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Effective Reliability-Centered Maintenance Strategy for a Centrifugal Pump in a Natural Gas Process Plant

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Abstract

In this study, an effective maintenance strategy using Reliability Centered Maintenance (RCM) integrated with Analytic Hierarchy Process (AHP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) multi-criteria decision analysis methods and risk-based maintenance for a centrifugal pump in a natural gas process plant has been carried out. AHP was used to determine the weights of the maintenance criteria and TOPSIS for the maintenance strategy selection for each chosen critical component (bearing, mechanical seal, impeller and shaft). The selected maintenance criteria and their respective weight obtained are Equipment Criticality (EC) at 10.83%, Mean Time To Failure (MTTF) at 23.44%, Mean Time To Repair (MTTR) at 6.46% and Applicability at 59.26%. The RCM maintenance alternatives were Reactive Maintenance (RM), Preventive Maintenance (PM), Proactive Maintenance and Predictive Testing and Inspection (PT&I). Applying TOPSIS, the most effective maintenance strategy for bearing was Preventive Maintenance at 82.79%, for the mechanical seal was Proactive Maintenance at 84.81% and both impeller and shaft were Predictive Testing and Inspection at 84.59% and 86.91% respectively. Finally, the average most effective maintenance based on that of critical components of the centrifugal pump was Predictive Testing and Inspection at 81.17%.

Keywords Maintenance Strategy**,** Reliability Centered Maintenance, Centrifugal Pump, Multi-Criteria Decision Making, AHP, TOPSIS

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INTRODUCTION

With the environmental challenges faced with fossil fuels and yet their current high potential especially for developing nations, natural gas tends to provide the required balance. Natural gas is earth’s cleanest burning hydrocarbon. The future for natural gas is very bright in helping meet growing demand for energy globally. Natural gas is predicted to increase 43% worldwide by 2040 (CAPP, 2019). The formation of natural gas within earth crust is due to the breakdown of organic materials caused by the heat as well as pressure of the underlying rock (Liang et al., 2012). Prior to usage, it is extracted from the ground and refined to separate or remove impurities in a process plant.

The extraction of ethane, propane, butane, as well as other heavier components out from gas flow is referred to as gas processing. Natural gas process plants are collection of equipment usually expensive and complex (in volume and size) operating under rigorous conditions. These harsh working conditions cause components, equipment, and plants to deteriorate, degrade and fail due to age, wear, corrosion, fatigue and other factors. The level of failures and their consequences are influenced by the criticality of equipment and components.

Pumping equipment are always part of a larger or smaller system, and pump failure can have serious implications (Laquet, 2015). Pumps are used in gas plants to move fluids (liquid or gas) from one area to another by creating a specified flow in a pipe, with centrifugal pumps being the most popular variety. A centrifugal pump, also known as a rotodynamic pump, utilizes centrifugal force to suck fluid into the pump's suction and expel it through the discharge region by rotating the pump impeller, which is propelled by a prime mover. They are robust, effective and relatively inexpensive to design, produce and maintain, pump variety of fluids, transfer large volumes, design for higher pressures, adaptable to arduous chemical environments and provide a steady-consistent flow.

Failure of this equipment has a detrimental impact on the facility owner's and host community's safety, environment and economics. As a result, a natural gas process plant reliability, operation and maintainability may be utilized to evaluate its effectiveness. Wear, tear and ageing of centrifugal pumps increases the likelihood of failure, resulting in lower performance and reliability. These machines require proper maintenance to keep them running smoothly and delivering the appropriate output at all times. An adequate maintenance approach could be created to limit the effects of failure.

Organizations make efforts to implement effective maintenance strategies in order to reduce the pace of equipment degeneration and the losses. Maintenance operations are actions conducted on an asset, whether technical or administrative, or both, to guarantee that the asset is available to properly function at the lowest possible cost. According to Er-Ratby and Mabrouki (2018), factors that emphasizes the necessity of efficient maintenance system are higher production rates, rigid schedules for manufacturing, increased use of the machine and marketplace competition. On the other hand, a production with poor maintenance system will result to excessive machine failures, frequent emergency repairs, shortened facility lifespan, underutilization of maintenance personnel, inferior product quality, irrational operating changes, poor investment in spare parts and maintenance supplies, excessive maintenance costs and many others (Er-Ratby and Mabrouki, 2018). Therefore, maintenance enhances and reconditions equipment in order to increase output while lowering cost of production. However, if the maintenance approach is implemented incorrectly, the cost may rise without a corresponding gain in equipment reliability. To maintain optimal equipment availability, minimal downtime and production loss, maintenance must be effectively aligned with production requirements as well as demands.

According to Moubray (2000), the evolution of maintenance can be divided into generations with each generation having its own timeline. They include the Neolithic Revolution which major on corrective maintenance, advent of the preventive maintenance, condition monitoring strategy and the reliability centred maintenance. In recent times, several scholars have classified maintenance into three groups which are preventative, corrective, and predictive maintenance while others divided it into four categories (Sharma et al., 2005; Gebauer et al., 2008; Moayed and Shell, 2009; Perajapati et al., 2012; Mondal and Srivastava, 2013). Basically, maintenance could be divided into two broad category which are preventive and corrective maintenance based on the principal goal of maintenance, and that is to keep or return equipment to or to its best condition. The other listed forms of maintenance are sub-categories of these two major classes of maintenance.

The goal of reliability centred maintenance is to optimize the maintenance process by establishing a value and productive maintenance method to ensure that equipment continues to fulfil its purpose within the present operating environment. RCM guarantees that the system's intrinsic reliability is sustained (Rausand, 1998). This is due to the fact that reliability of equipment is influenced by reliability of its various components. The RCM maintenance techniques rely on safety, equipment criticality, cost, failure effects, and the necessity for operation (Dhillon, 2002). Rausand (1998) stated that RCM helps maintain important equipment operating at the specified availability and reliability while expending the least amount of money on maintenance. Selvik and Aven (2011) noted that aside from cost savings, it improves safety and process reliability.

According to Dhillon (2002), reactive maintenance, preventive maintenance, proactive maintenance and predictive testing and inspection are the four fundamental components of reliability centred maintenance. The reactive (corrective or breakdown) maintenance is defined as an unplanned, responsive failure-oriented maintenance approach in which repairs to engineered assets are made when it has failed (Mondal and Srivastava, 2013; Sharma et al., 2005). Preventive maintenance is a routine or time-sensitive actions carried out at regular or according to prescribed criteria to keep availability and reliability at acceptable levels thereby reducing the possibility of failure or degradation of functioning item or equipment (Mobley, 2002; PrEN 13306, 1998). Proactive maintenance, according to Moubray (1997), are those that are taken before a failure takes place to halt the object from entering a failing condition. Proactive maintenance entails efforts such as proper design, craftsmanship, setup, planning, and maintenance processes in order to improve maintenance. According to Mondal and Srivastava (2013), the operational parameters of equipment are evaluated in predictive testing and inspection, and the results are compared to predefined standard values to make maintenance decisions.

Reliability-centered maintenance is a well-known and widely utilized strategy for preserving operational efficiency in important sectors such as oil and gas industry, power plants, artillery systems, aircraft, maritime industry and railway networks (Khanis, 2000). Deepak and Jagathy (2013) identified limitations of traditional RCM, calling for a new RCM framework in petroleum refineries, which comprise comparable oil and gas process plants as well as other process plants. Although, conventional RCM has had its merits, the latest model seeks possibilities to improve the method as well as the benefits derived off it. RCM had been largely studied by many researchers with improvement made. Selvik and Aven, (2011), established the framework for reliable and risk-based maintenance, that proposed extending RCM to include risk that is not properly addressed in standard RCM. Cheng et al. (2008) incorporated artificial intelligence into RCM analysis, which entails doing RCM evaluation on new machinery using a guide derived from past comparable equipment RCM analysis data. Abid et al. (2014) created an alternative RCM technique that incorporates life data analysis into RCM.

RCM techniques have found application in decision making in various industries such as oil and gas process plants. An evaluation of the multi-criteria decision-making methodologies utilised in the adoption of maintenance strategies reveals that they assist in improved decision making (Gandhare and Akarte, 2012). Analytic Hierarchy Process (AHP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) have been found to be very effective in determining effective maintenance strategies. AHP, a hierarchical decision-making method had been found to be useful for maintenance decision making (Bevilacqua and Braglia, 2000; Triantaphyllou et al., 1997; Wang et al., 2007). While TOPSIS a multi-criteria decision method has also been modified and utilized by various authors for maintenance strategy selection (Momeni et al., 2011; Zare, et al., 2018). Researches had integrated AHP and TOPSIS, with AHP used to compute the criterion weights, while TOPSIS used to rank the maintenance strategy options had compensated for the AHP's poor ranking in determining a maintenance strategy (Shyjith et al. 2008; Balakrishnan et al., 2016; Emovon, 2016; Panchal and Kumar, 2017).

Although, an integrated AHP-TOPSIS model had been applied in various industries even in Nigeria, no research was found to have been implemented in the nations natural gas processing plants as at the time of the study. Therefore, this work will help improve RCM through providing a new model for continual assessment and enhancement of equipment maintenance to deal with the static nature of RCM, application of quantitative analysis into RCM instead of relying solely on experience and reasoning, and simplifying RCM by removing the time-consuming FMECA analysis.

METHODOLOGY

The study technique employs RCM maintenance techniques, with minor adjustments to integrate Analytic Hierarchy Process (AHP) and Technique for Order Procedure for Similarity to Ideal Solution (TOPSIS) multi-criteria decision methods in determining the most effective maintenance strategy for the components of a selected centrifugal pump in a natural gas production plant. **Figure 1** presents the algorithm model that was employed in this study.

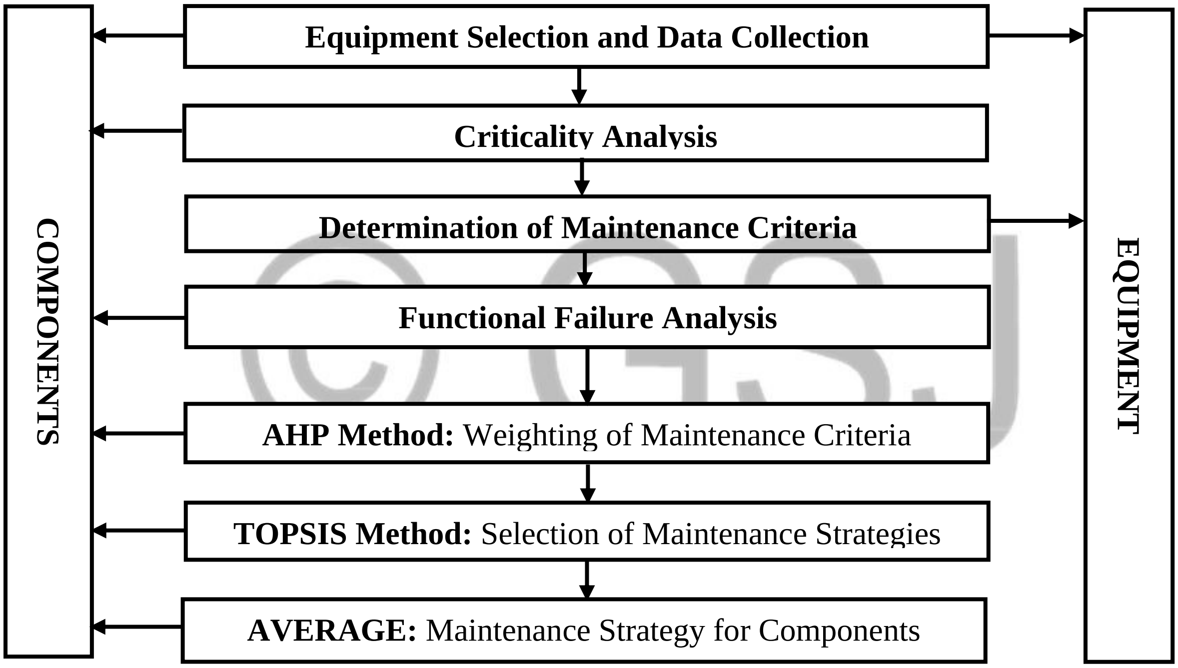

Figure 1: Algorithm for Effective Maintenance Strategy Selection

Equipment Selection and Data Collection

A centrifugal pump from a natural gas process plant is selected for case study. The centrifugal pump selection was due it’s criticality and impact in the natural gas production process. The pump is located at the acid gas removal unit of the natural gas process plant. The unit collects natural gas from the pressure control station and feed output to the dehydration unit for water remover. The acid gas removal unit removes acid gas such as Carbon (IV) Oxide (CO_2) and Hydrogen Sulphide (H_2S) by absorption using circulating activated methyl di-ethanol amine solution to prevent corrosion and freezing at low (cryogenic) temperature. The centrifugal pump charges the di-ethanolamine solution from the storage tank to contact the high-pressure natural gas in a counter current flow to absorb the acid gases to a safe and acceptable natural gas processing level.

The primary data for this research was obtained from the equipment history file. While other data were obtained through professional discussions and issuing of questionnaires to ten mechanical professionals who are experts in the maintenance of the selected equipment.

Components Criticality Analysis

The criticality analysis is used to assess the impact of component failures on organisational performance. The equipment components criticality is determined using the formula:

$$\boldsymbol{EC} = \frac{(30\boldsymbol{P} + 30\boldsymbol{S} + 25\boldsymbol{A} + 15\boldsymbol{V})}{\mathbf{3}} \tag{1}$$

Where: ***EC*** is equipment criticality in percentages, ***P*** is the production index, ***S*** is the safety index, ***A*** is the equipment availability (standby) index and ***V*** is the value or capital cost index of equipment. **Table 1** shows various equipment criteria, weights and levels.

The impact of the component failure is utilized to determine its criticality group, which ranges from A to D. The evaluation is carried through employing D < 45%; 45≤C < 60%; 60 ≤ B < 74%; A ≥74%. Class A components are maintenance critical items, indicating that their failure have impact on production, safety, or both.

Table 1: Equipment Components Criticality Table

Criteria	Symbol	Weight	Level
Production index	**P**	30%	(3) Very high (2) High (1) Medium
Safety index	**S**	30%	(3) Very high (2) High (1) Medium
Standby index	**A**	25%	(3) No standby (2) Standby and medium availability (1) Standby and high availability
Cost index	**E**	15%	(3) High cost (2) Medium (1) Low cost

Determination of Maintenance Criteria

The maintenance criteria implemented are Mean Time to Failure (MTTF), Mean Time to Repair (MTTR), equipment criticality, and applicability. They were selected based on a literature research and consultation with case study experts.

Functional Failure Analysis

Failure analysis of the components of the equipment are focused on the failure rate, MTTF, MTTR, and availability. Equations (2), (3), (4) and (5) were applied on the primary data obtained to determine the various functional failure analysis.

$$Failure\ Rate\ (\lambda) = \frac{Items\ failure}{Total\ Operating\ Time} = \frac{1}{MTTF} \tag{2}$$

$$MTTF\ (\theta)\ =\ \frac{Total\ Time}{Total\ Number\ of\ Failures} = \frac{1}{\lambda} \tag{3}$$

$$MTTR(\varphi) = \frac{Total\ Maintenance\ Downtime}{Total\ Number\ of\ Maintenance\ Actions} \tag{4}$$

$$Operational\ Availability\ (A_0) = \frac{MTTF}{MTTF + (MTTR)} \tag{5}$$

AHP Method: Weighting of Maintenance Criteria

Saaty (1980) invented the AHP, which is a multi-criteria decision-making technique. Vargas (1990) defines it as a measurement tool for dealing with quantitative and immaterial criteria that has been used in a variety of domains such as decision theory. The step-by-step approach for AHP is as follows:

Step 1: Development of Pairwise Comparison

A pair-wise comparison matrix of maintenance criteria (Equipment Criticality, MTTF, MTTR and Applicability) using Saaty's scale of 1 to 9 (Saaty, 1980) as shown in Table 2 below. Even numeric ratings of 8, 6, 4, 2 can also be assigned. Respective pair of decision criteria is ranked in order of significance. The criteria are positioned horizontally and vertically in a matrix, and the matrix comprises numerical ratings matching the horizontal (first) criterion with the vertical criterion (second).

Table 2: The Relative Pairwise Rating of Importance for Alternatives

Relative Importance Pairwise Comparison	**Numerical Rating**
Extremely preferred	9
Very strongly preferred	7
Strongly preferred	5
Moderately preferred	3
Equally preferred	1

A rating that is reciprocal when the second criteria is judged to be superior to the first, a numerical rating is awarded. When comparing the same, the value 1 is always assigned.

$$C = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{23} & C_{33} \end{bmatrix} \tag{6}$$

Step 2: Normalised Development

Each value in a pairwise comparison matrix column is split by its column total.

Sum of the values in each column:

$$C_{ij} = \sum_{i=1}^{n} C_{ij} \tag{7}$$

Normalised Pair-wise matrix:

$$X = \frac{C_{ij}}{\sum_{i=1}^{n} C_{ij}} = \begin{bmatrix} X_{11} & X_{\ 12} & X_{13} \\ X_{21} & X_{22} & X_{23} \\ X_{31} & X_{32} & X_{33} \end{bmatrix} \tag{8}$$

Step 3: The Priority Vector Development

The each normalized matrix row is averaged. The averaged row represents the priority vector of criteria choices in relation to the specific criterion. The values in the priority vector sum to 1.

Weighted Matrix:

$$W_{ij} = \frac{\sum_{j=1}^{n} X_{ij}}{n} = \begin{bmatrix} W_{11} \\ W_{12} \\ W_{13} \end{bmatrix} \tag{9}$$

Step 4: Calculate a Consistency Ratio

The consistency ratio is used to determine the consistency of the subjective pairwise comparison matrix that has been inputted. According to Saaty (1980), the value C.R ≤ 0.1 is enough for achieving consistency in pair-wise comparisons. When the ratios exceed 0.1, the input must be re-evaluated.

Consistency Vector:

$$\begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{23} & C_{33} \end{bmatrix} * \begin{bmatrix} W_{11} \\ W_{12} \\ W_{13} \end{bmatrix} = \begin{bmatrix} Cv_{11} \\ Cv_{12} \\ Cv_{13} \end{bmatrix} \tag{10}$$

$$Cv_{11} = \frac{1}{W_{11}} [C_{11}W_{11} + C_{12}W_{12} + C_{13}W_{13}] \tag{11}$$

$$Cv_{12} = \frac{1}{W_{21}} [C_{21}W_{21} + C_{22}W_{22} + C_{23}W_{23}] \tag{12}$$

$$Cv_{13} = \frac{1}{W_{31}} [C_{31}W_{31} + C_{32}W_{32} + C_{33}W_{33}] \tag{13}$$

Step 1: The weighted sum in each row of the pairwise comparison matrix is the sum of the multiples of the entries by the priority of the matching (column) criteria.

Step 2: Divide the weighted sum of each row by the priority of the matching (row) criteria.

Step 3: Determine the average λ_{max} of the results of step 2.

$$\lambda = \sum_{i=1}^{n} Cv_{ij} \tag{14}$$

Step 4: The consistency index, CI, of the *n* criteria computed by Equation (15).

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{15}$$

Step 5: From the standard Random Index (RI) tables as given in **Table 3**, determine the RI.

Table 3: Random Index Values for *n* Alternatives

Alternative (n)	**3**	**4**	**5**	**6**	**7**	**8**
Random Index (RI) Value	0.58	0.90	1.12	1.24	1.32	1.41

Step 6: Calculate the Consistency Ratio, ***CR*** as given by Equation (16).

$$CR = \frac{CI}{RI} \tag{16}$$

TOPSIS: Selection of Maintenance Strategies/Alternatives

The classical TOPSIS method is used to select the best maintenance strategies for each critical component identified by the equipment critical analysis. The qualitative criterion is explained using linguistic factors, followed by the criteria ratings on a 1-9 scale in **Table 4**. (Jadidi et al, 2008).

Table 4: The Scale of Criteria Ratings for Qualitative Criterion in Classical TOPSIS Method

Scale	**Rating**
Poor (P)	1
Medium poor (P)	3
Fair (F)	5
Medium good (MG)	7
Good (G)	9
Intermediate values between the two adjacent judgments	2,4,6,8

According to Shih et al. (2007), the detailed procedure for classical TOPSIS method for group decision making is systematically described in the following steps:

Step 1: Construct the Decision Matrix and then Determine the Weight of Criteria.

Let $X = (x_{ij})$ represent a decision matrix and $W = [w_1, w_2, \dots , w_n]$ a weight vector, where $x_{ij} \in \Re$, $w_j \in \Re$ and $w_1 + w_2 + \dots + w_n = 1$.

Criteria of the functions can be: non-beneficial criteria or cost functions (less is better) and benefit functions (more is better). The weight of the criteria of the components have been determined by AHP method.

Step 2: Calculate the Normalised Decision Matrix

This process converts multiple attribute dimensions into non-dimensional attributes, allowing for cross-criteria comparisons. Because different criteria are frequently assessed in different units, the scores in the assessment matrix X must be normalised. The normalisation of values (n_{ij}) can be performed by:

$$n_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}^2} \qquad (17)$$

For $i = 1, \ldots, m; j = 1, \ldots, n$.

Step 3: Calculate the Weight Normalised Decision Matrix.

The weighted normalised value v_{ij} can be calculated by the equation (18).

$$v_{ij} = w_j n_{ij} \tag{18}$$

Where w_j is the weight of the *j*-th criterion, $\sum_{j=1}^{n} w_j = 1$.

Step 4: Determine the Positive Ideal and Negative Ideal Solutions.

Determine the positive ideal alternative (highest performance on each criterion) and the negative ideal alternative (lowest performance on each criterion). The ideal positive solution maximises the benefit criterion while minimising the cost criteria, whereas the ideal negative solution maximizes the cost criteria while minimising the benefit criteria

Step 5: Calculate the Separation Measures from the Positive Ideal Solution and the Negative Ideal Solution.

A variety of distance metrics can be used in the TOPSIS approach. The distance between each alternative and the positive ideal solution is provided as:

$$d_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^2}, \qquad i = 1, 2, \ldots, m. \tag{19}$$

$$d_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2}, \qquad i = 1, 2, \ldots, m. \tag{20}$$

Step 6: Calculate the Relative Closeness to the Positive Ideal Solution.

The relative closeness of the *i*-th alternative A_j with respect to A^+ is defined as:

$$R_i = \frac{d_i^-}{d_i^- + d_i^+}, \tag{21}$$

$where\ 0 \leq R_i \ \leq 1, i = 1, 2, \ldots, m.$

Step 7: Rank the Alternative Closest to 1.

The set of maintenance alternatives can be ranked by the descending order of the value of R_i.

AVERAGE: Maintenance Strategies for Critical Components

The selection of average maintenance strategy for the critical components, R_{Av} can be achieved by determining the arithmetic mean of the relative closeness to the positive ideal solution, $R_i$of the critical components. The aggregation of each maintenance strategies, R_{Av} is given by:

$$R_{Ay} = \frac{\sum_{k=1}^{k} R_i^{k^+}}{K} \tag{22}$$

RESULTS AND DISCUSSIONS

The results obtained in this research were calculated with the application of Microsoft Excel. The failure records for the critical components were collected within a three years period (2014 to 2017), as shown in **Table 5** from the equipment maintenance data record.

Table 5: Rate of Component Failures within Three Years

S/N	Component	Year 1	Year 2	Year 3	Total Failures
1	Bearing	4	4	3	11
2	Mechanical Seal	5	4	5	14
3	Impeller	1	0	1	2
4	Shaft	0	0	1	1

Results for Component Criticality Analysis

Eight components were selected which are bearing, bolts and nuts, impeller, mechanical seal, shaft, shaft key, volute casing and wear rings. Four components as shown in **Table 6** were found to be in class A after applying equation (1).

Table 6: Result for Criticality Analysis

Criteria	Component Criticality (%)	Group
Bearing	85.00	A
Mechanical Seal	95.00	A
Impeller	85.00	A
Shaft	100.00	A

With the application of equation (1) and the conditions of **Table 1**, from the eight components analysed, four were found to be critical meeting the criteria of Class A with results ≥74%. The four components as shown in **Table 6** are bearing, mechanical seal, impeller and shaft with criticality values as 85%, 95%, 85% and 100% respectively.

Results for Functional Failure Analysis

Table 7 shows the results for the functional failure analysis applying equations (2), (3), (4) and (5).

Table 7: Results for Functional Failure Analysis

Component	Failure Rate	MTTF (Hours)	MTTR (Hours)	Availability (%)
Bearing	0.00041857	2389.09	55.00	99.75
Mechanical Seal	0.00053272	1877.14	70.00	96.40
Impeller	0.00007610	13140.00	10.00	99.92
Shaft	0.00003805	26280.00	5.00	99.98

Equations (2), (3), (4) and (5) were applied to determined the failure rate, MTTF, MTTR and availability respectively for the four critical components (bearings, mechanical seal, impeller and shaft) as shown in **Table 7**. For the failure rate, mechanical seal has the highest failure rate at 0.00053272 failure/hour, the second is bearing at 0.00041857 failure/hour, the next is impeller at 0.00007610 failure/hour and finally shaft at 0.00003805 failure/hour. MTTF among the components first is shaft at 26280.00 hours, the second is impeller at 13140.00 hours, the third is bearing at 2389.09 hours and finally mechanical seal at 1877.14 hours. Mechanical seal has the highest MTTR at 70.0 hours, the next is bearing at 55.0 hours, the third is impeller at 10.0 hours and the last is shaft at 5.0 hours. For the availability of the critical components, the first is shaft at 99.98%, the second is impeller at 99.92%, the third is bearing at 99.75% and the last is mechanical seal at 99.40%.

AHP Results for Equipment Criteria Weight

Table 8 shows the result from the application of the AHP method to determine the equipment criteria weights. The criticality ratio (CR) is 0.04113 which is less than the standard value of 0.1, which implies that the AHP analysis is consistent.

Table 8: Results for Equipment Criteria Weights

EC	MTTF	MTTR	Applicability
0.1083	0.2344	0.0646	0.5926

With the application of AHP method to determine the weight of the maintenance criteria as shown in **Table 8**, applicability leads with 0.5926 (59.26%), the next is MTTF at 0.2344 (23.44%), then EC at 0.1080 (10.80%) and finally MTTR at 0.0646 (6.46%).

TOPSIS Results for Maintenance Strategies Selection

Table 9 shows the result of the relative closeness to the ideal positive solution for the critical components and their respective averages. While **Table 10** shows the ranking of the results obtained in **Table 9**. **Figure 2** is the chart representation of results obtained in **Table 9**.

Table 9: Relative Closeness to the Positive Ideal Solution for Critical Components and Average Maintenance Strategies

Components		Bearing	Mechanical Seal	Impeller	Shaft	Average
Alternatives	**RM**	0.1721	0.1519	0.1541	0.1495	0.1569
	PM	0.8279	0.5775	0.2714	0.5692	0.5615
	PrM	0.6008	0.8481	0.6073	0.6898	0.6865
	PT&I	0.7717	0.7603	0.8459	0.8691	0.8117

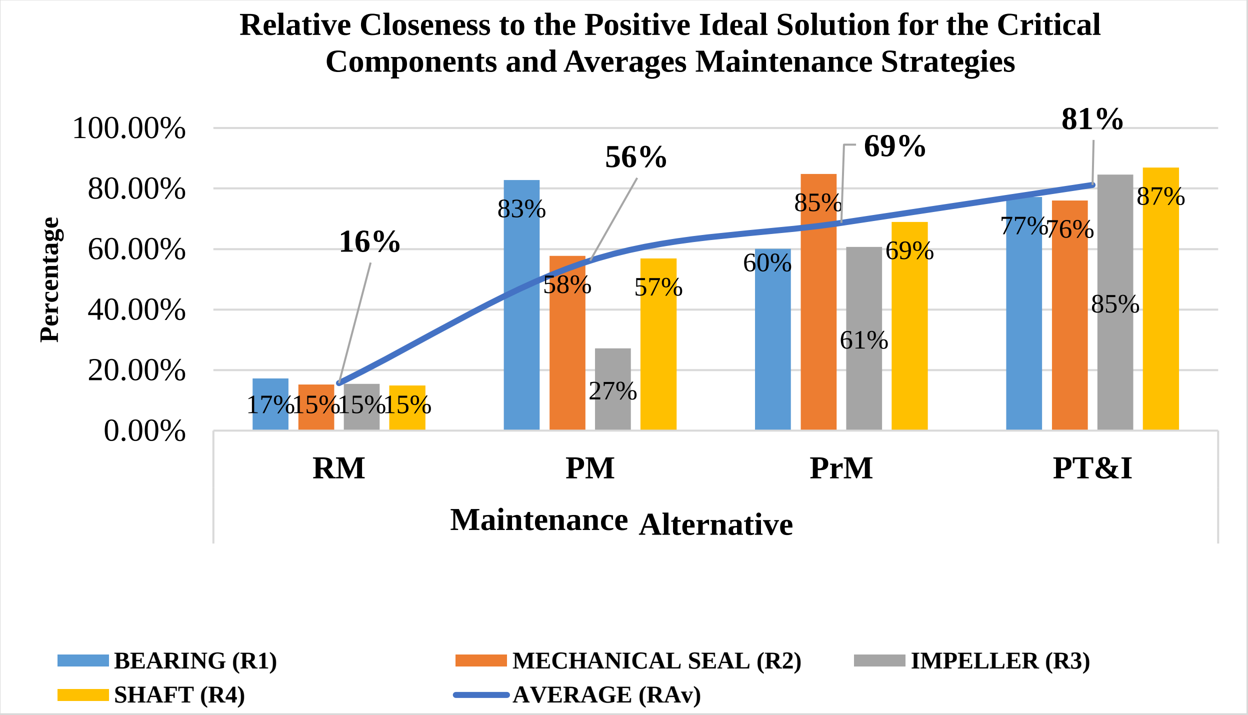

Figure 2: Relative Closeness to the Positive Ideal Solution for the Critical Components and Averages Maintenance Strategies

The result in **Table 9** and chart in **Figure 2** gives the relative closeness to the ideal positive solution for the critical components and their respective averages for the various maintenance alternatives from the application of TOPSIS method for the selection of maintenance strategies. For bearing the closest maintenance alternative to the ideal positive solution is PM at 0.8279 (82.79%), the next is PT&I at 0.7717 (77.17%), then PrM at 0.6008 (60.08%) and finally RM at 0.1721 at (17.21%). While for mechanical seal, the first is PrM at 0.8481 (84.81%), the second PT&I at 0.7603 (76.03%), the third is PM at 0.5775 (57.75%) and the fourth is RM at 0.1519 (15.19%). Then for impeller, the first is PT&I at 0.8459 (84.59%), the second PrM at 0.6073 (60.73%), the third is PM at 0.2714 (27.14%) and the fourth is RM at 0.1541 (15.41%). And for shaft the first is PT&I at 0.8691 (86.91%), the second PrM at 0.6898 (68.98%), the third is PM at 0.5692 (56.92%) and the fourth is RM at 0.1495 (14.95%). Finally, the average based on the individual results obtained first is PT&I at 0.8117 (81.17%), the second PrM at 0.6865 (68.65%), the third is PM at 0.5615 (56.15%) and the fourth is RM at 0.1569 (15.69%).

Table 10: Results for Components and Average Maintenance Alternatives Ranking

Components		**Bearing**	**Mechanical Seal**	**Impeller**	**Shaft**	**Average**
Alternatives	**RM**	4	4	4	4	4
	PM	1	3	3	3	3
	PrM	3	1	2	2	2
	PT&I	2	2	1	1	1

Table 10 gives the ranked result obtained in Table 9. Bearing in descending order gives PM, PT&I, PrM and RM. Mechanical seal in same order gives PrM, PT&I, PM and RM. Impeller in same order gives PT&I, PrM, PM and RM. Shaft in same order gives PT&I, PrM, PM and RM. Finally, the average in same order gives PT&I, PrM, PM and RM.

CONCLUSIONS

The proposed hybrid MCDM technique combines a risk-based criticality analysis, AHP and TOPSIS methods. The risk-based criticality analysis was used to determine the critical components in the centrifugal pump among those identified. And both AHP and TOPSIS were used to determine the weight of each of the selected maintenance criteria and determination of the ranking of the maintenance strategies/alternatives respectively. The pump bearing, mechanical seal, impeller and shaft were found to the critical components by equipment criticality analysis. This place them in class A category for criticality analysis. Hence, they have the potential of affecting the process plant production output, safety and cost of production. Applying functional failure analysis (failure rate, MTTF, MTTR and availability) for the critical components, the failure rate in descending order is mechanical seal, bearing, impeller and shaft. The MTTF in descending order is shaft, impeller, bearing and mechanical. Also, the MTTR in descending order is mechanical seal, bearing, impeller and shaft. Finally, the availability in percentage in descending order is shaft, bearing, impeller and mechanical seal. With the application of AHP method to determine the equipment criteria weight, applicability is the first, the second is MTTF, then equipment criticality and finally MTTR. Using TOPSIS to determine the ranking of the various maintenance strategies/alternatives for bearing, mechanical seal, impeller and shaft, Preventive Maintenance was found the optimum maintenance alternative for bearing, Proactive Maintenance for mechanical seal, Predictive Testing and Inspection for both impeller and shaft. Finally, the overall optimum maintenance based on the average of the individual maintenance alternatives was also found to be Predictive Testing and Inspection.

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AUTHORS CONTRIBUTION

The authors wish to inform you that this work is a part of the thesis by the first author, under the supervision of the second author. The thesis is available at the Department of Mechanical Engineering, University of Port Harcourt, Rivers State, Nigeria.

CONFLICT OF INTEREST

The authors declared that there is no potential conflict of interest with respect to the research, authorship and/or publication of this article. Also, Data for this research can be made available if requested.

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