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Development of a Maintenance Strategy for Centrifugal Pumps

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ABSTRACT

In this work, a maintenance strategy was developed for centrifugal pumps. The strategy involves running the centrifugal pump for a predetermined period and the mechanical seal is taken out for maintenance and reused. The period of first usage of the mechanical seal depends on the level of debris in the fluid (low level, medium level and high level). The centrifugal pumps of an oil multinational company based in Rivers state was used as a case study. The cost implications of the existing maintenance strategy and the developed maintenance strategy were evaluated and compared. Selected reliability-centred maintenance tools were also applied to assess the level of criticality of the various components. It was observed that the impeller, the mechanical seal and the shaft are the most critical components of the centrifugal pump with relative criticality values of 16.80, 15.08 and 13.35 respectively. In applying the new maintenance strategy, it is possible to run the centrifugal pump for up to 11 days, 8 days and 5 days respectively for the three different cases of fluid before the mechanical seal is reused. Reused mechanical seals on the average can run to failure in 9 days, 7 days and 4.5 days respectively. Applying the new maintenance strategy leads to reduction in maintenance cost of the mechanical seal between ₦13.6 million to ₦24.4 million annually. The developed maintenance strategy can be applied to other devices which has components that fail often.

Keywords: Centrifugal pumps, Critical components, Maintenance strategy, Reliability-centred maintenance

INTRODUCTION

Centrifugal pumps play very vital role in the oil and gas industry. Generally, centrifugal pumps are used to provide motion (driven usually by gas turbines) in transporting liquid from one point to another. Centrifugal pumps consist of a number of parts including impeller, shaft bearing, mechanical seal, casing, suction and discharge flanges, barrel, shaft sleeve, coupling and wear rings. When driven by a motor, the motor is also considered when talking about maintenance of centrifugal pumps. The failure of any of these parts will affect the proper functioning of the pump. Maintenance is carried out, usually on routine basis following laid down timelines/schedules provided by the original equipment manufacturers (OEM). In the field, it is obvious following the OEM timelines becomes ineffective as pumps are put into use over time. Thus, a maintenance strategy based on equipment failure information obtained from the field is necessary. Maintenance is any activity geared towards the proper functioning of any device, equipment or system. There are basically two types of maintenance- corrective maintenance and preventive maintenance (Tavner, 2022). While corrective maintenance is sub-divided into immediate maintenance and deferred maintenance, preventive maintenance has several sub-divisions from the views of several researchers (Gackowiec, 2019; Wang et al., 2015; Zaim et al., 2012). In most cases, preventive maintenance is categorized as time-based maintenance (or routine maintenance) and condition-based based maintenance. A further division derived from the condition-based maintenance has gained prominence with the advent of advanced technologies such as machine learning and internet of things. This is predictive maintenance.

Corrective maintenance is also known as curative maintenance. In corrective maintenance, maintenance is carried out when failure occurs. This may be suitable in some cases but should be completely avoided in some other cases. An immediate corrective maintenance implies that maintenance is carried out as soon as failure occurs. In deferred corrective maintenance, maintenance is carried out at a later date. In this case, a standby system must be in place as the failed system is billed for maintenance in a later date. In preventive maintenance, maintenance is carried out in order to prevent failure. Preventive maintenance practice is more widely used compared to corrective maintenance. Routine maintenance is the most common type of preventive maintenance. It is also referred to as time-based maintenance. In routine maintenance, maintenance is carried out at regular time intervals. Centrifugal pumps also undergo routine maintenance practice, usually following OEM guidelines. Condition-based maintenance is more advanced maintenance practice exploiting observable conditions of the system operation to carry out maintenance.

A lot work has been done concerning the operation, diagnostics/prognostics and maintenance of centrifugal pumps. Sakthivel, Sugumaran, and Babudevasenapati (2010) presented the use of the C4.5 decision tree algorithm for fault diagnosis through statistical features extracted from vibration signals of good and faulty conditions. Centrifugal pump plays an important role in industries and it requires continuous monitoring to increase the availability of the pump. Gandhi and Mistry (2011) improved the durability of Centrifugal Pump KSB (40-160) in Chemical Plants using preventive maintenance the existing scenario of the chemical plant they are using breakdown maintenance due to that some time emergency breakdown of the pump accrued since they do not see any associated maintenance cost they would view this period as saving money. McKee et al. (2011) reviewed the major modes of fault inherent in centrifugal pumps. They focused on those used in water and sewage industry. They noted that the production and transportation of fluid in pipelines is interrupted when problems occur in the pumps. This ultimately leads to slowing down the other parts of the processing system or behaving in undesirable manner. The correlation between the performance parameters of pumps and surface vibration was investigated by Albraik et al. (2012). The pump performance parameters include the head, the flow rate, and the energy consumption. The correlation was investigated for both condition monitoring and assessment of performance. They used an in-house pump system and carried out several experiments where five impellers were utilized – one in good working condition while the other four has various defects. Azadeh et al. (2013) presented artificial neural networks (ANNs), support vector classification with genetic algorithm (SVC-GA) and support vector classification with particle swarm optimization (SVC-PSO) algorithm for accurate classification in the manufacturing area. They posited that condition monitoring is a viable maintenance technique applied in the diagnosis of faults in rotating machinery. Rapur and Tiwari (2019) considered mechanical faults of varying severities in centrifugal pumps, while cavitation in pumps is the focus of the study by Al-Obaidi (2020). Achieving early fault prediction of centrifugal pumps in the oil and gas sector was studied by Orrù et al. (2020).

Some latest developments concerning the internal flow field and the external characteristics of centrifugal pumps were summarized by Tong et al. (2020). A comprehensive review of a noise study induced by flow in centrifugal pumps was presented by Guo, Gao, and He (2020). Zhao et al. (2020) considered the upgrading an existing monitoring system to take care of the operating range of a pump-turbine system that has been extended. Bozorgasareh et al. (2021) used experimental and numerical approaches to explore the impact of a new impeller configuration with shrouds that are designed innovatively on the pressure and efficiency of a semi-open centrifugal pump. Gonçalves et al. (2021) proposed a novel output-only method based on the Markov parameters to diagnose faults. The real time operating condition of pumps and the prediction of potential failures in pumps was monitored in another study (Chen et al., 2022). Avianto and Madelan (2022) applied the reliability centered maintenance method in carrying out maintenance and repair of pumps in companies dealing in fuel distribution. The move is to ensure increased reliability of the pumps.

The aim of the current study is to develop a maintenance strategy for centrifugal pumps. Special focus of this study is the mechanical seal which fails more often. Although routine maintenance is carried out, centrifugal pumps are usually run until failure of mechanical seals occur. If failure pattern of the mechanical seal under different operating environment is known, the seal can be replaced or removed for maintenance while standby pump is put in use. The mechanical seal can be put to use again once or twice before final disposal. Running to failure disrupts planned operations and leads to too frequent replacement of mechanical seals. The most suitable time to carry out maintenance on mechanical seal so as to extend its life is estimated in this study. Also, the economic implications of carrying out maintenance on mechanical seal at the interval that extends its life are investigated.

METHODOLOGY

Qualitative as well as quantitative maintenance analysis was carried out in this study.

Qualitative Maintenance Practices Applied

Qualitative maintenance analysis leads to the identification of the components in systems which are prone to failure, the potential modes of failure, the causes of failure and the effects of their failure. This requires the application of RCM tools. Failure modes, effects and criticality analysis (FMECA) one of the tools of RCM was applied in this work. The FMECA approach involves identification of the components of the system, identification of the failure modes of the different components, identification of the functions of the different components, causes of the various failures, the effects of the failure and identification of the level of criticality of the various components. Figure 1 shows the basic steps involved in the implementation of FMECA.

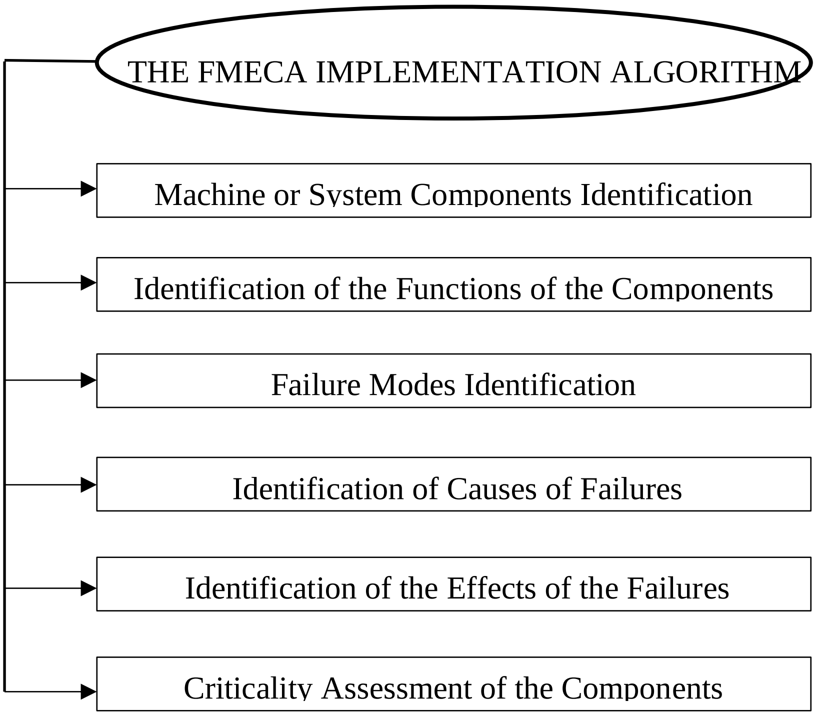

Figure 1: Algorithm of the FMECA implementation

The first five steps can be investigated via personal participation for maintenance personnel or via questionnaire requiring input from maintenance personnel. In this study, the information was sought from experienced operators of centrifugal pumps. Table 1 shows the type of information looked for in the FMECA implementation process. In Table 1, the components are provided. The functions of the various components, their failure modes, the causes of the failures and the effects of the failures are to be identified. This requires experience and expertise in the operation of centrifugal pumps; hence the information was sought from experienced operators. The last step in the FMECA implementation process involves assessing the criticality level of the various components. This is achieved via the estimation of the risk priority (RPN) of the various components. This is considered next.

Table 1: FMECA parameters sought

S/No.	Component	Function	Failure mode	Cause	Effect
1	Bearing	Identify	Identify	Identify	Identify
2	Shaft	Identify	Identify	Identify	Identify
3	Impeller	Identify	Identify	Identify	Identify
4	Mechanical seal	Identify	Identify	Identify	Identify
5	Shaft sleeve	Identify	Identify	Identify	Identify
6	Coupling	Identify	Identify	Identify	Identify
7	Barrel	Identify	Identify	Identify	Identify
8	Suction flange	Identify	Identify	Identify	Identify
9	Discharge flange	Identify	Identify	Identify	Identify
10	Casing	Identify	Identify	Identify	Identify
11	Wear rings	Identify	Identify	Identify	Identify

Estimation of Risk Priority Numbers of the Pump Components

The risk priority number of a given component in a system (which has to do with the failure of the component) consists of three parameters - failure occurrence, failure detection, and severity of the failure. Occurrence refers to the probability that failure will occur. Some components are more prone to failure compared to others. Detection refers to the ease with which failure can be detected if it occurs. Severity has to do with the level of danger or seriousness failure of the component imposes on the system. Each of the three parameters is usually given a scale of 1-10. Table 2 shows the RPN rankings with each rating clearly defined.

Table 2: Detailed ranking of RPN parameters

Rating	Occurrence	Detection	Severity
10	One failure in a week	Absolute Uncertainty	Dangerously high
9	One failure in a month	Very remote	Extremely high
8	One failure in three months	Remote	Very high
7	One failure in six months	Very low	High
6	One failure in a year	Low	Moderate
5	One failure in three years	Moderate	Low
4	One failure in five years	Moderately high	Very low
3	One failure in seven years	High	Minor
2	One failure in ten years	Very high	Very minor
1	One failure in twenty years	Almost certain	None

Source: Dappa-Brown et al. (2015)

The RPN is given mathematically by Equation (1)

$$RPN = O \times D \times S \tag{1}$$

where O, D and S stand for occurrence value, detection value and the severity value respectively.

The RPN was calculated for all components of the pump. To do the calculation of the RPN the RPN parameters were estimated for all the components of the pump. These were obtained from the field from experienced operators of centrifugal pumps. Average values of the RPN obtained from different operators were used in this study.

Quantitative Maintenance Analysis

Quantitative maintenance analysis was also carried out. The quantitative analysis involves the determination of various parameters pertaining to failure for each component in the system. These parameters are mean time to failure (MTTF), mean time to repair (MTTR), failure rate and availability.

Mean Time to Failure (MTTF)

The mean time to failure is the average time taken for an equipment to fail. It is usually expressed in two different ways depending on whether only one equipment is being considered or a number of equipment is under investigation. For single equipment, MTTF is expressed as the ratio of the total operating hours of the equipment to the total number of failures. This is given by Equation (2),

$$MTTF = \frac{T_{op}}{N_f} \tag{2}$$

where T_{op} is the total operating hours and N_f is the total number of failures. From the definition above, it is implied that the component or equipment is repairable. Actually, for repairable devices, mean time between failures (MTBF) is used in the place of mean time to failure. When a number of equipment is considered, the definition of takes the form of Equation (3) which is the ratio of the total operating hours of the items to the total number of items that failed;

$$MTTF = \frac{T_{op}}{n_f} \tag{3}$$

where n_f is the total number of items that failed after operating for time interval of T_{op} hours. The MTTF of the various components in the centrifugal pump were estimated in this work using information about equipment failures obtained from the field.

Mean time to repair (MTTR)

The mean time to repair (MTTR) is a measure of the maintainability of the equipment in question. It is expressed mathematically as in Equation (4)

$$MTTR = \frac{T_D}{N_R} \tag{4}$$

where T_D is the total downtime and N_R is the total number of repairs carried out. The MTTR for selected components of the centrifugal pump were derived from information obtained from pump operators. The values are presented under results and discussions.

Failure Rate

Failure rate expresses the number of failures per unit time. It is the reciprocal of the mean time to failure expressed by Equation (5),

$$\lambda = \frac{1}{MTTF} \tag{5}$$

where λ is failure rate. It is expressed as number of failures per hour (in most case as number of failures per year).

Availability

The availability of a component or device expresses how available the component is and put to use. It is affected by both the frequency of failures which has to do with the MTBF and the level of maintainability which has to do with the MTTR. It is given by Equation (6),

$$A = \frac{MTBF}{MTBF+MTTR} \tag{6}$$

where A is the availability of the component.

Investigation of Optimal Maintenance Interval of Mechanical Seal

From previous works, experience and data gathered in the course of this study, mechanical seal is the component in the centrifugal pump that fails more often. In the field, from personal experience and those of others, when a centrifugal pump is put into continuous usage, mechanical seal failures of between 26 to 54 times in a year were reported. A closer investigation showed that failure is affected mainly by erosion of mating surfaces caused by dirt in the fluid. The last eight months of this work was thus devoted to checking when best to take the mechanical seal for cleaning/replacement in the field. In the field, sometimes, the fluid transported has a lot of dirt, mainly sand. We thus categorized the fluid into three categories based on the level of sand. These are:

i. Fluid with low level of sand;
ii. Fluid with medium level of sand, and
iii. Fluid with high level of sand.

Because of the high frequency of failures of mechanical seals, standby systems are always in place in the field.

The normal practice is to run until failure of the seal, then, the standby system is put into use while maintenance is carried out on the failed system. In this case, based on the level of sand in the fluid, the standby system was should be put to use before failure when a new mechanical seal is in place. It is removed, cleaned of debris and put back into use. It is then run to failure after the first maintenance. Since the field operations are business in practice, incessant stoppage was frowned at but the operators gave some room for putting the standby systems to use while the mechanical seal was checked for debris and cleaning. The intervals accepted depended on the level of debris in the fluid which was monitored while the pump operation was in progress. Table 3 shows the different time intervals standby systems were put to use before failure. These are actually time intervals for checking the mechanical seals for debris and cleaning.

Table 3: Time intervals for checking mechanical seals for debris and cleaning

S/No.	Level of debris	Time of operation before usage of standby system (days)
1	Low	10-15
2	Medium	7-10
3	High	4-7

Economic Implications of New Maintenance Practice

In employing this new strategy of maintenance of centrifugal pumps, more frequent stoppage will be encountered while the life span of the mechanical seal will be extended. The economic implications of the maintenance practice were investigated for one year period in this study. For any of the three categories of debris in the fluid, for the new maintenance let, the annual maintenance cost is obtained as follows:

Let x be the number of hours the pump is in operation before a new mechanical seal is taken for maintenance, y be the number of hours a reused mechanical seal is put in use before failure, C_{pm} be the preventive maintenance cost of mechanical seal and C_{cm} the corrective maintenance cost of failed mechanical seal. The average number of preventive and corrective maintenance carried out in one year period is given by Equation (7),

$$N_m = \frac{8760}{x+y} \tag{7}$$

where N_m is the number of times preventive plus corrective maintenance is carried out and 8760 are the number of hours in a year. The annual maintenance cost A_{mc} due to maintenance seal is,

$$A_{mc} = \left(C_{pm} + C_{cm}\right) N_m \tag{8}$$

For the existing maintenance practice, mechanical seals are run to failure. Let z be the average number of hours a mechanical seal is in operation before failure. The number of corrective maintenance in a year N_{cm} with this practice is given by Equation (9),

$$N_{cm} = \frac{8760}{z} \tag{9}$$

The annual maintenance cost with the existing practice is given by Equation (10),

$$A_{cmc} = C_{cm} \times N_{cm} \tag{10}$$

The cost implications of both the existing and the proposed maintenance practices were estimated for a period of one year in this work. The preventive maintenance cost used in this work (obtained from the field) is ₦ 18,400 per hour, involving two maintenance personnel. It consists of basically labour cost. The corrective maintenance cost comprises labour cost which is ₦ 18,400 per hour, plus the cost of the mechanical seal which varies based on the type used. The cost of mechanical seal used in this work is ₦ 1,420,000. It takes about two hours to carry out preventive maintenance and about three hours to carry out corrective maintenance. The costs for preventive and corrective maintenance are thus ₦ 36,800 and ₦ 1,456,800 respectively.

RESULTS AND DISCUSSION

The results obtained in this study came in three different categories. These are results of the qualitative analysis, results of the quantitative analysis and results of optimal time carry out maintenance on mechanical seal.

The qualitative analysis led to the determination of the risk priority numbers of the different components of the centrifugal pump and the FMECA of the components. Table 4 shows the RPN of the components while the level of criticality of the pump components bare shown in Table 5. In order to compare the criticality levels of the different pump components, a new concept is introduced here. It is relative criticality. Any number can be used as a basis from which the components will share from based on their RPN value. In this case, 100 was used as a base. The value allotted to each component from 100 is a measure of its RPN value. The highest RPN values in the various failure modes are used for each component. Figure 2 shows the relative criticality of the different pump components. The FMECA results are shown in Table 6.

Table 4: RPN of the pump components under different failure modes

S/No.	Component	Failure mode	RPN
1	Bearing	1.1 Burnt insulator	84
		1.2 Power coil/bearing noise	124
2	Shaft	2.1 Bending of shaft	186
		2.2 Worn shaft	136
3	Impeller	3.1 Corrosion	113
		3.2 Unbalanced impeller	234
		3.3 Cracked impeller	113
4	Mechanical seal	4.1 Eroded mating surface	210

		4.2 misalignment	154
5	Shaft sleeve	5.1 Bending	128
		5.2 Eroded surface	78
6	Coupling	6.1 Bolt shearing	113
		6.2 Membrane shearing	172
7	Barrel	7.1 Eroded surface	79
		7.2 Misalignment	110
8	Suction flange	8.1 Eroded surface	52
		8.2 Misalignment	56
9	Discharge flange	9.1 Eroded surface	99
		9.2 Misalignment	83
10	Casing	10.1 Eroded surface	32
		10.2 Cracking of surface	34
11	Wear rings	11.1 Worn out	36
		11.2 Misalignment	40
		11.3 Breakage	18

Table 5: Criticality level of pump components

Pump components	Level of criticality
Bearing	Moderate
Shaft	High
Impeller	Very high
Mechanical seal	Very high
Shaft sleeve	Moderate
Coupling	High
Barrel	Moderate
Suction flange	Low
Discharge flange	Moderate
Casing	Very low
Wear rings	Low

Table 6: FMECA results of the pump components

S/No.	Component	Function	Failure mode	Cause(s)	Effect
1	Bearing	Nears the load of the shaft and keeps it in the correct alignment	1.1 Burnt insulator	Overheating (from lubricant failure)	Deformation of bearing
			1.2 Power coil/bearing noise	Misalignment	Failure of bearing
2	Shaft	Transmits torque and power to the impeller from the motor	2.1 Bending of shaft	Misalignment, high radial thrust	Noise vibration, shaft/pump failure
			2.2 Worn shaft	Corrosion	
3	Impeller	Causes pressure increment and fluid flow	3.1 Corrosion	Excess heat	Vibration and low performance
			3.2 Unbalanced impeller	Cavitation	
			3.3 Cracked impeller	Excess heat	
4	Mechanical seal	Prevent fluid leakage to shaft	4.1 Eroded mating surface	Excess heat, dry running	Leakage of fluid, damage of shaft
			4.2 misalignment	Cavitation	
5	Shaft sleeve	Protects the shaft from wear/tear	5.1 Bending 5.2 Eroded surface	Misalignment	Vibration noise and leakage

6	Coupling	Connects the shaft and the prime mover	6.1 Bolt shearing 6.2 Membrane shearing	Misalignment/ internal stress	Noise vibration, shaft/pump failure
7	Barrel	Houses the shaft and the impeller	7.1 Eroded surface 7.2 Misalignment	Corrosion	Vibration of components
8	Suction flange	Guide the inflow of fluid	8.1 Eroded surface 8.2 Misalignment	Vibration of flange and poor installation	Leakage of fluid
9	Discharge flange	Guides the outflow of fluid	9.1 Eroded surface 9.2 Misalignment	Vibration of flange and poor installation	Leakage of fluid
10	Casing	Houses the pump components	10.1 Eroded surface 10.2 Cracking of surface	Long usage	Exposure of components to corrosion attack
11	Wear rings	Helps in sealing leakage of fluid within the pump	11.1 Worn out 11.2 Misalignment 11.3 Breakage	Excess heat / poor installation	Decrease in pump efficiency/leakage

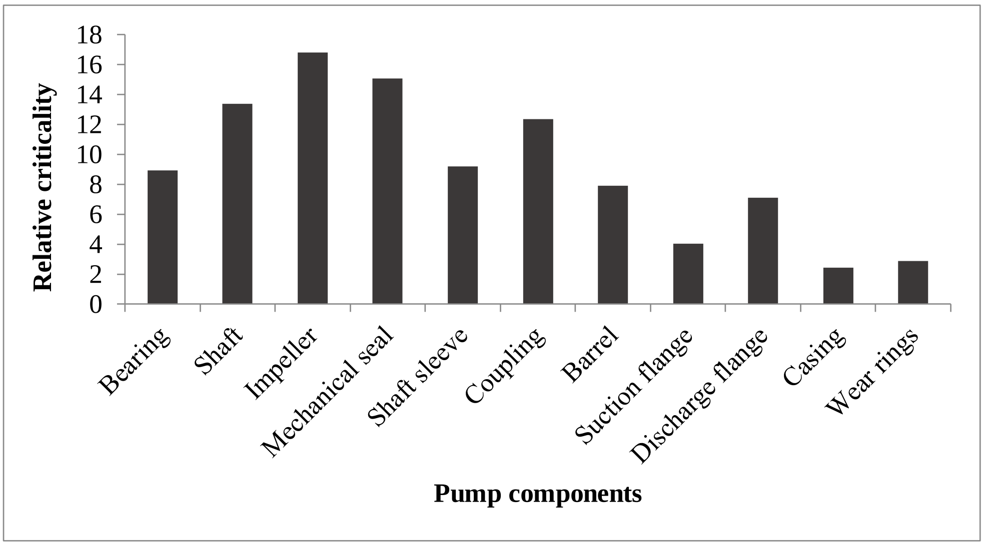

Figure 2: Relative criticality of pump components

The results of the quantitative analysis are presented below. The quantitative parameters include failure rate, mean time to failure, the mean time to repair and the availability. These parameters are shown in Table 7.

Table 7: Quantitative failure parameters of the centrifugal pump

Component	Failure rate (per hr)	MTTF (hr)	MTTR (hr)	Availability (%)
Bearing	0.00025685	3893.33	4	99.8974
Shaft	0.00012842	7786.67	9	99.8846
Impeller	0.00012842	7786.67	3	99.9615
Mechanical seal	0.00410959	243.33	4	98.3827
Shaft sleeve	0.00012842	7786.67	2	99.9743
Coupling	0.00025685	3893.33	2	99.9487
Barrel	0.00025685	3893.33	3	99.9230
Suction flange	0.00001189	84096	5	99.9941
Discharge flange	0.00001189	84096	5	99.9941

Casing	0.00001189	84096	6	99.9929
Wear rings	0.00012842	7786.67	4	99.9487

The new or proposed maintenance practice involves putting the standby system to work before the failure of mechanical seals. The time interval to do this under different conditions of the fluid was sought. Table 8 shows the average time taken for mechanical seal to fail under different conditions of the fluid handled while the recommended intervals before failure of seals are shown in Table 9. For reused mechanical seals, the average time taken for them to fail is shown in Table 10. The cost implications of the proposed maintenance practice and the existing maintenance practice for the different fluid conditions for a period of one year are shown in Figure 3.

Table 8: Average number of days before failure of mechanical seal under different conditions of fluid

S/No.	Level of debris	Time of operation before failure (days)
1	Low	13`
2	Medium	9.5
3	High	6.5

Table 9: Recommended maintenance interval of mechanical seal under different conditions of fluid

S/No.	Level of debris	Time of operation before usage of standby system (days)
1	Low	11
2	Medium	8
3	High	5

Table 10: Average number of days before failure of reused mechanical seal under different conditions of fluid

S/No.	Level of debris	Time of operation before failure (days)
1	Low	9
2	Medium	7
3	High	4.5

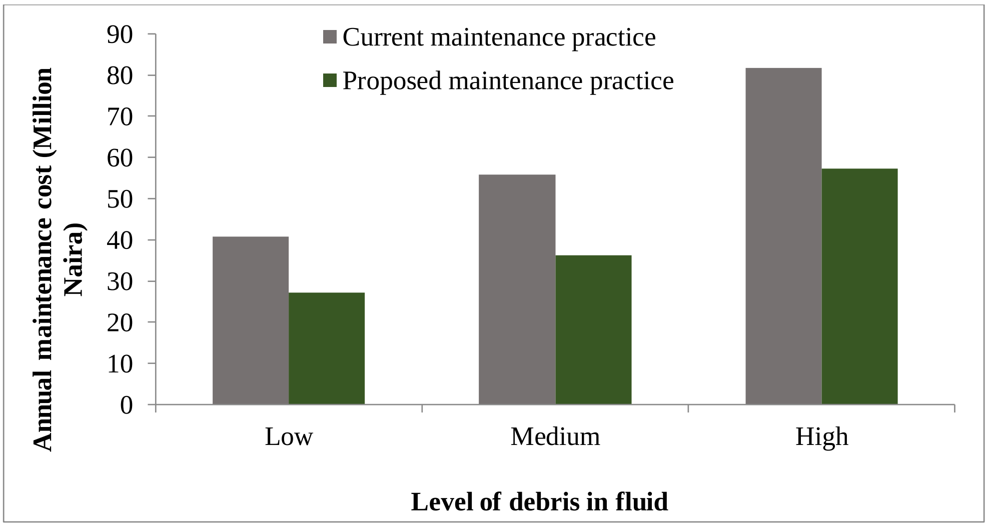

Figure 3: Annual maintenance cost pertaining to mechanical seal for the current and proposed maintenance practices

From the results of both the qualitative and quantitative analyses, it is observed that failure of components comes in different forms. For instance, mechanical seal can fail due to erosion of surfaces and misalignment while impeller failure can stem from corrosion, unbalanced impeller and cracked impeller. For the shaft, the failure comes in the form of bending and worn shaft. The causes of the different failure modes differ. Taking the shaft as a case study, shaft bending is caused by misalignment and high radial thrust while worn shaft is due to corrosion. Also, the effects of the failure of different components of the centrifugal pump differ. Comparing the impeller and the mechanical seal, failure of the impeller leads to vibration and low performance but that of the mechanical seal leads to leakage of fluid/damage of the shaft if left to continue in operation.

For the results of the quantitative analysis, mechanical seal has the highest value of failure rate (0.0041 per hour) which is several times the failure rate of the bearing, coupling and barrel which failure rates value stood at 0.000257 per hour. Thus, the MTTF of the mechanical seal is the lowest (243.33 hrs). The shaft has the highest MTTR value of 9 hrs, followed by the casing with MTTR value of 6 hrs. Interestingly, the mechanical seal which fails more often has shorter MTTR value of 4 hrs. In terms of the availability of the components, the mechanical seal is the least available component of the centrifugal pump with availability of 98.3827%. Every other component of the system has availability value of over 99.8 %.

Introducing a new maintenance practice concerning the mechanical seal, it was observed that it is possible to remove the mechanical seal for cleaning and reuse it. Depending on the level of debris of the fluid handled, the mechanical seal can be used for up to 11 days and taken for cleaning if the fluid has low level of debris. For medium level and high level of debris in the fluid handled the mechanical seal can be used for 8 days and 5 days respectively before it is cleaned and reused. For reused mechanical seals, it was observed that they can run to failure for an average period of 9 days, 7 days and 4.5 days respectively for the three different levels of debris of the fluid handled. The new maintenance practice with the mechanical seal can lead to savings in maintenance cost of between ₦13.6 million to ₦24.4 million annually. Too sudden failures due to mechanical seal failure can be avoided with this maintenance practice.

CONCLUSIONS

Selected reliability centred maintenance tools were applied to the maintenance of centrifugal pumps. Also a new maintenance practice was introduced to assess the reusability of mechanical seals and the associated cost savings. The basic findings in this work are summarized below:

i. The top three most critical components of the centrifugal pump are the impeller, the shaft and the mechanical seal;
ii. The failure of any of the components of the pump can come in different forms;
iii. The effects of the failure of the different components of the pump differs;
iv. The mechanical seal is the most frequently failing component of the centrifugal pump, thus it has the lowest meant time to failure value;
v. The shaft has the highest mean to repair value;
vi. It is possible to remove the mechanical seal for cleaning and re-use, and
vii. When the mechanical seal is reused, maintenance cost savings of over to ₦24 million annually can be achieved.

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