Availability Based Comparison of Fixed Age and Life Cycle Cost Replacement Maintenance

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Abstract
Determination of the best approach to preventive replacement maintenance on repairable systems can guarantee maximum efficiency. Availability comprises both reliability and maintainability, and can be considered more suitable in system replacement analysis. The paper investigates the economic replacement period for a typical repairable system in a manufacturing industry, called Rex Company in this paper for privacy. The system had a design replacement period based on fixed age, which was compared with the replacement period from the research. The mean availability of the system over the studied period was approximately 50%. The result show that the 19 years replacement period obtained from analysis of maintenance cost data is in very fair agreement with the designers' estimate of 20 years, though the Authors were not privy to the method of remaining useful life estimation used by the designers. However, the authors argue that the research result is superior to the fixed age replacement period given by the manufacturers. This conclusion is predicated on the non-linearity of the availability of the centrifugal pumps during the study stretch. The result also shows that availability evaluation can offer a good insight to determining the replacement period of deteriorating systems.

Keywords
Availability, repairable system, replacement period, fixed age, maintenance cost analysis

1. Introduction
Maintenance is a subject of significant concern to many manufacturing sectors as it is geared at retaining systems in acceptable levels of operational reliability. It occurs in a multiplicity of forms, ranging from breakdown, preventive, corrective, inspection, predictive, running among others (Martorell et al., 2010). High system availability ultimately results to sustained system performance and can be achieved through redundancy, but it comes with prohibitive cost. Other procedures targeted at increasing system uptime while minimizing maintenance frequency and set up costs has been considered (Olde Keizer et al., 2018). The time for maintenance is an important parameter to maintenance and operation managers. Too few or too frequent time regimes can lead to unbearable consequences. In particular, some researchers hold that maintenance of repairable systems should be performance dependent (Mo et al., 2018) for more reliable control. Maintenance strategy for Power distribution systems have been suggested (Carnero and Gomez, 2017, Rusin, and Bieniek, 2017). Making the right decision of when a system or unit should be replaced is key to the maintenance function, especially when there are availability constraints (Do et al., 2015). Technically speaking, when the efficiency of any service producing system continues to deteriorate with time (gradual failure), two courses of action are open to the maintenance department. An operational maintenance cost threshold at which replacement with a new one must be implemented, can either be considered or the fixed replacement period specified by the manufacturers be totally relied upon. This is not only necessary to ensure system availability or to up returns on the industry investment, but more importantly to contain huge expenses expectations in the event of catastrophic breakdown. It is often necessary, but not always mandatory that the maintenance personnel chose from alternative courses of action after informed comparative study of the available options. This is with due respect to the fact that most repairable systems designers and manufacturers normally specify the expected replacement age of machines subject to some specified terms and conditions. The real issue is whether all possible conditions which the designed system will inherit from installation can be adequately incorporated into the design parameters, or if there can emerge new realities capable of altering the fixed replacement age. The key indices of such

comparison should not be unrelated to the methodology that reflects the actual online variables affecting the system operation and maintenance. The running cost, proficiency of service crew, as well as the type of production system in place, among others; can differ from what was intended at the design stage. It will be reasonable to consider goods producing systems on the basis of minimum cost and the service producing counterparts on acceptable levels of operational reliability (Malik, 1979, Ozor, 2008). There is an existing report on preventive replacement strategy for service systems and notable policies have been suggested (Levitina et al., 2017). Some authors labored on optimizing existing preventive replacement maintenance policy (Hamidi et al., 2016, Afrinaldi et al., 2017). A method for reducing the negative effects of poorly replaced systems to both economy and environment was recently reported (Ahmadi and Wub, 2018).

Generally, if maintenance cost of a service producing system is represented as an increasing function with time, and if the salvage value is in a steady state condition while time is continuous, then the associated mean annual cost can be minimized by preventive replacement when the mean cost to date is equivalent to the existing cost of maintenance (Sharma, 2005). However, if time is measured in discrete units, then the average annual cost will be minimized by replacing the machine when the next period's maintenance cost becomes greater than the current average cost. This approach is related to previous capital replacement models and can be investigated in a manufacturing Industry for any repairable system. Models whose aims were to establish the best preventive replacement period of deteriorating or degradable but repairable systems with gradual increment in running cost as time progresses has been proposed (Sharma, 2005). The models assume that the value of money should not be counted within the period. The two are varied by the state of time (i.e. whether it is a continuous or discrete variable). The author did not relate the method to availability information on the component which actually provide for the instantaneous status of the system. That is; whether the system is actually in use or is depreciating by age only. Equipment can deteriorate by age without ever being used. Therefore, a preventive replacement strategy based on precise availability evaluation of concerned systems can reveal how well the system is performing its desired function at any point in time, if it is used under stated operating conditions. At the same time the time for economic trend changes can be determined realistically and needed preventive replacement steps taken. The major effort of this paper is to determine the suitability of preventive maintenance replacement via availability assessment and spot the best strategy and time for the replacement, among the fixed age policy and maintenance cost analysis undertaken.

2 Materials and Methods

The data required for this research can be classified into two major types: quantitative and qualitative. Quantitative data are the maintenance and cost data of the pumping units abstracted from Rex Company records. In particular; data on respective downtime and uptime of the various units were collected. This enabled the determination of the mean time between failures. The design life was obtained from the system manuals to be 20 years. The data set collected through observed information, opinion surveys and interviews with relevant personnel are referred to as Qualitative data. Quantitative were basically sourced from maintenance records and other archival document. There were also series of brainstorming interviews and opinion surveys with the maintenance personnel. The essence of the session was to mesh theory and practice with a view to finding best replacement maintenance solution used in the factory. The maintenance data obtained are essentially the units down time in hours for five years (2000-2004). The averages of the downtime for all the years are displayed in Table 1. Data bordering on other availability and cost parameters were also collected as abstracted from the company records. With the data collection phase completed, the remainder of the procedural steps involve sorting of the most suitable literature models that can fulfill the objectives of the research. Availability models were elicited to properly analyze the system for a realistic replacement threshold. It was necessary to use cost models to find cost dependent replacement strategies in tandem with the thrust of the research. The results inferred from the analyses were later discussed in details and the optimum replacement period for the studied system defined.

Table 1: Centrifugal Pumps (CP) Average Down Time in Hours

CP Unit	2000	2001	2002	2003	2004
CP 01	6091.94	103.77	1807.90	3446.58	2830.33
CP 02	4035.60	8016.00	8760.00	8760.00	4368.00
CP 03	3005.75	1509.00	6135.65	1575.21	556.53
CP 04	3743.31	730.92	856.43	1314.17	1867.37
Total	16876.60	10359.69	17559.98	15095.96	9493.37

2.1 Availability models

The analysis of effectiveness of maintained systems is better achieved through availability evaluation as it promises to be a more accurate measurement tool than reliability. The reason is because the field of availability encompasses both maintainability and reliability of the concerned degradable system. This research work surveys the major parameters relevant to the availability of the centrifugal pumps in the Rex refinery Company. Availability is normally concerned with the percentage of time a unit or system is operating, within a defined time interval. It can also be interpreted as the percentage of components operating at a specified period of time with respect to some pre-stated conditions (Ebeling, 2010). A general model for the computation of availability is found in literature (Lie et al., 1977):

$$A(T) = \int_0^T A(t)dt \qquad (1)$$

Where:

$A(T)$ = availability at time t and is the average availability over the interval (0, T)

In particular, there can be other aspects of equation (1), depending on whether the availability is (1) Inherent, (2) achieved or (3) operational. The three can respectively be represented by the following dependence (Lie et al., 1977):

$$A_i = \frac{MTBF}{MTBF + MTTR} \qquad (2)$$

$$A_a = \frac{MTBM}{MTBM + \bar{M}} \qquad (3)$$

$$A_o = \frac{MTBM + ready\ time}{(MTBM + read\ time) + MDT} \qquad (4)$$

Where:

$MTBF$ = Mean time between failures
$MTTR$ = Mean time to repair
$MTBM$ = Mean time between maintenance
$\bar{M}$ = Mean corrective and preventive maintenance downtime

It should be noted that $MTBM$ does not include the ready time, preventive maintenance time and logistics delay time. It takes only the corrective maintenance downtime into consideration. Likewise, $\bar{M}$ does not account for logistic or administrative time. Accordingly, the terms in equation (4) can be elaborated to allow for the deduction of other variables (Ebeling, 2010):

$$ready\ time = operational\ cycle = (MTBM + MDT) \qquad (5)$$

$$MDT = M + delay\ time = mean\ delay\ for\ maintenance. \qquad (6)$$

2.2 Cost models

As presented in literature for the decision on best preventive replacement time for units, component or system that present time dependent increasing running cost, with a steady state value of money within the period (Sharma, 2005):

$$R_n = \frac{1}{n}\{C - S + \int_0^n R(t)dt\} \qquad (7)$$

$$ATC_n = \frac{1}{n}\{C - S + \sum_{t=0}^{n} R(t)\} \qquad (8)$$

Where:

R_n = system running cost for the year n
C = capital or procurement cost of new system
n = replacement age
S = salvage value i.e, value of the system at the end of n years

$R(t)$ = system running cost for year t
ATC_n = Average total cost

If the variable "t" is discrete, then the total mean cost incurred by the system over the period n, can be computed using model (8). The major difference in the two models presented is the state of time 't' (i.e. whether t is a continuous variable or a discrete variable).

3. Analysis and Discussion of Results

The maintenance data obtained for the units were used to solve the availability and cost models. From figure 1, the annual availabilities vary from 37.9% to 61.9%. Figure 1 present the overall availability for the entire period (2000-2004) as displayed with the bar chart. It is agreed by some maintenance practitioners that preventive replacement of degraded systems or systems thought to have entered into unacceptable failure zone is more economical than waiting to embark on the replacement when the system has grounded. It follows that all aspects of activity ought to be improved for sustained plant reliability. All hands in the maintenance and production departments, and indeed the administrative channels should be on deck so as to pinpoint the best preventive replacement period. Improving routine checks and inspection policies can go a long way towards accomplishing the task.

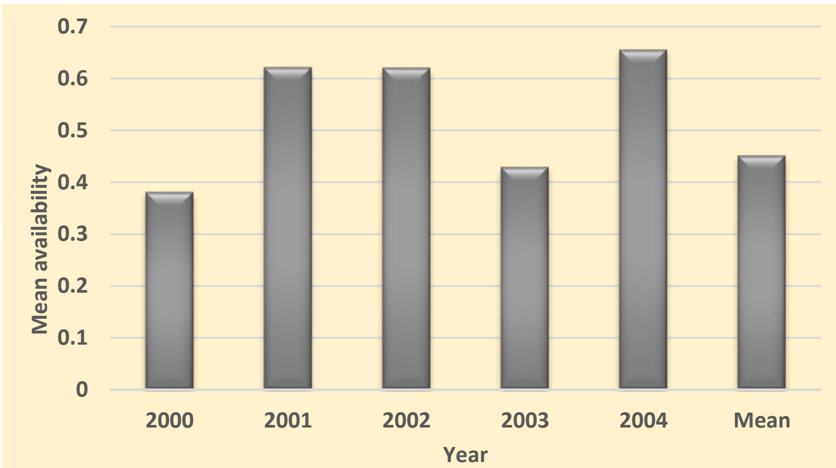

Figure 1: Annual Average and Mean Availability of Centrifugal Pumps

The level of operational availability decline which varies from 37.9% to a maximum of 61.9% is expected to affect the productivity of the refinery negatively. The immediate implication of the results is that the plant cannot work at its design capacity. There would be inefficient generation and distribution of electrical power to all the departments of the refinery. In addition, this will have a ripple effect on the economy of the country whose major source of foreign income is 85% crude oil. The effect is that the country will not be able to refine enough oil for its citizenry. As it stands, there has been so much investment on importation of refined crude oil products from elsewhere which further decrease the employability of the citizens of the country in question. Table 2 gives the overall maintenance cost of the refinery from 1993-2003.

Table 2: Maintenance Cost 1993-2003 (Source: Rex Company)

Year of service	Running cost R_n (₦)
1993	185,505,631
1994	168,700,465
1995	410,524,600
1996	563,426,109
1997	819,699,797
1998	959,597,659
1999	1,006,394,712
2000	790,069,414
2001	1,252,955,721
2002	1,520,909,025
2003	1,829,026,791

4. Determination of the Optimum Replacement Time by Maintenance Cost Analysis

Models (7) and (8) are employed for the determination of best replacement period of the power plant. Preliminary data analyses as well as direct interviews reveal that most of the time results from the centrifugal pumps. The information from Company records puts the cost of installing a slurry centrifugal pump at eleven million, two hundred thousand naira (₦11.2m). Maintenance cost data on four identical centrifugal pumps purchased during 1996 were relied upon in the study. Hence, the capital or purchase cost of new centrifugal pumps as at 1996 will be forty four million, eight hundred thousand naira (₦44.8m). The maintenance data bordering on the variables of models (7) and (8) were analyzed using descriptive statistics and applied to the models to compute the replacement period for the Turbo-generators. Table 3 presents the results of the analysis.

Table 3: Results of Maintenance cost data analysis for the centrifugal pumps

S/N	Year	n	R_n	CRC*	S	$C-S$	Total Cost (₦)	ATC_n
	0	(1)	(2)	(3)	(4)	(5)	(6)=(3)+(5)	(7)= (6/n)
1	1996	1	0.448	0.448	4.256	40.544	40.992	40.992
2	1997	2	0.672	1.12	4.032	40.768	41.888	20.944
3	1998	3	0.896	2.016	3.808	40.992	43.008	14.336
4	1999	4	1.12	3.136	3.584	41.216	44.352	11.088
5	2000	5	1.344	4.48	3.36	41.44	45.92	9.184
6	2001	6	1.568	6.048	3.136	41.66	47.712	7.952
7	2002	7	1.792	7.84	2.912	41.888	49.728	7.104
8	2003	8	2.016	9.856	2.688	42.112	51.968	6.496
9	2004	9	2.24	12.096	2.464	42.336	54.432	6.048
10	2005	10	2.464	14.56	2.24	42.56	57.12	5.712
11	2006	11	2.688	17.248	2.016	42.784	60.032	5.4574
12	2007	12	2.912	20.152	1.792	43.008	63.16	5.2633
13	2008	13	3.136	23.288	1.568	43.232	66.52	5.1169
14	2009	14	3.36	26.648	1.344	43.456	70.104	5.0074
15	2010	15	3.584	30.232	1.12	43.68	73.912	4.9274
16	2011	16	3.808	34.04	0.896	43.904	77.944	4.8715
17	2012	17	4.032	38.072	0.672	44.128	82.2	4.8353
18	2013	18	4.256	42.328	0.448	44.352	86.68	4.8155
19	**2014**	**19**	**4.48**	**46.808**	**0.224**	**44.576**	**91.384**	**4.8097**
20	2015	20	4.704	51.512	0.0000	44.800	96.312	4.8156

*CRC = Cumulative running cost

From table 3, it is observed that the average total cost started to increase after the nineteenth year of installation, precisely on the twentieth year. Hence, it is more economical to replace the turbo generators after the nineteenth year of installation and working. This result closely agrees with the designers predicted economic or design life of the pumping units, which is 20 years. All the four pumps have the same characteristic rating and operate in same environment under the same condition. Hence uniform depreciation was assumed. It should be noted that the costs have not been discounted for inflation. It was stated earlier that service producing systems maintenance or preventive replacement should be executed when it is due, and without regards to cost in line with previous authors (Ozor, 2008, Malik, 1979). This is correct because the system at the replacement due age will no longer be performing at its installed capacity. In that state also, there is higher probability of dependent failures which will certainly hasten the total grounding of the system. It is therefore recommended that availability of all the factory units be regularly conducted and relevant maintenance or renewal actions inferred from the results in other to constantly improve the effectiveness of the system. The term effectiveness as used in this presentation can be taken to mean the probability that a specified system will perform its desired function or mission both satisfactorily and successfully, provided that such system is operated within the specified terms and conditions. This study has raised concern for a full scale failure and risk analysis of the studied plant as it was not part of the work. Future research effort should be directed towards investigating the reason for high failure rate recorded in these pumping units, with particular emphasis on the failure modes and mitigating actions.

4.1. Comparison of Age replacement policy and Maintenance Cost based Replacement

From the foregoing analysis, it is evident that both procedure compare favorably in determining the replacement period of the studied system. The replacement period obtained by analyzing the maintenance and repair costs of the system using literature models is more accurate on a point to point evaluation. The methodology is found to be comprehensive and flexible. It brings out the systems actual operating behavior while reflecting some environmental influences. It is however characterized by some discomforting realities, which include rigorous data analysis and the requirement of extensive amounts of data needed to quantify many variables. The application of this method is worthwhile only for repairable systems already in operation which have accumulated significant amounts of data for its realistic application. Otherwise, it will require that future maintenance costs can be determined with certainty if it is to be applied in determining system replacement period at the design stage. This can pose authenticity questions to the replacement period determined using the approach at systems design phase. This method is compatible with the availability of the centrifugal pumps studied in the work, as there is a higher correlation between system usage and failure, than will be observed for standby or idle but aging systems.

The fixed period or fixed Age replacement period is predicated on the assumption that the system should have exhausted its useful life within a set period of time, which is twenty years for the particular case of the systems studied in this work. The results indicate that waiting for the set period will increase the maintenance cost and from this view, the systems should be replaced after 19 years. The additional one year, going by the 20 years estimate given by the manufacturers can translate to huge economic losses for the factory, short of the 19 years period indicated by the Maintenance and replacement cost analysis approach. The former still suffers the disadvantages of inability to account for variations in the availability of the system. The availability plot of figure 1 shows that the system availability is not constant. In other words, the system experiences varying degrees of uptime and downtime; with its attendant wear and tear, which can differ from one operating environment to another. The fixed age replacement policy can hardly account for such obvious operational, maintenance and environmental dissimilarities. There are some instances where the Case factory lies fallow for considerable period of time. Though, the centrifugal pumps cannot be assumed to be in a state of suspended animation at such periods, but its state can be captured within availability analysis environment. Using fixed age approach in this case can lead to replacement of a reliable system which may still possess ample years of service life before going into a costly repair zone. Consequently, the application of this method in the studied case should be subject to some hypothetical conditions that can fully take care of the availability and other important specifics of the system.

5. Conclusion

This presentation studied availability evaluation and preventive replacement period of centrifugal pumps in a typical production and maintenance intensive plant. The methodology followed in prescribing an optimum replacement period for the studied system is clearly outlined. The maintenance data was robustly analyzed to ascertain the overall idle time experienced by the system within the study stretch. Among other merits, the work has led to the prescription of an optimum replacement time for the centrifugal pumps in the case study. The result show that the replacement time from the research method is in very fair agreement with the designers estimate, though the Authors are not privy to the method of useful life estimation used by the designers. The Authors argue that the results obtained through analysis of the maintenance and repair cost data is superior to the fixed age replacement period given by the manufacturers. This conclusion is predicated on the non-linearity of the availability of the centrifugal pumps due to variations in important cost and maintainability quantities. Even though the work made use of qualitative and quantitative data sourced from a typical crude oil refinery (Rex Company) power plant, to obtain the maintenance policies prescribed, its application to repairable service producing systems in the manufacturing plant and other spheres with similar parameters can be explored.

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