Generation of Maintenance Task for the Minimization of Maintenance Cost in the Operation of Centrifugal Pump System

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Abstract
Consideration of difficulties inherent in maintenance management system in the operation of centrifugal pump, and to minimizes the maintenance cost by generating a maintenances task. Broad based results showed that the RCM had great impact on the preventive maintenance (PM) tasks. The Run-To-Failure (RTF) frequency was reduced. The result showed that by carrying out the proposed RCM labour plan on the plant equipment- the labour cost decreased from ₦162.900, 000.00/year to ₦31.028, 400.00/year. The proposed PM task results indicated a saving of about 80.95% of the total annual downtime cost as compared with the current maintenance (RTF) plan. The maintenance technique applied in this study could be adopted by production firms to improve the reliability of their plant and minimize its failure rate and operational cost.

Key ward: *cost, minimize, maintenance, task*

1. INTRODUCTION

A centrifugal pump is a mechanical device designed to move or transport fluids through a suction-discharge head by the conversion of rotational kinetic energy to the hydrodynamic energy of the fluid flow (Singh & Suhane, 2015). The rotational energy typically comes from an engine or electric motor. Centrifugal pumps are the most widely used type of pumps in domestic, agricultural and industrial applications. Over 80 percentage of all the pumps used are single-stage, end-suction type centrifugal pumps (Amachaghi, 2010).
In industrial applications, the probability of occurrence of critical problems such as component damage and pump failure is high due to heavy loads and the demand for continuous operation of the pump. In such cases, the entire plant will have to be shut down until the pump is either brought back to service or replaced.

Deeptesh and Amit (2015) carried out a research on study of centrifugal pump using failure mode effect and critical analysis based on fuzzy cost estimation; it was observed that the total downtime cost was reduced after the treatment..
Dolas *et al*. (2014) carried out a research on estimation of the system reliability using weibull distribution. The Windchill quality solution 10.1 Tryout' software was used to estimate the weibull parameters. Results proved that the two-parameter Weibull distribution can represent a decreasing,

constant or increasing failure rate. Conglin *et al*. (2013) carried out a study on marine propulsion system using the Fault Tree Analysis (FTA). The result shows that FTA can assess the reliability of the marine engine system effectively within a period of time, but it cannot assess its whole life.

Khaeroman *et al.* (2016) studied failure analysis and evaluation of a six cylinders crankshaft for marine diesel generator. Their study discussed the failure of a diesel engine crankshaft of a four stroke 6 cylinders, used in a marine diesel generator. A correct analysis and evaluation of the dimension of the crankshaft are very essential to prevent failure of the crankshaft fracture and cracks. The crankshaft is liable to deformation due to misalignment of the main journals bearings. Their study presented the result of crankshaft failure analysis by measuring the mean diameter of the rod journal and the main journal, on the wear, out of roundness, taper, etc. The measurement results must be compared with the acceptable value in the engine specification and manual service and also should follow the American Bureau of Shipping (ABS) guidance notes on propulsion shafting alignment. The measurement results of their study show that the main journal diameter of the third cylinder exhibits an excessive wear, 1.35 % above the permissible lowest rate. It also has a taper for 0.23 mm and out of roundness of 0.13 mm. The diameter of the rod journal indicates excessive wear, 1.06 % higher than the permissible lowest rate, the taper of 0.41 mm and out of roundness of 0.65 mm. The crankshaft warpage or run-out journal, the analysis of the crank web deflection are also evaluated and presented in their study.

Navneet and Bhangu (2018) examined implementation of reliability centered maintenance technique on boiler and accessories in a thermal power plant. They maintained that there has been a significant change in the maintenance techniques used in industrial and power sectors due to the new complex designs, advanced technology and a huge increase in the number and variety of physical assets (plant, equipment and buildings). They asserted that in face of this avalanche of change, modern maintenance managers seek the most appropriate maintenance technique to deal with each type of failure process.

2. MATERIALS AND METHODS

2.1 Maintenance Plan of the Centrifugal Pump System

For the objectives, the SPSS Software and MATCAD computer program were employed to analyse the reliability parameters of the centrifugal pump system from which a maintenance plan, centred on the analysed centrifugal pump system's reliability was generated, that reduces the operational cost of the centrifugal pump system in the Port-Harcourt Refinery. The reliability-centred maintenance plan that was generated uses a predictive and preventive maintenance strategy (not just the corrective maintenance strategy as currently used in the refinery) for the production system that minimizes the centrifugal pump downtime, consequently reducing the improving the plant operations in terms of costs and time. The RCM approach identifies all the perspectives of failures in the centrifugal pump systems' function and employs the appropriate maintenance approach for each failure respectively.

2.2 Components of Centrifugal Pumps

Each centrifugal pump is made of hundreds of parts. There are a few components that virtually every centrifugal pump has in common. These components can be subdivided into the wet end and the mechanical end. The wet end of the pump includes those parts that determine the hydraulic performance of pump. The two primary wet ends are the impeller and casing. In some cases the first radial bearing can be water lubricated. In this case also bearing can belongs to wet ends. The mechanical end includes those parts that support the impeller within the casing. The mechanical end of the pump includes the pump shaft**,** sealing, bearings and shaft sleeve (See Figure. 1). The main components of the centrifugal pump are enumerated and described as follows:

1. Wear rings
2. Impeller
3. Shaft (rotor shaft)
4. Shaft seal package
5. Bearings
6. Flywheel
7. Auxiliary systems

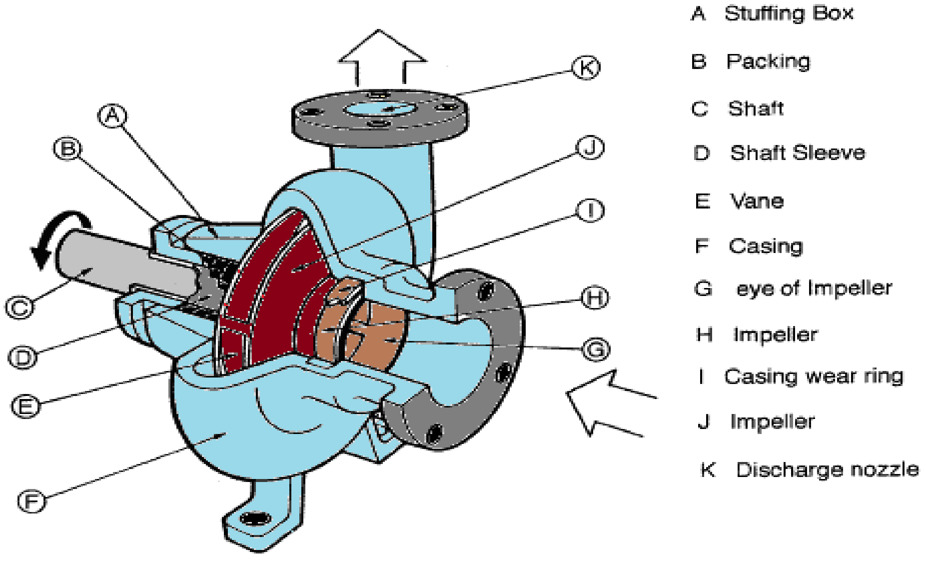

Figure 1: Components of Centrifugal Pump System

i. **Wear rings:** Wear rings are used to prevent any fluid from leaking up the impeller into the pump casing or containment.
ii. **Impeller.** Impeller is a rotor used to increase the pressure and kinetic energy (flow) of fluid.
iii. **Shaft (Rotor).** Shaft is a mechanical component for transmitting torque from the motor to the impeller.

iv. **Shaft seal package.** Shaft seal package is used to prevent any fluid from leaking up the shaft into the containment.

v. **Bearings.** Bearings constrain relative motion of the shaft (rotor) and reduce friction between the rotating shaft and the stator. Centrifugal pumps usually use a combination of fluid dynamic bearings and hydrostatic bearings in the radial bearing assembly **(**water lubricated; close to the primary fluid) and oil lubricated bearings used in the thrust (axial) bearing assembly (in the motor section).

vi. **Flywheel.** The flywheel provides flow coast down in case of loss of power.

vii. **Auxiliary systems:** they include oil lubrication system, oil lift system, seal leak off system, seal cooling system etc.

2.2.1 Causes of Failures of Centrifugal Pump

The failures associated with the operations of the centrifugal pumps are mainly due to:

i. Corrosion
ii. Erosion
iii. Wear/fatigue
iv. Electric motor failure
v. Mechanical failure

Components of Reliability-Centred Maintenance

Reliability Centred Maintenance (RCM) is the optimum mix of reactive, time or interval-based, condition-based, and proactive maintenance practices. These principal maintenance strategies, rather than being applied independently, are integrated to take advantage of their respective strengths in order to maximize facility and equipment reliability while minimizing life-cycle costs. Total productive maintenance (TPM), total maintenance assurance, preventive maintenance, Reliability centered maintenance and many other innovative approaches to maintenance problems all aim at enhancing the effectiveness of machines to ultimately improve productivity. The components of RCM program are shown in Figure 2. This figure showing that RCM program consists of (reactive maintenance, preventive maintenance, condition based maintenance, and proactive maintenance) and its patterns (Devaraj & Pradeep, 2016).

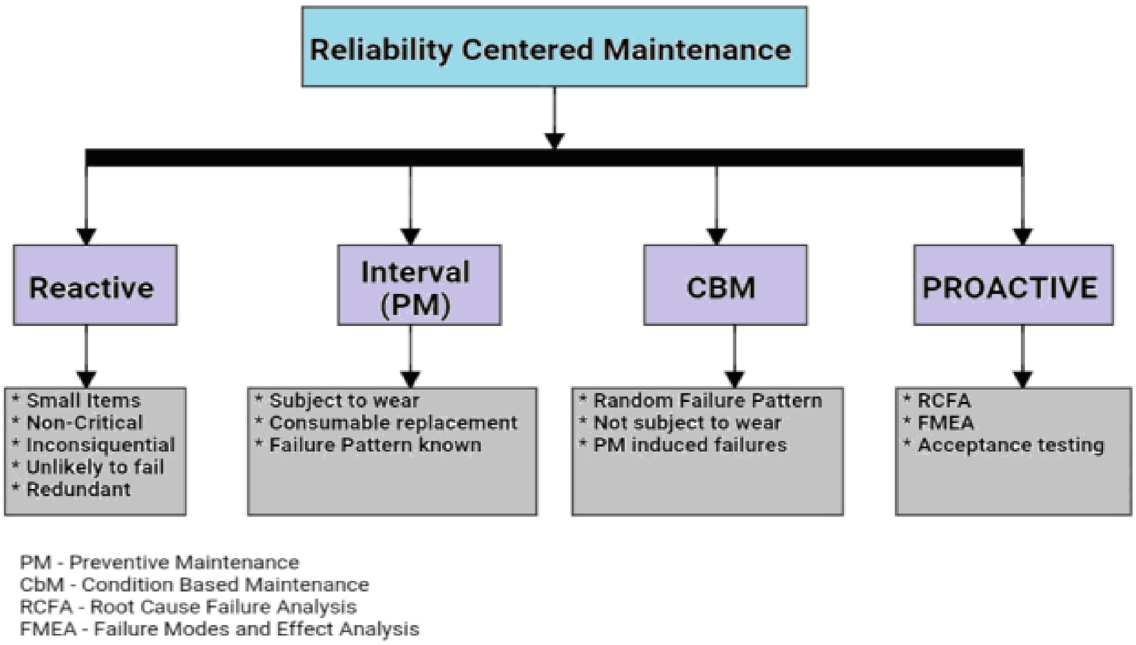

Figure 2: Components of RCM program

i. Reactive Maintenance

Reactive maintenance is also known as breakdown, fix-when-fail, run-to-failure, or repair maintenance. When using this maintenance approach, equipment repair, maintenance, or replacement takes place only when deterioration in the condition of an item/equipment results in a functional failure (Devaraj & Pradeep, 2016). In this type of maintenance, it is assumed there is an equally likely chance for the occurrence of a failure in any part, component, or system. When reactive maintenance is practiced solely, a high replacement of part inventories, poor use of maintenance effort, and high percentage of unplanned maintenance activities are typical. Furthermore, an entirely reactive maintenance program overlooks opportunities to influence equipment/item survivability.

ii. Preventive Maintenance

Preventive Maintenance (PM) consists of regularly scheduled inspection, adjustments, cleaning, lubrication, parts replacement, calibration, and repair of components and equipment. PM schedules periodic inspection and maintenance at pre-defined intervals (time, operating hours, or cycles) in an attempt to reduce equipment failure. It is performed regardless of equipment condition.

Depending on the intervals set, PM can result in a significant increase in inspections and routine maintenance. PM also reduces the frequency and seriousness of unplanned machine failures for components with defined, age-related wear patterns.

iii. Proactive Maintenance

Proactive maintenance improves maintenance through better design, installation, maintenance procedures, workmanship, and scheduling. The characteristics of proactive maintenance are: Using feedback and communications to ensure that changes in design or procedures are rapidly made available to designers and managers; employing a life-cycle view of maintenance and supporting functions; ensuring that nothing affecting maintenance occurs in isolation; employing a continuous process of improvement; optimizing and tailoring maintenance techniques and technologies to each application; integrating functions that support maintenance into maintenance program planning; using root-cause failure analysis and predictive analysis to maximize maintenance effectiveness; adopting an ultimate goal of fixing the equipment permanently; periodic evaluation of the technical content and performance interval of maintenance tasks (PM and PT&I). Proactive maintenance employs the following basic techniques to extend machinery life: specifications for new/rebuilt equipment; commissioning; precision rebuild and installation; failed-part analysis; root-cause failure analysis; reliability engineering; rebuild certification/verification; age exploration (AE) and the relationship with replacement of obsolete items (ROI) as well as recurrence control

3. RESULTS AND DISCUSSION

3.1 Results of Maintenance task that Minimizes the Cost of Operating the centrifugal pump system

The maintenance task for the centrifugal pump is illustrated in Table 3.1. The table reveals that for low discharge pressure failure mode of the centrifugal pump, caused by water excessively hot which was analysed with medium-high criticality level (criticality group B); the maintenance task prescribed is the condition-directed (CD) maintenance as it has a moderately high effect on the system. For failure mode high bearing temperature caused by bent shaft, worn bearing, lack of lubrication and improper installation of bearing which were all analysed with high criticality level (criticality group A), the maintenance task prescribed for all the failure causes are: the condition-directed (CD) maintenance tasked with checking and replacing bent shaft, worn bearing, adequate lubrication and checking bearing for proper installation, monthly, as the failure caused has a high effect on the system.

Table 1: Centrifugal Pump Maintenance Task Selection.

Equipment	Failure Mode	Failure cause	Group	Task	Description	Frequency
	Low discharge pressure	Water excessively hot	B (Medium-High)	CD	Check temperature of water	Monthly

		Bent shaft	A (High)	CD	Check and Replace bent shaft	Monthly
	High bearing temperature	Worn bearing	A (High)	CD	Check and Replace worn bearing	Monthly
Pump		Lack of lubrication	A (High)	CD	Lubricate adequately	Monthly
		Improper installation of bearing	A (High)	CD	Check bearing for improper installation	Monthly
	Pump casing overheats	Misalignment of pump drive motor	A (High)	CD	Check pump drive motor for misalignment	Monthly
		Shaft sleeve worn	A (High)	CD	Check and Replace worn shaft sleeve	Monthly
	Low flow	Impeller damaged on loose shaft	A (High)	CD	Check for loose shaft and Replace damaged impeller	Monthly

For failure mode pump casing overheats caused by misalignment of pump drive motor and shaft sleeve worn which was analysed with high criticality level (criticality group A), the maintenance task prescribed is condition-directed (CD) maintenance, tasked with checking pump drive motor for misalignment by employing soft foot test and laser alignment kit and checking and replacing worn shaft sleeve, monthly, as the failure caused has a high effect on the system Finally, for failure mode low flow caused by impeller damaged on loose shaft was analyzed with high criticality level (criticality group A), the maintenance task prescribed is the condition-directed (CD) maintenance, tasked with checking for loose shaft and replacing damaged impeller, monthly, and as it has a maximal effect on the system.

3.1.1 Maintenance Labour Force

The size of the maintenance labour force is presented in Table 3.2. This table shows the size of maintenance labour force calculations for the PM levels (six monthly, monthly and weekly). Following the maintenance task presented in Table 3.2, tasks prescribed to be carried out every six month will be done twice (2) annually with 3 maintenance personnel working 21 hours on each schedule, totalling 126 (2 x 21 x 3) man-hour per PM level; tasks prescribed monthly will be carried out 10 times annually with 2 maintenance personnel working 5 hours on each schedule, totalling 100 (10 x 5 x 2) man-hour per PM level while task prescribed every week will be done 50 times annually with 1 maintenance personnel working 6 hours 9 minutes on each schedule, totalling 325 (50 x 6.15 x 1) man-hour per PM level.

Table 2: The Size of Annual Maintenance Labour Force for the Centrifugal Pump.

PM Level	Frequency	Duration (Hours)	No. of Workers	Man-hour per PM level
Six months	2	21	3	126
Months	10	5	2	100
Weekly	50	6.15	1	325

Maintenance labour force = 1 labour.

Table 3: Centrifugal Pump Labour Saving Cost.

Item	Labour type	Number of labours Per day (current maintenance)
Engineers (₦ 699, 000.00/month)	Mechanical	4
	Electrical	4
	Control	4

Technician (₦ 399, 000.00/month)	Mechanical Electrical	6 6
Total cost (Naira/year)		**162,900, 000**

3.1.2 Spare Parts Program

Table 4: Centrifugal Pump Proposed Spare Parts Plan (Yearly).

Equipment	**Spare part**	**Quantity (Current)**	**Cost (current) ₦ /year**
Feed water pump	Coupling	4	2, 400, 000
	Mechanical seal	6	4, 800, 000
	Motor bearing	6	9, 600, 000
	Pump bearing	6	4, 800, 000
Total cost (₦ /year)			**21, 600, 000**

Table 3.4. shows the spare parts for the centrifugal pump main component of the current maintenance (CM).

3.2 Optimization of Maintenance Labor Cost

The key decision in this work is not only on the failure rate and reliability analysis applied on the centrifugal pump system in the steam power plant of Port-Harcourt refinery but on maintenance cost optimization of the labour force for the centrifugal pump. Unlike the scheduling of labor problem where you consider labor times, due dates of finished tasks and penalties for not completing tasks on time but rather the objective is to obtain the best labour mix (engineer-mechanical, electrical and control and technician-mechanical, electrical and control) at minimum cost of maintenance in terms of salaries and wages of the labour force.

Table: 5 Model Formulation

		Labour type			Cost of Salaries
		M	El	C	(x 10^3Naira
Labour Rank	E	4	6	4	699
	T	6	6	1	399
Quantity available		20	14	13	

Let the quantity of engineers needed for maintenance (E) = x1
Let the quantity of technician needed for maintenance (T) = x2
Let F denote the cost to be minimized
The linear programming model for the above production data is given by:

$$Min \quad F = 699000x_1 + 399000x_2$$

$S.t.$

$$4x_1 + 6x_2 \quad _5 \geq 20$$

$$6x_1 + 6x_2 \quad _5 \geq 14$$

$$4x_1 + x_2 \quad _5 \geq 13$$

$$x_1 , x_2 \leq 0$$

Converting the model into its corresponding standard forms;

$$Min \quad F = 699000 \; x_1 + 39000 \; x_2 + 0s_1 + 0s_2$$

$S.t.$

$$4x_1 + 6x_2 + s_1 \geq 20$$

$$6x_1 + 6x_2 + s_2 \geq 14$$

$$4x_1 + x_2 + s_3 \geq 13$$

$$x_1 , x_2 , s_1 , s_2 \leq 0$$

3.2.2 Model Application and Simulation

These linear equations are then inputted and programmed into the LINDO Software as follows:

i. LINDO is menu-driven and Windows-based which makes it very user friendly.
ii. The LINDO software offers solutions to various models in operational research, but however for the purpose of this study, 'linear programming' model is selected.
iii. Then the 'input mode' and 'input format' of the linear program be selected and encoded.
iv. After which, the objective function of the problem title (Maximization or Minimization) is selected and entered. In this case we select minimization.
v. The number of variables and constraints in the linear model is also selected and entered.
vi. The coefficient values of the two (2) variables and the three (3) constraints in the linear program is modeled into the software and saved in the computer database.
vii. After entering the coefficient values of the variables in the maximization equation and the coefficient values of the constraints equations, then 'Solve Problem' is selected.
viii. After the 'Solve Problem' is selected, 'Algebraic' solution is selected followed by selecting 'iteration'. LINDO Software Interface with linear model in standard form.

$$F(x) = 699000x_1+399000x_2 \rightarrow \min$$

$$4x_1 +6x_2 \geq 20$$
$$6x_1 +6x_2 \geq 14$$
$$4x_1 +x_2 \geq 13$$

$$F(x) = 699000x_1+399000x_2+0x_3+0x_4+0x_5+Mx_6+Mx_7+Mx_8 \rightarrow \min$$

$$4x_1 +6x_2 -x_3 \boxed{+x_6} = 20$$
$$6x_1 +6x_2 -x_4 \boxed{+x_7} = 14$$
$$4x_1 +x_2 -x_5 \boxed{+x_8} = 13$$

The results for the first, second and third iteration is simulated and presented below as follows:

Table 6: First Iteration Results (Iteration: 1) for Prioritize Critical Components.

B	Cb	P	x_1↓	x_2	x_3	x_4	x_5	x_6	x_7	x_8	Q
			699000	399000	0	0	0	M	M	M	

x_6	M	20	4	6	-1	0	0	1	0	0	5
x_7 ←	M	14	6	6	0	-1	0	0	1	0	2.33
x_8	M	13	4	1	0	0	-1	0	0	1	3.25
Min		47M	14M-699000	13M-399000	-M	-M	-M	0	0	0	

Algorithm for the calculation of Table 3.5 elements is presented in Appendix III

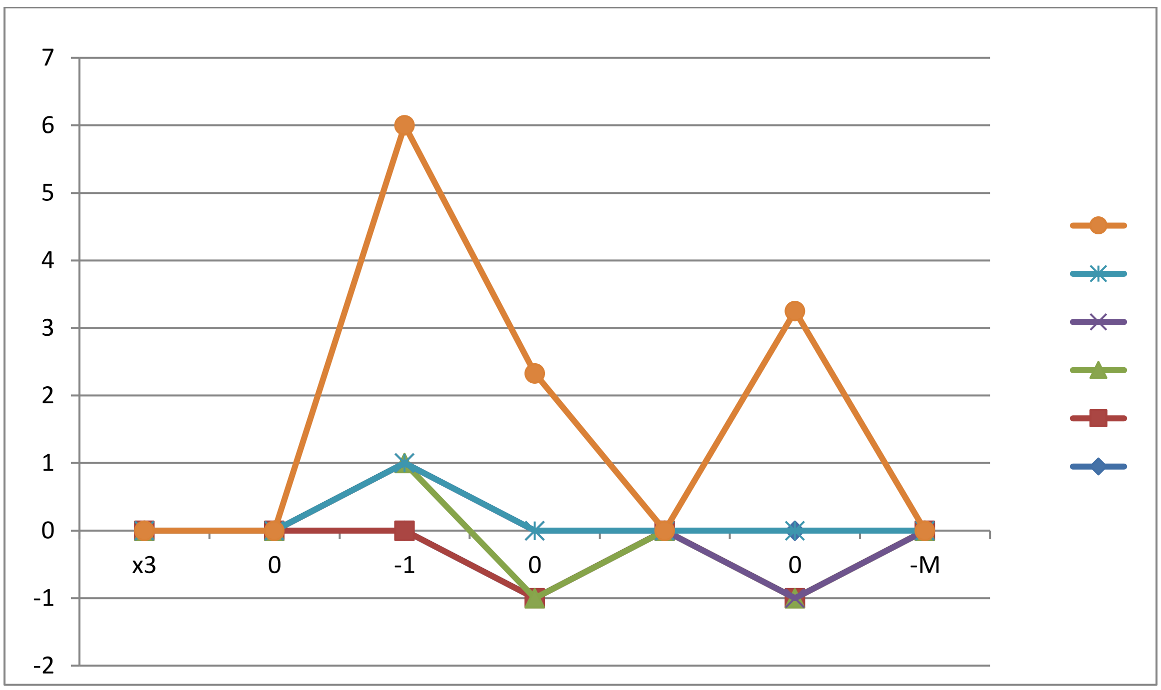

Figure 1. Prioritize Critical Components for Centrifugal Pump.

Figure 1 show the graphical illustration for prioritize critical components. This identify the maintaining components critical to overall system performance. Prioritizing tasks on these components minimizes costs while maximizing the impact on system reliability.

Table 7: Second Iteration Results (Iteration: 2) for Risk-Based Maintenance Approach

B	Cb	P	x_1	x_2	x_3	x_4↓	x_5	x_6	x_7	x_8	Q
			699000	399000	0	0	0	M	M	M	
x_6	M	10.67	0	2	-1	0.67	0	1	-0.67	0	16
x_1	699000	2.33	1	1	0	-0.17	0	0	0.17	0	-14
x_8 ←	M	3.67	0	-3	0	0.67	-1	0	-0.67	1	5.5
Min		14.33M+1631000	0	-M+300000	-M	1.33M-116500	-M	0	-2.33M+116500	0	

Algorithm for the calculation of Table 4.6 elements is presented in Appendix III

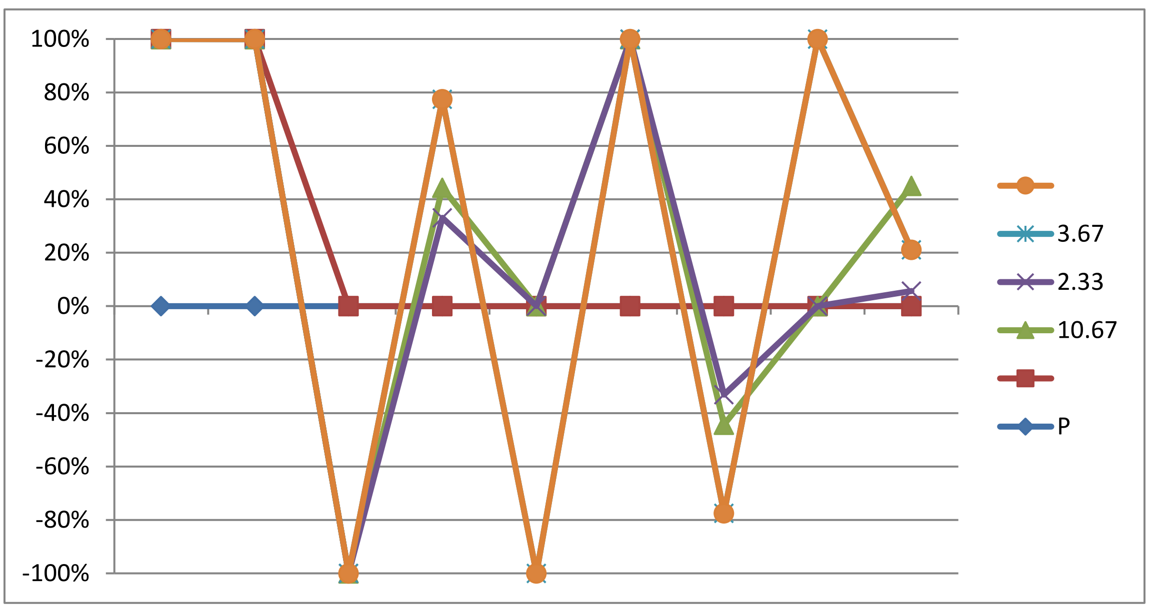

Figure 2: Risk-Based Maintenance Approach for Centrifugal Pump

Figure 2. show the graphical illustration of the risk based maintenance approach. This reveal the risk associated with each maintenance task.

Table 8: Third Iteration Results (Iteration: 3) for Proactive Maintenance Planning.

B	Cb	P	x_1	x_2↓	x_3	x_4	x_5	x_6	x_7	x_8	Q
			699000	399000	0	0	0	M	M	M	
x_6 ←	M	7	0	5	-1	0	1	1	0	-1	1.4
x_1	699000	3.25	1	0.25	0	0	-0.25	0	0	0.25	13
x_4	0	5.5	0	-4.5	0	1	-1.5	0	-1	1.5	-1.22
Min		7M+2271750	0	5M-224250	-M	0	M-174750	0	-M	-2M+174750	

Algorithm for the calculation of Table 3.7 elements is presented in Appendix III

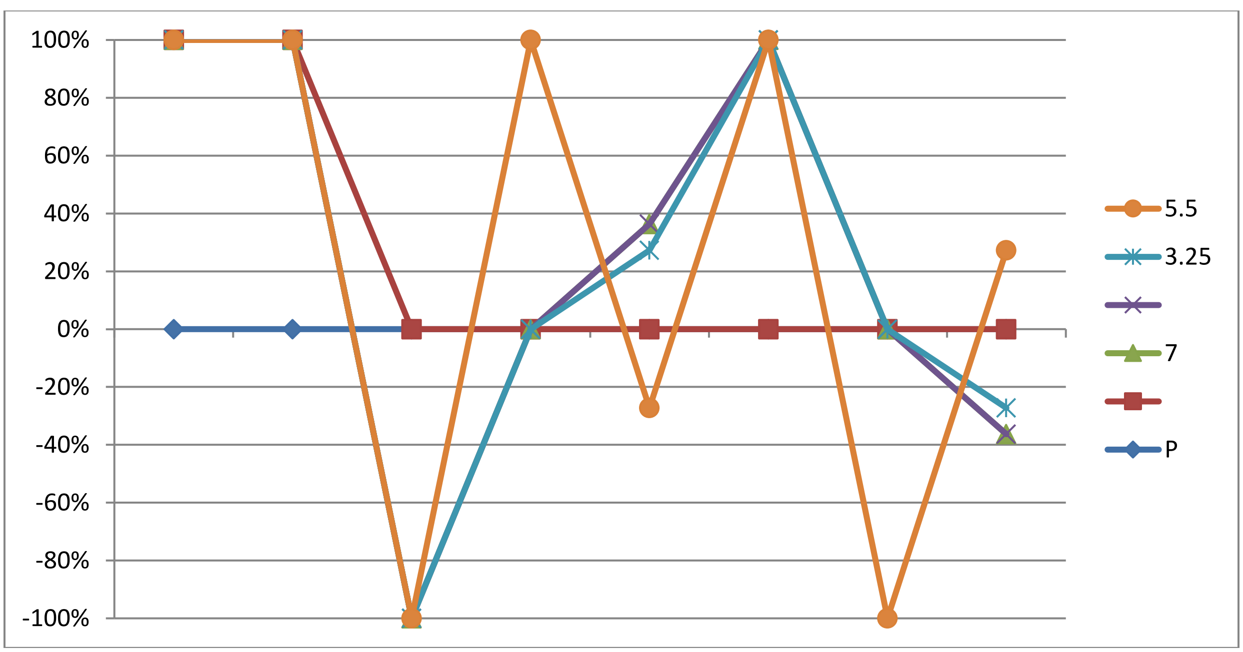

Figure 3: Proactive Maintenance Planning for Centrifugal Pump

Figure 3 show the graphical illustration of a shift from reactive to proactive maintenance planning by implementing predictive and preventive strategies that minimizes unexpected failures and reduces the need for costly emergency repairs.

Table 9: Fourth Iteration Results (Iteration: 4) for Optimal Maintenance Frequency

B	Cb	P	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	Q
			699000	399000	0	0	0	M	M	M	
x_2	399000	1.4	0	1	-0.2	0	0.2	0.2	0	-0.2	
x_1	699000	2.9	1	0	0.05	0	-0.3	-0.05	0	0.3	
x_4	0	11.8	0	0	-0.9	1	-0.6	0.9	-1	0.6	
Min		2585700	0	0	-44850	0	-129900	-M+44850	-M	-M+129900	

Algorithm for the calculation of Table 3.8 elements is presented in Appendix III

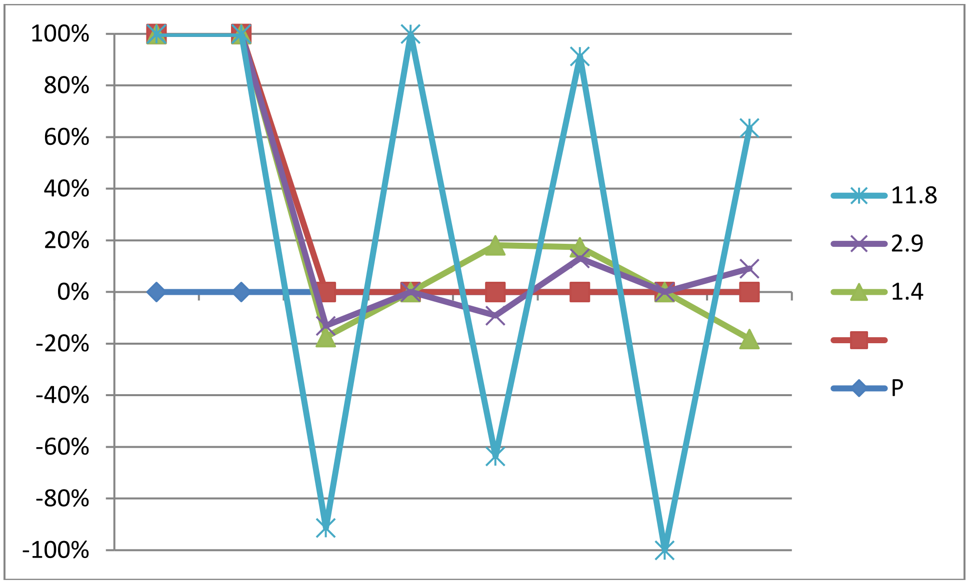

Figure 4. Optimal Maintenance Frequency for Centrifugal Pump

Figure 4. show the graphical illustration for the optimal frequency for routine maintenance tasks by considering equipment usage patterns, environmental conditions, and historical performance data.

Since there are no positive values among the estimates of the controlled variables, the current table has an optimal solution.

The value of the objective function:

F* = 2585700;

The variables that are present in the basis are equal to the corresponding cells of the column P, all other variables are equal to zero:

x_1 = 2.9;

x_2 = 1.4;

The formulated linear programming model was solved using LINDO software, and the fourth iteration gives an optimal solution of: x1 =2.9, x2 = 1.4 andF =2585700 naira. The optimized maintenance labour force gave that approximately 3 engineers and 2 technician should be employed for the maintenance task to spend a minimum of ₦2, 585, 700 naira as cost of salaries and wages for the labour force monthly.

4. CONCLUSION

The generation of a maintenance plan that minimizes the cost of operating the centrifugal pump system was achieved using SPSS Computer Software to analyse the reliability parameter of the components of the centrifugal pump system and to generate a maintenance plan which improves the operations of the plant by reducing the maintenance cost of the centrifugal pump system as presented in Table 3.2. The failure rate and reliability analysis applied reliability-centered maintenance (RCM) to reduce cost for refinery steam power plant in Rivers State. Nigeria. From the results, using the proposed maintenance plan the total cost of maintenance of the centrifugal pumps in the steam power plant was reduced by 80.95%. The results of the RCM technique applied on the refinery steam power plant centrifugal pump generated the proposed preventive maintenance (PM) tasks and plan. Moreover, the PM task consisted of on-condition and scheduled maintenance. The study showed that the RCM had great impact on the PM tasks. The Run-To-Failure (RTF) frequency decreased. It is recommended to perform these tasks (CD, TD and FF) annually, six monthly and monthly. The proposed labour program is carried out and the results showed that the labour cost decreases from ₦162, 900, 000.00/year to ₦ 31,028, 000.00/year (approximately 80.95% of the total labour cost) for the proposed PM planning. Moreover, the downtime cost (DTC) of the plant components was investigated. The system reliability increases with decreased labour cost when proposed PM planning is adopted other than the current maintenance (RTF) plan.

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