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(RESEARCH ARTICLE)

Cost effective maintenance strategy for centrifugal pumps using reliability centred maintenance

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Abstract

The aim of this work is to obtain a maintenance strategy that is cost effective for centrifugal pumps using reliability centred maintenance (RCM). The components of the centrifugal pump used for the study are the shaft, impeller, bearing, mechanical seal, coupling, shaft sleeve, wear-ring casing, suction flange and discharge flange. The motor that drives the pump was also considered. Two basic tools of the RCM strategy were applied. These are the failure modes, effects and criticality analysis (FMECA) and logic tree analysis (LTA). Failure data for a period of 10 years about a centrifugal pump was collected and the FMECA was applied to determine the failure modes, the effects of the failure, the criticality of the components, the mean time between failure (MTBF), the failure rate and the mean time to repair (MTTR). The risk priority numbers of all the components were estimated. The LTA was applied to come up with a new maintenance strategy for each of the components of the pump. The maintenance cost consisting of spare part cost and labour cost for the pump components were estimated for the current maintenance practice as well as the new or proposed maintenance practice. The most critical components observed were the motor, shaft, impeller and the mechanical seal. The motor has the highest MTTR value (58 hrs) while the mechanical seal has the highest failure rate (8.06E-04 per hr). The proposed maintenance strategy leads to reduction in spare part cost in a number of components, with the largest reduction of 19.88% occurring in mechanical seal. The proposed strategy also leads to reduction in labour cost in motor, shaft, impeller and the mechanical seal with the values 33%, 25%, 50% and 25% respectively. The methodology could be applied to other devices.

Keywords: Cost effective; Criticality; FMECA; LTA; MTBF; MTTR; RCM

1. Introduction

The lightest of all constituents of crude oil (fossil fuel which occur naturally from decomposing plants and animals which lived millions of years ago) is Liquefied Petroleum Gas (LPG). The transported crude oil which differs in colour from plain to coal black is pumped through the feed stock into the crude distillation column which has separation plates. Its constituents splitting apart are done at different temperature. The Liquefied Petroleum Gas(LPG), naptha, premium motor spirit(PMS), kerosene, diesel and bitumen are collected [1]. The gas transferred via centrifugal pump which has high flow rate since LPG has lowest viscosity. As viscosity rises, pump's efficiency declines [2].

A pump is a piece of machinery that uses suction pressure (partial vaccum) to lift or move the fluid, such as liquid, compress gases or forced air into inflatable gadgets like tyres or pass on fluid like liquid [3]. A mechanical tool designated a pump conveys energy and fluid [4]. A mechanical invention used to transfer fluid through the addition of rotational energy by one or more impellers is called centrifugal pump [5]. The failure of pump brings about alteration in the operation of the pump which causes reduction in efficiency and pump break down [6]. In order to take care of the pump health, maintenance is necessary.

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All procedure that are necessary to maintain or return a piece of machinery, apparatus or other property to a specific state have been referred to as maintenance [7]. Reliability centred maintenance refers to corporate level of maintenance strategy that is implemented to optimize the maintenance program of a company. The focus is to achieve maximum reliability and availability through minimization of the possibility of the system or company failure [8]. It is the best or favourable mix of time or interval based, reactive, conditional based and, proactive maintenance and practices; instead of applying the maintenance strategies independently [9]. Failure modes, effects and criticality analysis (FMECA) are some of the activities involved in RCM. It is a systematic process through which the mode of failure of every components or function within a system is being assessed for probability of occurrence, failure effect and criticality with respect to the successful operation, safety and maintenance. The elements of FMECA are failure mode, failure effect, failure cause, environment, failure detection, severity classification and criticality analysis [10].

Tupake *et al.* [11] did present in their work, a different maintenance method for the compressed air system. The purpose of their work is to obtain a maintenance program for the said system which can help reduce down time, minimize unplanned failure, and make it dependable and accessible. The RCM approach is utilized so equipment can be available to a very large extend and efficient. It was shown that, the approach used did reduce the time between failures and unplanned failure of equipment. The cost of labour for maintenance was reduced from $314000/year to $240000/year, meaning that, if the recommended RCM approach is executed, it will result in cost reduction. Afefy [9] did put forward the use of RCM technique which involves selecting a system, defining the limits, stating what it represent, failures, the failure mode effect analysis, logic tree analysis and deciding on the required task to produce or formulate a maintenance strategy for a steam process plant. The purpose of the study is to build a plan using RCM approach for the components of the said steam plant. It was observed that, when the said technique was used, the mean time between failure (MTBF) and the chance for unexpected failure of equipment did reduce. The labor cost reduced from $295200/year to $220800/year.

Olabisi, *et al.* [12] presented maintenance plan for centrifugal pump for Oando Plc in TSL logistics in their study. A number of failure occurrences were analyzed for diesel, premium motor spirit and kerosene. They evaluated and analyzed the centrifugal pump maintainability. Reliability centred maintenance technique was employed to plan maintenance using information obtained from the field. Ishiakawa diagrams were utilized to show the failure analysis root cause, by categorizing failure causes. Okwuobi*, et al.* [13] did look into an automated production, the trend in breakdown. The study was aimed at putting forward the use of RCM to help improve productivity through a recent preventive maintenance plan in a machine which produces bottles. Failure modes and effects analysis (FMEA) was used to plan the maintenance. It was suggested that, precision maintenance, selective run to failure and preventive maintenance when executed or applied independently will bring about decrease in downtime cost and increase in the reliability of the pusher assembly of the system. Petrovic, *et al.* [14] introduced the use of RCM in water works. This work dealt on means of equipment failure. The purpose of the work is to determine how feasible it is to use RCM technique in water works. The steps used include choosing a system, stating the boundary, defining the system, the failure, carry out FMEA and Decision Logic Tree Analysis (LTA), and choose the actions required.

Pereira *et al.* [15] put forward failure analysis of dry gas seal in their study. The RCM method was used to carry out the weibull analysis model. The research and analysis outcome shows that rubble from the seal filter was released in neat filter area and, the reason for seal filter failure was stated as the rubble which goes through the seal filter. It was established that 80% of the failure of seal that occurred is brought about by unwanted substances in the gas of the seal while other failures resulted from installment, issues with alignment and piping. Mphosa & Botha [16] investigated the unplanned down time of centrifugal pumps failure which reduces reliability and in-turn reduces the pump availability in air separation plants applying RCM approach. The purpose of the work is to discover the issues which affect the centrifugal pump reliability and key things which contribute to the improvement in air separation plants. It was stated that, not having proper understanding and experience about the business stages accounts for poor maintenance method. None availability of communication from one personnel to another is said to cause a breakdown in the passage of knowledge and pump technique improvement.

The reviewed literatures show that, the researchers did focus on reducing down time, break down, increasing availability, reliability and performance, analyzing failure and building a plan using RCM approach with FMEA tool. Several works have been done on centrifugal pump such as in gas plants but detailed analysis of cost of a built or proposed maintenance strategy for centrifugal pump is hardly considered. Thus, this study is aimed at creating a cost effective maintenance strategy for centrifugal pump in a refinery in Rivers State, using FMECA.

2. Methodology

2.1. System Description

The centrifugal pump has its main components as the impeller, shaft, mechanical seal and bearing. Others are shaft sleeve, case wearing, casing support, coupling, pump barrel and motor as driver. It has 19 numbers of stages and the impeller is a closed type. The established RCM Steps by Afefy [9] were employed with adjustments, having FMECA replacing FMEA to help carry out analysis. The steps are shown in Figure 1.

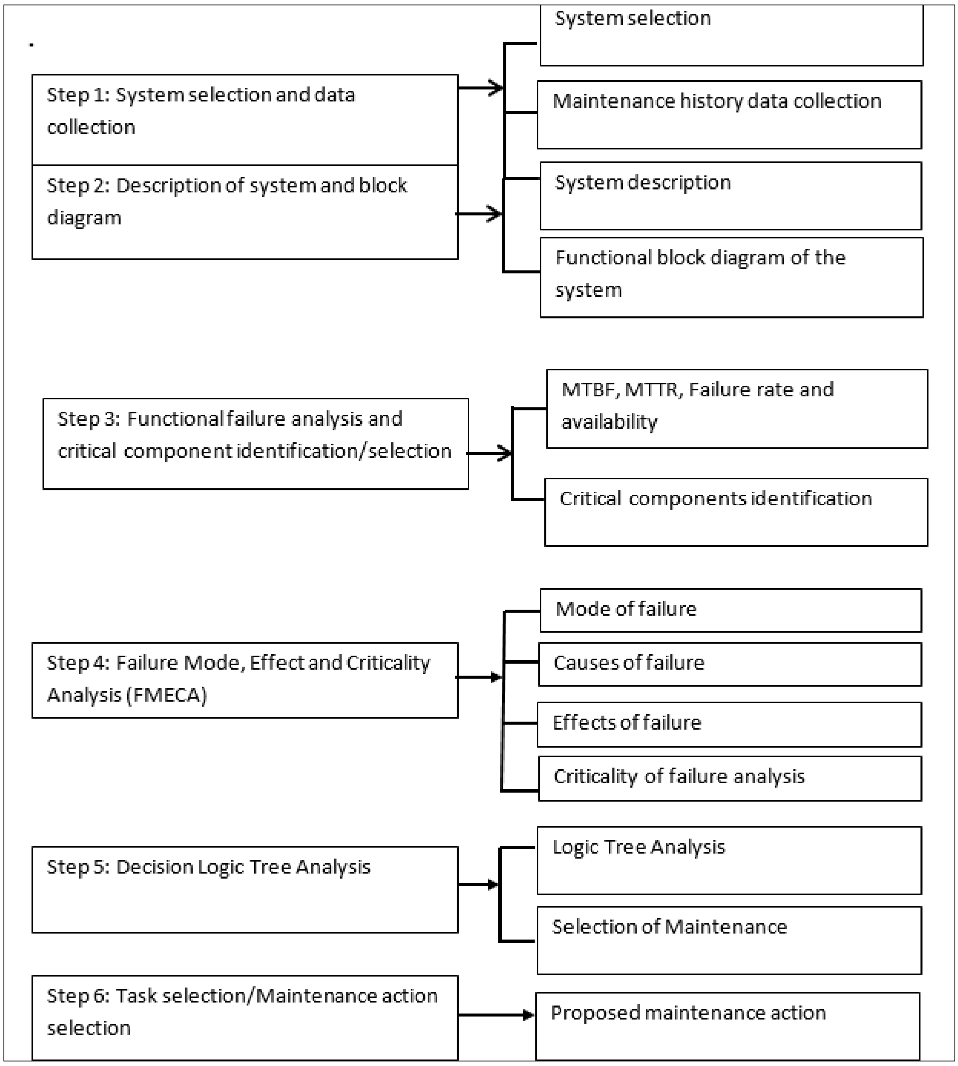

Figure 1 Adjusted reliability centred maintenance (RCM) steps

2.2. System selection

A liquefied petroleum gas (LPG) transfer pump called vertical barrel multi-stage centrifugal pump was selected for the analysis I this study. Maintenance data for a period of ten years was collected. The block diagram of the pump is shown in Figure 2.

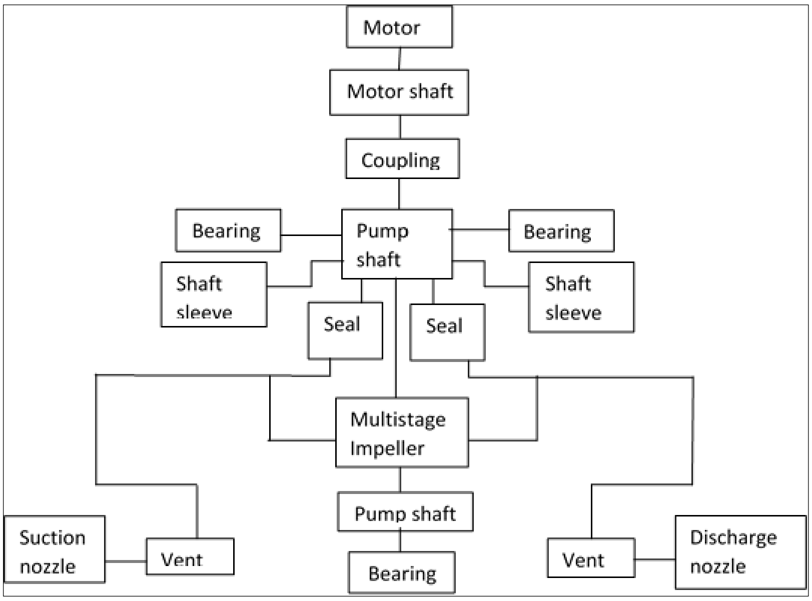

Figure 2 Pump block diagram

2.3. Functional Failure Analysis

The mean time between failure (MTBF), failure rate, availability and mean time to repair (MTTR) are factors which determine the selection of critical components. Mean time between failures is the metric for failure or measure of reliability for repairable items or systems. It is expressed by Trout [17] as in Equation (1),

$$MTBF = \frac{\sum t_1}{n} \text{.................... (1)}$$

where $\sum t_1$ is the total running time in operation of the pump and n is the number of failures or break down of pump or components. Mean time to repair is the average time it takes to troubleshoot and repair a failed machine or system in other for it to return to the normal operating condition. It is expressed by Equation (2),

$$MTTR = \frac{\sum t_2}{N} \text{.................(2)}$$

where $\sum t_2$ is the total maintenance or repair time (down time) of the pump and **N** is the number of repairs. Failure rate (λ) is the rate of failure occurrence. It is given by Equation (3),

$$\lambda = \frac{n}{\sum t_1} = \frac{1}{MTBF} \text{................ (3)}$$

where $\sum t_1$ is the total running time in operation of the pump and n is the number of failures or break down of pump or components. Availability (A) is the probability that the machine performs the required function over a stated period of time when it is operated and maintained as required [10]. It is expressed by Kumar & Krishnan [18] as in Equation (4),

$$A = \frac{MTBF}{MTBF+MTTR} \text{...................(4)}$$

2.4. Failure Mode Effect and Criticality Analysis (FMECA)

The failure mode impact assessment was carried out in this study. The risk priority numbers (RPN) of the components were obtained. The risk priority numbers is expressed mathematically as shown in Equation (5) [19].

$$RPN = O * S * D \text{ .... (5)}$$

where O is occurrence/frequency of failure, S is severity of the consequences and D is detection.

2.5. Decision Logic Tree Analysis (LTA)

Questions which aided the selection of the appropriate maintenance strategy for the failure modes were answered via the decision logic tree as shown in Figure 3.

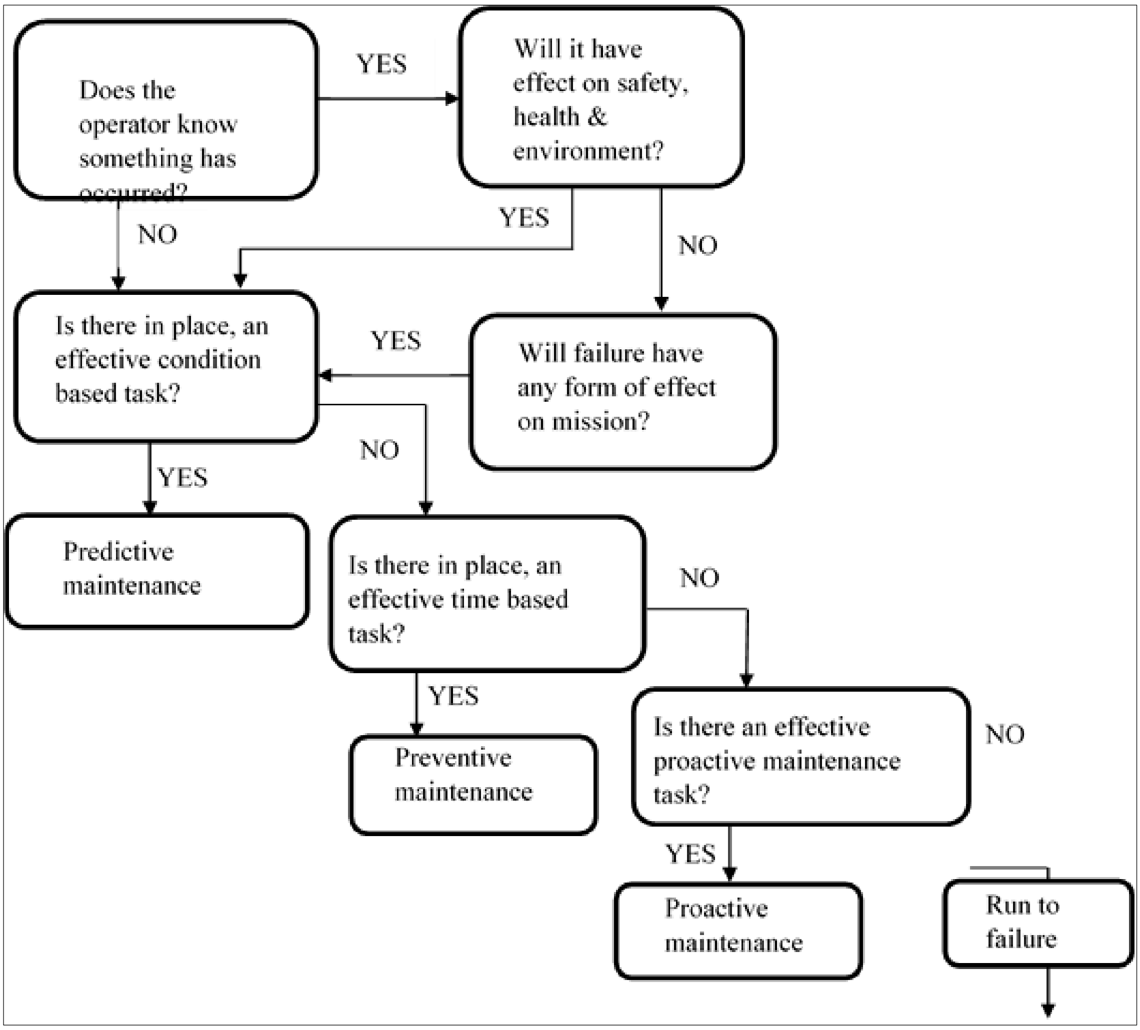

Figure 3 Decision logic tree analysis (LTA)

Based on the results of the FMECA and LTA, a maintenance strategy was proposed for each of the components of the pump. Maintenance cost due to the current maintenance strategy and the proposed maintenance were estimated for the various components of the pump.

2.6. Spare Part Cost

Cost analysis is based on the current online market prices as at when the analysis was carried out for a period of ten years for both current and proposed strategy based on spare part program. Cost of part (P_C) is given by Equation (6),

$$C_P = P_P * N_P \text{............}(6)$$

where C_P is cost of part or component, P_P is component or part price and N_P is spare part number or component quantity replaced. Total cost of spare part or component is given by Equation (7),

$$P_{TC} = \sum C_P \text{..................} (7)$$

where P_{TC} is total component or spare part cost and $\sum P_C$ is the component or spare part cost sum.

2.7. Labour Cost

Assumptions made for the purpose of this analysis is that, labour used is 10 and pay per hour is ₦8.333.33. Cost of labour (L_C) is given by Equation (8),

$$L_C = R_T * P_h * L_n \text{ ………………(8)}$$

where L_C is cost of labour, R_T is total repair time, P_h is pay per hour and L_n is labour number used. The total labour cost L_{TC} is given by Equation (9),

$$L_{TC=} \sum L_C \text{ ……………..(9)}$$

The total maintenance cost M_{TC} is given by Equation (10),

$$M_{TC} = P_{TC} + L_{TC} \text{ ………. (10)}$$

The labour costs for the current maintenance and the proposed maintenance strategy were obtained in this work.

3. Results and discussion

The quantitative maintenance parameters are shown in Table 1 while the results of the FMECA are presented in Table 2. In Table 3, the results of the risk priority numbers of the various components together with their respective criticalities are presented. The current maintenance strategy and the recommended maintenance strategy are presented in Table 4. The percentage reduction in spare part cost of selected components with the introduction of the proposed maintenance strategy is shown in Figure4 while the cost of labour for the current and proposed maintenance strategies for period of 10 years is shown in Figure 5.

Table 1 MTBF, failure rate, availability and MTTR

S/N	Components	MTBF (hrs)	λ (per hr)	MTTR(hrs	A (%)
1	Motor	5256	1.90E-04	58	98.91
2	Bearing	5256	1.90E-04	18	99.66
3	Shaft	7850	1.27E-04	36	99.54
4	Impeller	7850	1.27E-04	36	99.54
5	Mechanical seal	1240	8.06E-04	8	99.36
6	Casing	12824	7.80E-05	18	99.86
7	Suction flange	12824	7.80E-05	48	99.63
8	Discharge flange	12824	7.80E-05	48	99.63
9	Barrel	5256	1.90E-04	54	98.98
10	Shaft sleeve	7752	1.29E-04	18	99.77
11	Couplings	5256	1.90E-04	4	99.92
12	Wear-rings	7764	1.29E-04	18	99.77

Table 2 Results of pump failure mode and effect analysis

S/N	Component	Function	Failure mode	Cause(s)	Effect(s)
1	Motor	Powers the pump	-Amature breakdown -Bearing failure	Over loading and inadequate lubrication	Insufficient torque, premature wear leading to failure

2	Bearing	Keeps shaft in correct alignment Bears shaft load to reduce friction	-Burnt insulator -power coil and bearing noise	Overheating, lubricant failure and misalignment	Bearing deformation, failure and reduced life
3	Shaft	Transmit torque & power from motor to impeller	-Bent and worn shaft - Burnt shaft	Misalignment, corrosion and high radial thrust on shaft	Noise, vibration & ensuing shaft & pump failure
4	Impeller	Increases pressure & flow of fluid	-Eroded -Unbalanced & cracked impeller	Cavitation & excess heat	Vibration & low pump efficiency
5	Mechanical seal	Prevent leakage to shaft	-Cracked, eroded mating fac- Misaligned face scale	Excess heat, dry running, cavitation	Fluid leakage, shaft damage
6	Casing	Houses the pump components	-Corrosion -Cracking	Aging	Components exposure and possible corrosion
7	Suction flange	For fluid inflow	-Eroded surface -Misaligned flange	Flange vibration & improper installation	Fluid leakage
8	Discharge flange	For fluid outflow	-Eroded surface -Misaligned flange	Flange vibration & improper installation	Fluid leakage
9	Barrel	Houses shaft and impeller	-Eroded surface -Misalignment	Corrosion	Vibration of components
10	Shaft sleeve	Protect shaft from wear	-Worn & eroded surface Bent shaft sleeve	Misalignment or poor alignment	Vibration, noise, leakage near shaft seal and wear
11	Couplings	Connects shaft and motor	-Sheared flexible membrane -Sheared bolt	Internal stress and misalignment	Noise, vibration, seal damage and pump shut down
12	Wear-rings	Help seal pressure leakage of fluid within pump	-Worn and misalignment -Broken wear-ring	Leakage through tight clearance & increasing clearance due to further wear.	Leakage loses and decreased pump efficiency

NB: The failure modes are also identified with numbers corresponding to the various components.

Table 3 Mean of risk priority numbers, range and criticality category of each failure modes

Components	Failure Mode	Mean RPN	Range RPN	Ranking/Category
Motor	1.1	384	72	1/A
	1.2	233.3	98	2/A
Bearing	2.1	77.3	20	14/B
	2.2	105	75	11/B
Shaft	3.1	138	55	6/A
	3.2	132.6	150	7/A
Impeller	4.1	128	24	8/A

	4.2	151.3	146	4/A
Mechanical seal	5.1	140	30	5/A
	5.2	160	90	3/A
Casing	6.1	42.	32	23.A
	6.2	50.7	43	21/C
Suction flange	7.1	51.3	14	20/C
	7.2	64.7	102	17/C
Discharge flange	8.1	64.7	42	16/C
	8.2	57.7	87	19/C
Barrel	9.1	60.7	22	18/C
	8.2	76	88	15/C
Shaft sleeve	10.1	84	28	13/B
	10.2	108.7	102	10/B
Couplings	11.1	96	0	12/B
	11.2	109	138	9/B
Wear-rings	12.1	29.3	8	24/C
	12.2	44	60	22/C

Table 4 Recommended maintenance action for the critical components of the pump

Component	Failure mode	Criticality	CS	RS	Maintenance task
Motor	-Amature breakdown -Bearing failure	High High	PM PM	PDM PM PM	Monitor motor temp. Check more than two to three on attempt Lubricate bearing as re commended to avoid temp rise, crack & hard ness reduction
Bearing	-Burnt insulator -Power coil and bearing noise	Moderate Moderate	PDM PDM	PDM PDM	Monitor motor temperature Check for increasing vibration, temp, lubricant condition & re-mount unbalanced bearings
Shaft	- Bent and worn - Burnt shaft	High High	PM PM	PM PM	Check for impeller balancing, worn bearing, shaft vibration and misalignment
Impeller	- Eroded impeller - Unbalanced & Cracked	High High	PM PM	PM PM	Check impeller is well mounted Look for elevated vibration noise level
Mechanical seal	- Cracked, eroded mating face scale - Misaligned face Scale	High High	RTF RTF	PM PM	Check for loose bearing vibration & worn shaft Check for proper installation or alignment

Shaft sleeve	- Worn & eroded surface - Bent shaft sleeve	Moderate Moderate	PM PM	PM PM	Check out for unusual vibration, clean shaft surface Use recommended tool to remove and Replace
Coupling	- Sheared flexible membrane - Sheared bolt	High High	PM PM	PM PM	Check for coupler alignment or angular misalignment Check for insufficient or under tightening

CS = current strategy, RS = recommended strategy, RTF = Run to failure

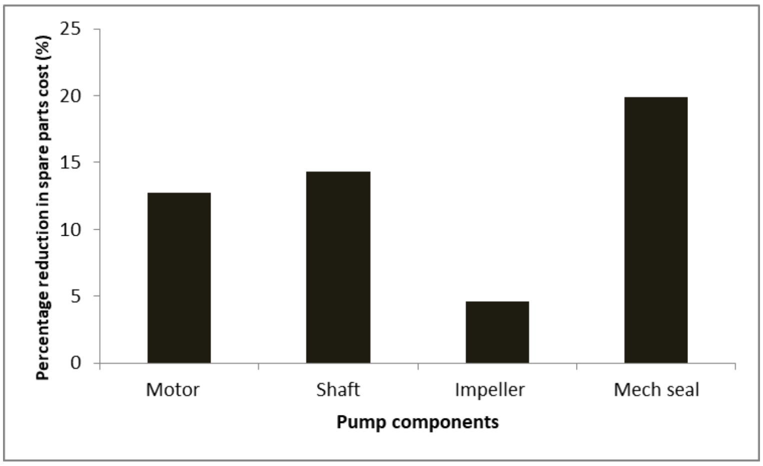

Figure 4 Percentage reduction in spare part cost for proposed maintenance strategy for period of 10) years

From Table 1, coupling has the least MTTR value of 4 while motor has the highest MTTR value of 58. This means that coupling can be repaired the quickest, has least down time and lesser impact on the system. The motor on the other hand, has the highest down time and this will impact the system. Mechanical seal has the highest failure rate value of 8.06E-04. Meaning that, the seal fails often compared to other components even though it does not have the highest MTTR value. Shown as well is the coupling having the highest availability value of 99.92% and motor having the least availability value of 98.91%. This means coupling will be available the most while motor will be down the most. Further shown on the table is mechanical seal having the least MTBF value of 1240 hrs. This simply means that mechanical seal has the shortest time between two failures.

The results of the FMECA are shown in Table 2. Two possible failure modes are identified for each component of the pump. The failure modes can be referred to with the numbers corresponding to each component and the failure number. For instance, failure mode 1.1 refers to amature breakdown of motor. The causes of the failure and the effects are also provided. The mean of the risk priority numbers of the various components and their criticalities are presented in Table 3. It can be observed that failure mode 1.1 has the highest mean RPN value as 384 and is ranked as 1/A which means that, the motor is the most critical (signified by 1) and is categorized as A to show that, it is highly critical. This implies it has huge impact on the system. Failure mode 12.1 has the least mean RPN value as 29.3 and is ranked as 24/C. This means that, wear-ring is least critical (signified by 24) and categorized by C to mean less critical. For the failure modes 7.2 and 8.1, they have the same mean RPN value as 64.7, the range of their RPN is used for the ranking. The failure modes 7.2 and 8.1 have their Range RPN values as 102 and 42. The least range RPN is 42 for failure mode 8.1 and is ranked as 16/C while 7.2 is ranked as 17/C. This means that, the component of failure mode 8.1 is more critical than 7.2 despite both are categorized as C (less critical). The criticality starts with the highest value of mean RPN and decreases downward. The motor, shaft, impeller and the seal have their category as A. It means they are highly critical components. The bearing, shaft sleeve and coupling are categorized as B, meaning they are moderately critical.

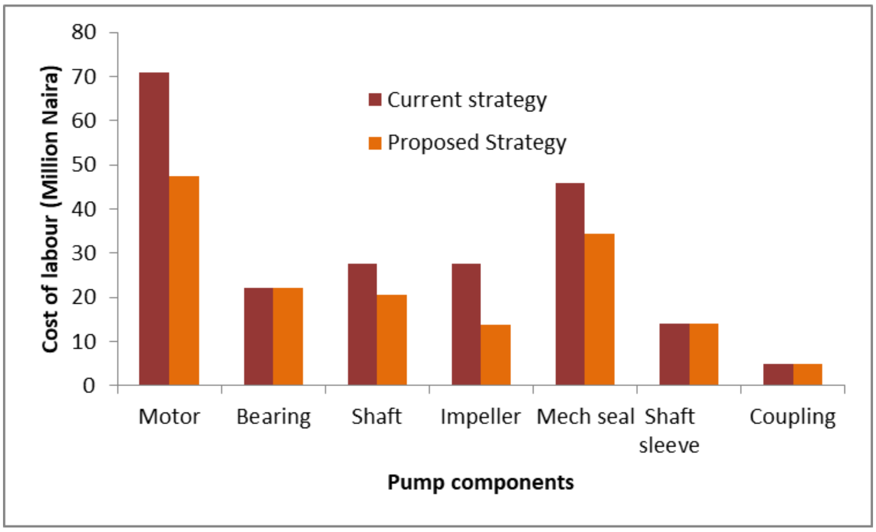

Figure 5 Cost of labour for current and proposed maintenance strategies for period of 10 years

The results of the FMECA and LTA led to the formulation of a new maintenance strategy for selected components of the pump. Both the current maintenance strategy and the recommended maintenance strategy are presented in Table 4. The percentage reduction in spare part cost for as a result of the introduction the proposed maintenance strategy for period of 10 years is shown for four components in Figure 4. Of the four components, the largest reduction in spare part cost was obtained from mechanical seal, the most frequently failing component. The labour cost for the current maintenance strategy is compared with the proposed maintenance strategy for seven components in Figure 5. The labour cost for the proposed strategy is smaller than that of the current strategy for the motor, shaft, impeller and the mechanical seal while it is the same for the bearing, shaft and coupling. The motor has the highest labour cost. This is because of the high MTTR value associated with the motor. The labour cost of the mechanical seal is also high. This is because of the high failure rate of the mechanical seal leading to several maintenance activities in the period considered. In terms of percentage reduction in the labour cost with the proposed strategy, the values for the motor, shaft, impeller and the mechanical seal are 33%, 25%, 50% and 25% respectively.

4. Conclusion

Conclusion derived from the study is that the motor, bearing, shaft, impeller, mechanical seal and shaft sleeves are critical components. The motor is ranked 1/A and 2/A for failure modes 1.1 and 1.2 respectively. This implies it has huge or serious impact on the operation. The introduction of the new maintenance strategy leads to reduction in spare part cost. The highest reduction in spare part cost is associated with the mechanical seal, with a value of 19.88% while the least reduction in spare part cost was obtained from the impeller. The proposed maintenance strategy also led to reduction in the cost of labour for some components. The motor which has the highest labour cost also has the highest reduction in labour cost with the introduction of the proposed maintenance strategy. The mechanical seal also has high labour cost as it fails often. The labour cost does not change with the proposed maintenance strategy for some components.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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