behaviour is ignored. Combining the steady state approach for pipeline resistance with the dynamic behaviour of pumps, pump drives and the second law of Newton, the dynamic behaviour can be simulated. One should consider that mathematical modeling is an attempt to describe reality without having any presumption of being reality.

This study introduced to us the use of Life Cycle Costs as a special tool in evaluating both fixed and variable cost. This has been a useful tool in engineering[7]. Life cycle costs include cradle-to-grave costs. LCC provides the tools to engineer maintenance budgets and costs. When failure costs are included, the quantity of manpower required can be engineered which avoids the use of antique rules of thumb about how maintenance budgets are established as a percentage of installed capital.

LCC techniques provide methods to consider trade-off ideas with visualization techniques as described above which are helpful for engineers. Likewise LCC analysis provides NPV techniques of importance for financial organizations, and LCC details give both groups common ground for communication. With LCC details the financial organizations can complete DCF calculations.

Each example described above can be made more accurate by using more complicated models. For one example, in the Monte Carlo model, repair time can be changed from a fixed interval to a statistical interval.

We know failure as the termination or degradation of the ability of an item to perform its required function(s) but the following outages should not be considered as failure:

(1) Unavailability due to preventive or planned maintenance
(2) Shutdown of the items due to external conditions or where no physical failure condition of the items is released. A shutdown is not to be considered a failure unless there is some recorded maintenance activity.
(3) Degraded failure which does not cease all functions but compromises that function.
(4) Incipient failure as imperfection in the state or condition of an item which has no immediate effect on function.

3.0 Data presentation / Methodology

Theoretical Analysis:

It is very important to have a clear and obvious stand regarding the theory and methodology adopted in the research as these affect the validity and research result. Data was collected from information gathered from Port-Harcourt refinery, interviews as primary sources while secondary sources were from library visits, text books, journals, periodicals, dissertations and abstracts from industrial/production engineering sources and internet.

Because of the inherent uncertainty in predicting a failure, reliability parameters, were defined in probabilistic terms so that random variables such as density and distribution functions can be evaluated[5]. The particular distribution used depended on the nature of the data in each case. The theories are stated in the mathematics of probability and statistics[17].

Because of the numerous advantages which include providing reasonable accurate failure analysis and forecast, the **Weibull model** was used to model the failure distributions. In predicting the reliability growth, the **CROW/AMSAA DUANE model** was also used, while analyzing the failure distribution, the **Monte Carlo simulation** as seen in Excel™ spreedsheets was also used.

The Reliability plot was generated using rank regression method.

Maintainability: This is the ability to be restored quickly to working condition after failure.

Availability: This is being in working condition when required.

Security: Remaining safe in case of failure.

Constant failure rate (the exponential law): Most electrical and/or mechanical components fail exponentially (show constant failure rate).That is why spare parts are paramount.

The log normal model: Mechanical failures suit this type of model where objects fail due to fatigue or wear e.g. the vehicle brake pad, lining and clutch plates and discs etc.

R(t)=1-F(u), where u=(Int-m)/a,

where; m=0 and a=1.

Weibull model: This is a more general law which include many of the simpler models represented thus: R(t)=1-F(t). 1.

A non parametric data was obtained from the operating downtime log from March, 2017 through November 2019.

Events which rendered pumps inoperable in which they do not perform their intended function are seen as failures. All the pumps were spared and plant run for twenty four hours all through the year (8760hrs).

The accuracy of the data is dependent upon the accuracy of input in the operations log. No record is available to document cost of downtime and the days downtime estimated from the log book. The cumulative distribution function (unreliability) is plotted against the time on a special Weibull log-log graph paper.

Prediction procedures depended upon reliability data and experiences obtained from comparable system and components under similar conditions. The procedures depend on elemental activities of failure as the fundamental elements of down time (Akpan, 1996). Reliability tools showed their real value in the 1930s, 40s, and 50s when used on exotic military programs. Fortunately many reliability tools do not need a rocket scientist to use them cost effectively. Some simple reliability tools provide big gains quickly and defer the use of higher powered tools for squeezing out the remaining improvements. In all cases, scorecards for reliability improvements in business need measurements in naira. Use of reliability tools is evolutionary[18].

We built Monte Carlo models to simulate plant availability, reliability, maintainability, capability, and life cycle costs for deciding reliability strategies.

Data acquisition has been a difficult task and a such cameras were used in this respect as recommended by[4].

4.0 Result and Discussion

4.1 Results

The results from calculation are provided in the summary boxes of the pump systems. The failure rates for the pumps are summed up in series to find the overall system failure rate for the year. From the overall system failure rate, the reliability of the system were calculated for a (8760hrs/yr) one year period.

Table 1 : Study interval showing failure rates

	16PO2 →	16PO3 →	14PO2	SUMMARY
Sturdy Intervals (hrs)	16638	11088	19112	8760 hrs/y
Number of failures	30	24	24	31.6 failure/yr
MTBF	5546	462	796.3	277.0 hr/failure
Failure rate	$18.0x10^{-5}$	$21.65x 10^{-4}$	$12.6x10^{-4}$	$36.1x10^{-4}$ fail/hr

Also from the failure rates the lost time per pump is calculated and the overall lost time for the system is determined as 756.68hrs/ yr. From the figure below we also see money lost from pump failure and set priorities.

System Reliability R_s;

$R_{s(f)} = R_A \times R_B \times R_C = e\text{-}\lambda_s{}^t$

$\lambda_s = \lambda_A \times \lambda_B \times \lambda_C$

$= \quad 18.0x10^{-5} \times 21.65 \times 10^{-4} \times 12.6x10^{-4}$

$= \quad 36.1x10^{-4}$ failure/hr

$R_A = e\text{-}\ \lambda_A{}^t = e\text{–}(18.0x\ 10\text{-}5\ x8760) = 0.2066\%$

Where; t=8760hrs.

$R_A = e\ \text{–}\lambda_B{}^t = e^{-(21.65x10\text{-}4\ x\ 8760)} = 0.0000000058\%$

$R_B = e^{-Ч_C t} = e^{-(12.6x10-4\ x8760)} = 0.000016\%$

$Rst = e^{-Ч_s t} = e^{-(36.1x10-4\ x8760)} = 1.85x10^{-14}\%$

TABLE 2: Annual cost of failure showing pare to priority

	H	I	J	K	L	M
	NUMBERS DRIVEN BY RELIABILITY AND MAINTAINABILITY					
	Annual failure	Annual failure time	Labour + expense	Materials per repair	Annual cost	Pareto rank for corrective action
	Failure/ yr	Hrs/yr	₦/yr	₦/yr		
16P02	1.57	37.68	188,4000.00	15,700.00	204,100.00	3
16P03	18.96	455	2,275,000.00	189,600.00	24,646,600.00	1
14P02	11.00	264	1,320,000.00	110,000.00	1,430,000.00	2
Overall System	31.53	756.68	3,783,400.00	315,300.00	26,280,700.00	

4.2 Discussion of the results

This result means that the pump system has ONLY $1.85x10^{-14}\%$ chance of running for 1 year (8760hrs) without a failure. However, for a 30 days (720hrs) period, the reliability will be;
$R720 = e^{-(36.1x10-4x720)} = 0.074\%$

Using a one year payback rule of thumb, the picture clearly states to management the expenditure limits for corrective actions. That is engineering should not exceed N69,198,000.00 in correcting 16PO3. This pump has the most pare to problem, the highest failure/year, highest annual failure time, highest labour and expense, highest material per repair and the highest annual cost. The least being 16PO2 which requires not more than N5,730,500.00 only.

The reliability plots were generated using rank regression calculation method. The β value from the graph shows that the failure type in infant mortality which is attributed largely to installation defects. It is clearly evidenced by the abysmally low mean time between failures.

Conclusion and Recommendations

Management requires making reliability a visible and manageable characteristics in order to prevent failure. When the approximate time for the next failure based on the reliability forecast is known, preventive ways should be sought to prevent the occurrence.
A reliability policy should be formulated in our refineries particularly the Port Harcourt refinery, a case study to prevent unreliability problems early in the formative stages by channeling cooperative efforts to make things happen rather than reacting to events.

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