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Improving the Maintenance Practice of Pumps in Crude Oil Production Plants Using Reliability Analysis

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Abstract

The study' Improving the Maintenance Practice of Pumps in Crude Oil Production Plant Using Reliability Analysis' was investigated in detail. The primary objective of this study was to analyze the reliability of centrifugal pumps using failure data, focusing on identifying the optimal maintenance strategy for pumps used in the crude oil export unit at the SPDC plant. A centrifugal pump from this unit served as the case study. Key metrics such as operational time, Mean Time Between Failure (MTBF), Downtime (DT), failure rate, repair rate (η), reliability, unreliability, availability, and unavailability were calculated using the Monte Carlo reliability analysis model. Data from the maintenance department of SPDC, spanning a five-year period, was collected and analyzed. The study identified the failure modes of the pumps and the reliability and availability of individual pump components. The results showed an increasing failure rate in pump components over time. For instance, the reliability of key components such as the bearing decreased from 26.89% in the first year to 6.39% by the fifth year, while the shaft seal dropped from 19.36% to 6.03%, and the ring declined from 19.36% to 5.92% over the same period. The volute exhibited the highest reliability, starting at 37.56% in the first year. The study reveals that every pump component had a sharp decline in uptime, or operational time, between the first and fifth years of use. The study also showed that the External Leakage-Process (ELP) medium has a higher occurrence rate as a failure mode. Finally, the reliability analysis study revealed that the pumps' components require regular maintenance monitoring to reduce DT and increase productivity in the company. The study suggests transitioning from time-based to condition-based maintenance for certain components while enhancing existing practices. Predictive maintenance techniques such as vibration, temperature, and noise monitoring are recommended to predict failures better, allowing for timely shutdowns and switchovers to improve efficiency and pump uptime. The bearing, shaft, and ring components have been identified in this study as the most significant sensitive, and particular care is needed if the pumps' reliability is to be increased. This research highlights the need for a reliability-centered maintenance strategy to enhance the performance of centrifugal pumps in the crude oil export unit.

Keywords: Maintenance, Crude oil, Reliability analysis, Production plant, Pumps, Improving.

1 | Introduction

According to recent research, operational maintenance is one of the most essential components of a workplace since it is necessary for maintaining a company's competitive production system [1–3]. Production

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firms' operations have changed significantly because of the growing global competition. Due to these changes, maintenancee changes, maintenance is now much more essential to [1]. Businesses must keep improving the efficiency and efficacy of their operational techniques to be competitive. Lean production also brings questions about equipment availability. Consequently, effective maintenance is in considerably more demand [2].

Moreover, the rise in mechanization and automation suggests that availability and dependability are now key issues in many industries, including oil and gas production plants. These companies need preventive maintenance since high degrees of rotating equipment raise the possibility of component failure, rendering the entire piece of equipment useless [4]. Conversely, regular maintenance keeps rotating equipment running at optimal levels, extending the equipment's lifespan and maintaining its production capacity. Apart from the functioning and safety of the equipment, maintenance activities directly affect machine availability.

Natural aging of components and equipment guarantees wear and tear. Apart from design defects, operational environment problems (human mistakes, untrained workforce, and overload) aggravate the matter. Maintaining availability and functionality is thus absolutely crucial. From the conventional fault repair strategy to fault prevention, or from reactive to proactive, industrial asset maintenance has changed throughout time. Constant observation of onshore production platforms helps to control the industrial asset's performance and condition, optimizing output consistency at the lowest feasible maintenance cost. Especially more important is the application of HSE as mandated by national and international laws as well as corporate goals. Thus, rather than cutting down maintenance costs to save money, optimization of maintenance is the process of balancing meeting HSE standards with maximizing production regularity [5].

One-fifth of the energy consumed in the sector overall goes towards hydraulic systems [6]. Moving liquids most commonly require a pump, a mechanical instrument used for elevating, moving, or compressing liquids. Usually driven by an electric motor, mechanical energy is used here to increase fluid kinetic energy and pressure.

Pumps are extensively used in a wide range of industries, such as food, energy, petroleum, wastewater trea ment, paper products, garbage, manufacturing facilities, combustion appliances, nuclear power plants, heat t ransfer systems, electrical and hydraulic services, and pulp sectors.Pumps are among the most often used ins truments in oil and gas production facilities, manufacturing sites, and several other industries. Research on the various types of pump failures and methods for identifying failures and establishing maintenance schedules is crucial given the extensive use of pumps in the industrial sector. This helps to minimize early pump failure. Many efforts have been made to check, locate, and diagnose any early issues or breakdowns in the pumps using fault diagnosis tools so as to monitor their state [7].

The daily total oil output in the oil and gas production sector largely depends on critical equipment like pumps. Performance requirements such as reliability, availability, maintainability, and safety should be included in the design stage and maintained throughout the system's or equipment's operation [3].

Apart from experiencing a total loss of output, if the failure rate were large, the company would definitely lose millions of dollars daily. Prevention of this situation depends on dependability testing on the system and its components. Udo [3] argues that dependability and maintainability define plant availability, the main indication of system performance. Equipment dependability requires consistent maintenance. Low Overall Equipment Effectiveness (OEE), which falls between 15 and 25 percent below the goal level, is a main concern facing the sector, as [8] pointed out. The OEE figures have dropped rather than increased over the past few decades. Most of the work carried out by maintenance staff nowadays is reactive rather than predictive. These findings further support the difficulties in converting from a reactive to a preventative mental approach [9]. It seems that direct machine problems cause the majority of low OEE. Low OEE also indicates insufficient use of the available production resources, resulting in low output and inefficient use of resources. From an economical and environmental perspective, these factors make modern production less sustainable, claims [10]. Future studies should focus on helping production firms and maintenance companies achieve higher levels of overall production and manufacturing system efficiency.

Thus, an empirical topic of interest that deserves consideration is the maintenance of the pumps in crude oil plants. Wang and Chen published a paper in 2007 on a technique for diagnosing faults in centrifugal pump systems using frequency-domain symptom characteristics. The system used fuzzy neural networks, wavelet transforms, and rough sets to classify issue categories and discover faults early on. The wavelet transform is applied to cover the ideal frequency range for feature extraction. Rough sets are used to offer diagnostic data while training neural networks. It is recommended to utilize a fuzzy neural network known as a partially-linearized neural network to rapidly and reliably identify between the many sorts of machinery failures based on the probable grades of symptom characteristics. This approach may be used to a variety of spinning machines and is effective in assessing the condition of centrifugal pump systems. Tsarouhas et al. [11] used a best-fit distribution of failure and repair rates to assess the availability, dependability, and maintainability of a strudel production line.

Quantitative Maintenance Optimization (QMO), seeks the lowest overall cost by minimizing component failures, lost output, extra labor and materials, and direct maintenance expenses (labor, materials, and administration) that grow with the intensity of maintenance procedures. According to Besnard et al. [12], QMO approaches differ in using mathematical models to quantify maintenance costs and benefits and determine the optimal ratio between them.

Garg and Sharma [13] created a two-stage key tool called Particle Swarm Optimization-Based Lambda-Tau (PSOBLT), which integrates the Lambda-Tau approach with particle swarm optimization. This resulted in the development of Lambda-Tau PSOBLT, a revolutionary approach for conducting stochastically accurate investigations into the behavior of a complicated repairable system. They use the Lambda-Tau approach and particle swarm optimization to create reliability indices and membership function estimates.

Examples include the system's dependability, availability, Mean Time Between Failures (MTBF), anticipated number of failures ENOF, repair time, failure rate, and reliability. Petri nets may be used to demonstrate how a system's functional components interact. According to sources, the greatest example of the suggested technique is a feeding unit at a paper mill in northern India, which produces around 200 tons daily. The system's behavior is also investigated via sensitivity analysis. The PSOBLT approach's behavior analysis conclusions have a tighter prediction zone than those from previous technology domains, reducing analysis uncertainty. It evaluates the system's present condition and any related uncertainty before proceeding with a more meaningful analytical approach.

Barbera et al. [14] proposed an innovative approach to comparative industrial plant maintenance and integrated management. The recommended structure ensures that the company's broad objectives are aligned with the local maintenance goals.

According to Abid et al. [15], this method, in which life data analysis is integrated with RCM in order to accurately estimate the failure mode followed by each component of the system, results in a better failure management policy while considering individual pieces of equipment. Because this RCM technique is cost-effective and reduces system Downtime (DT), it increases system dependability. Kamiel [16] proposed a novel method for detecting vibration issues in centrifugal pumps that integrates statistical features, Principal Component Analysis, the symlet wavelet transform, and k-nearest Neighbors. The wavelet decomposition of the low-frequency area produced six statistical characteristics, which were then used to retrieve the input data for the PCA model. T2 and Q statistics were used to detect faults, whilst k-nearest Neighbors and score matrices were used to identify them.

Aggarwal et al. [17] investigated long-term availability, reliability, and MTBF by varying the rates of fertilizer plant subsystem failure and repair. The research focused on the dependability analysis and Markov modeling of urea production systems in fertilizer plants. The system was modeled using the Markov birth-death process, with each subsystem's failure and repair rates following an exponential distribution. The mnemonic rule creates the first-order chapman-kolmogorov differential equations, which are then solved using the runga-kutta fourth-order technique. The MTBF, reliability, and long-term system availability was estimated for different subsystem failure and repair rates. The fertilizer plant crew examines the article's findings in order to design and execute suitable maintenance plans or strategies to increase the efficiency of the urea synthesis system.

Corvaro et al. [18] developed a technique to evaluate the output of reciprocating compressors that considers efficiency, availability, maintenance, and the exponential distribution of failure and repair rates. The research was carried out in collaboration with a company to determine and analyze the impact of RAM-like properties. Its basis was an analysis of the behavior of the defined states for every component of a reciprocating compressor. This descriptive study's methodologies included documentation, bibliographical research, and primary literature content analysis. Their study's major goal is to give a new approach to analyzing maintenance schedules. Future maintenance plans were evaluated using the RAM criteria for reliability, availability, and maintainability. After it was built and installed, they assessed the reciprocating compressor plant's suitability for the end-user site project.

Almost 96% of the availability objective value was achieved during ordinary production. The equipment and subsystems that were the principal reasons for the unavailability were to be evaluated and explained by the quality team. These particular components were discovered. Finally, a variety of affordable strategies for ensuring target availability were proposed and assessed. The reciprocating compressor study findings from RCM were used to demonstrate the benefits of scheduled preventive maintenance operations. Component criticality analysis may be used to create an effective maintenance window and identify failures and important events that might jeopardize the production process.

To monitor and assess RAM performance, the study recognizes the need for a systematic strategy to develop quantitative RAM objectives from the conceptual design phase and apply them throughout the plant's life cycle. Olabisi et al. [19] investigated the centrifugal pump's problem frequency and component life. The information came from a facility that reserves petroleum products for later use. Forty pump problems involving five different products (DPK, AGO, and PMS) were investigated.

Gupta et al. [20] used the RAMD approach at the component level to study numerous dependability measures of steam turbine generators used in STPs. To do this, mathematical models based on the Markovian birth-death process were created for each subsystem of generators. These sorts are quite advantageous in terms of generator availability, dependability, and maintenance. The RAMD study, which identified the critical system components, will allow the development of appropriate maintenance plans. Generator component failure and repair rates are intended to follow an exponential distribution and be continually accessible.

This current study's primary goal or main objective is to evaluate the pump repair schedule in crude oil plants using reliability analysis. When Monte Carlo is used in reliability analysis, it uses statistical distributions of individual equipment component failure and repair to mimic the system's behavior over time. The result will assist decision-makers in improving the accuracy of their attempts to boost system reliability. The issue of pump failure in crude oil production is very serious, as seen from the above review. The less reliable components of the pump will be discovered and monitored regularly so that the entire pump becomes reliable. This current approach is completely different from the maintenance approaches reviewed above.

2|Materials and Method

2.1|Materials

The Monte Carlo reliability model was used to evaluate the reliability of vital pump components such as bearings, shafts, rings, volute, and impellers. Journals, the SPDC operating guide, the SPDC turnaround repair work-pack, and centrifugal pumps (WUC API 610) were all used in this investigation.

2.1.1 | Data collection

The acquired data was used to execute criticality analyses and failure mode effects. The pump component failure data is based on a history of pump failures in the SPDC plant's crude oil export unit. In this research, we examined random component failures. Secondary data was gathered from historical data, maintenance logs, and operational records.

These data contain the Number of Failures (NF), repair time, maintenance time (measured in years), and failure rates for different centrifugal pump components such as rings, bearings, volutes, and impellers. *Eq. (1)* and *Eq. (2)* were used to compute the Mean Time to Failure (MTTF) and lambda (λ). Finally, the MTBF was important for reliability calculations since it provided precise information about a component's random failure history [21].

$$\Lambda = \frac{\text{number of failures}}{\text{number of unit tested x duration of test}}. \tag{1}$$

$$\text{MTTF} = \frac{1}{\lambda}. \tag{2}$$

MTTF is the MTTF. λ is failure rate.

2.2 | Methods

There are several methods and tools for guaranteeing the dependability of plant and pump components. In the following case study, the Monte Carlo dependability model was used to evaluate the dependability of bearings, shafts, rings, volute, and impellers. It was also used to investigate these components' statistical occurrences and maintenance circumstances. A useful tool for determining plant operating parameters, such as size, efficacy, and cost-effectiveness, is the Monte Carlo simulation model, which helps to prevent short duration failures and optimize equipment performance.

2.2.1 | Analytical methods

Mean time between failures

To guarantee that the tested performance was met, the mathematical model for this study incorporated the five years of research (2018-2022), the NF, and the Correction Time Per Failure (CTPE). *Eqs. (3)-(6)* were utilized to achieve this objective [21]. The MTBF was evaluated based on *Eq. (3)*.

$$(\text{MTBF}) = \frac{\text{SI}}{\text{NF}}. \tag{3}$$

where: SI is study interval (hour/year).

NF is the NF (year).

Total mean time between failure

The total MTBF is obtained using *Eq. (4)*.

Total failures per year.

$$(\text{TFPy}) = [(\frac{1}{\text{MTBF})\text{A}} + (\frac{1}{\text{MTBF})\text{B}} + (\frac{1}{\text{MTDF})\text{C}} + (\frac{1}{\text{MTBF})\text{D}} + (\frac{1}{\text{MTBF})\text{E}}] \tag{4}$$

(2) x Annual hour per year,

$$\text{TMTBF} = \frac{\text{Annual hours per year}}{\text{Total failures per year}} = \frac{\text{AHPy}}{\text{TFPy}}, \tag{5}$$

where TMTBF is the total mean time between failure.

Failure rate

The failure rate was calculated as per *Eq. (5)* and *Eq. (6)* [22].

$$\mathrm{FR} = \frac{1}{\mathrm{MTBF}} = \frac{1}{\mathrm{SI}/\mathrm{NF}} = \frac{\mathrm{NF}}{\mathrm{SI}}, \tag{6}$$

where FR is the Failure Rate.

The failure rate for each component per year is as follows:

$$(\mathrm{FR})_A = \left(\frac{1}{\mathrm{MTBF}}\right)_A = \left(\frac{\mathrm{NF}}{\mathrm{SI}}\right)_A, \tag{7}$$

where $(\mathrm{FR})_A$ is the failure rate for component A (Bearings).

Total failure rate

The Total Failure Rate was obtained as expressed in *Eq. (8)*.

$$\mathrm{TFR} = [(\mathrm{FR})_A + (\mathrm{FR})_B + (\mathrm{FR})_C + (\mathrm{FR})_D + (\mathrm{FR})_E]. \tag{8}$$

The time lost due to unreliability per year of the generator components was obtained as expressed in *Eqs. (9)-(12)*.

$$\mathrm{Fpy} = [\text{failure rate for each product}] \times [\text{annual hours per year}]. \tag{9}$$

$$\mathrm{Fpy} = (\mathrm{FR})\ (\mathrm{AHPy}). \tag{10}$$

Recall that the failure rate is the NF divided by the study interval. So

$$\mathrm{Fpy} = \left(\frac{\mathrm{NF}}{\mathrm{SI}}\right)\ (\mathrm{AHPy}). \tag{11}$$

Also, recall that the NF divided by the study interval is given as the reciprocal of the MTBF.

Therefore,

$$\mathrm{FPY} = \left(\frac{1}{\mathrm{MTBF}}\right)\ |\mathrm{AHPy}|, \tag{12}$$

where: FPy is failure per year.

FR is the failure rate.

AHPy is annual hours per year.

SI is study interval.

NF is the NF.

Total Failure Per Year (TFPy).

$$\mathrm{TFPy} = \sum(\mathrm{FPy})A + \sum(\mathrm{FPy})B + \sum(\mathrm{FPy})C + \sum(\mathrm{FPy})D + \sum(\mathrm{FPY})E. \tag{13}$$

Reliability, unreliability, and availability model.

Reliability model

To determine the Pump's Component Reliability (PCR), *Eq. (14)* was used as expressed [21].

$$\mathrm{PCR} = e^{-}\left(\frac{1}{\mathrm{MTBF}}\right) \times t, \tag{14}$$

where PCR is the pump component reliability.

MTBF is the meantime before failure and t is the operating time per year.

Whereas for the various pump components investigated, the reliability is determined by the summation of each pump component reliability, as stated below [23].

$$\mathrm{BR} = e^{-}\left(\frac{1}{\mathrm{MTBF}}\right)_A + \left(\frac{1}{\mathrm{MTBF}}\right)_B + \left(\frac{1}{\mathrm{MTBF}}\right)_C + \left(\frac{1}{\mathrm{MTBF}}\right)_D + \left(\frac{1}{\mathrm{MTBF}}\right)_E \times t. \tag{15}$$

Unreliability model

To determine the Pump Components Unreliability (PCUR) we used the expressed [23].

$$BU = 1 - e^{-}\left(\frac{1}{MTBF}\right) \times t, \tag{16}$$

where BU= unreliability of Pumps

Availability model

To determine the Pump Components Availability (PCA), *Eq. (17)* was used [23].

$$PCAV = \frac{\text{Mean Time Between Failure} - \text{lost time per year}}{\text{Mean Time Between Failure}}, \tag{17}$$

where: PCAV is the pump component availability.

Repair rate (η)

The mean time between repairs (MTBR) was calculated according to *Eq. (18)* [21].

$$MTBR = \frac{1}{\eta} = \frac{\text{downtime}}{\text{number of failure}}, \tag{18}$$

where η is the repair rate.

$$\text{Repair rate } \eta = \frac{1}{MTBR}. \tag{19}$$

Monte carlo model

When used in reliability analysis, Monte Carlo uses statistical distributions of individual equipment component failure and repair to mimic the system's behavior over time. The results will assist decision-makers in improving the accuracy of their attempts to boost system reliability. After numerically modeling a real-world process, Monte Carlo analysis uses statistics to compute the likelihood of many outcomes.

3 | Results and Discussion

3.1 | Results of Reliability Analysis for the Centrifugal Pump Components

As mentioned in the materials and methods section, five separate components of a centrifugal pump were examined for the study, and the findings are shown below.

The reliability analysis results for the bearing component are summarized in *Table 1* below, which shows key reliability parameters such as uptime, MTBF, MTBR, failure rate, and availability over a five-year period.

Table 1. Results of bearing analysis.

Parameters	Period (Year)				
	1	2	3	4	5
Uptime (UT)	2880	2592	2496	2306	2064
Study Interval (SI)	8760	8760	8760	8760	8760
Meantime Between Failure (MTBF)(hrs)	720	432	312	256	158.7
Failure Rate (FR)	0.000456	0.000684	0.000913	0.001027	0.001484
DT	8	12	16	18	26
MTBR hrs	2	2	2	2	2
Repair rate	0.5	0.5	0.5	0.5	0.5
Reliability (R)	0.2689	0.1698	0.1024	0.0938	0.0639
Unreliability (UR)	0.7311	0.8302	0.8976	0.9062	0.9533
Availability (A)	0.9972	0.9952	0.9936	0.9922	0.9875
Unavailability (UA)	0.0028	0.0047	0.0064	0.0078	0.0125

3.1.1 | Results of reliability analysis for the bearings

Fig. 1 shows the plot of the failure rate of bearing against the study interval.

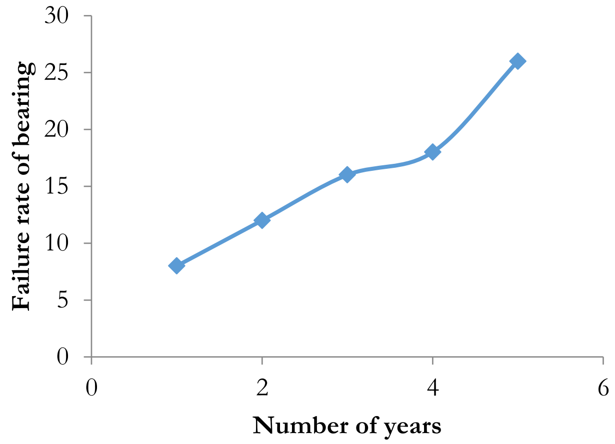


Fig. 1. Failure rate of bearing against study interval.

Checking the centrifugal pump's bearing component failure rate, as shown in *Fig. 1*. The figure shows that the failure rate of the bearing increases as the study interval time increases. *Table 1* shows the expected bearing values from the first year (2880 hours) to the fifth year (2060 hours), indicating a steady decrease in uptime or running time. When DT grows from 8 hours in the first year to 26 hours in the fifth, the average yearly interval between failures decreases. In addition, the failure rate increased from 0.000456 in their first year to 0.001484 in their fifth, as seen in *Fig. 1*.

The results align with those of [18], who also found increasing failure rates over time in reciprocating compressors. This suggests that wear and tear over prolonged use is a consistent factor in pump component degradation. Studies on reciprocating compressors show that failure rates rise from the first to the fifth year when Reliability, Availability, and Maintainability (RAM) is utilized. The information or results also support a recent study [20], which investigated the operational availability of steam turbine power plant generators and found an increase in failure rates from the first to the fourth year. Using the study as its base, a bar graph was built to show the link between the years and the total amount of errors and DT.

Fig. 2 shows the bar chart of DT of the bearing against the study interval time.

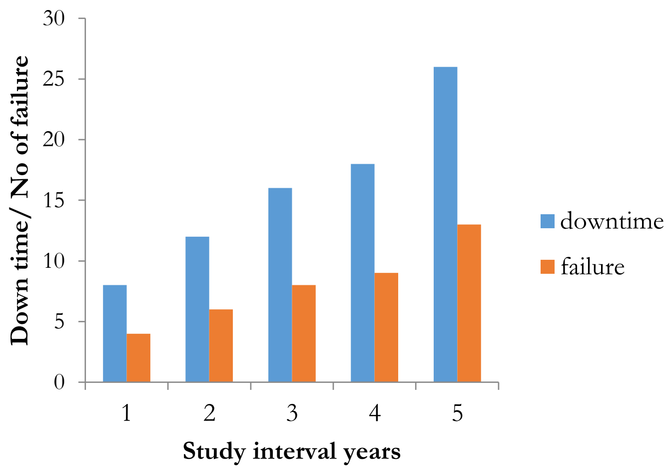


Fig. 2. Amount of failures/year and DT against the year for bearing.

Fig. 2, the bar chart of DT and no of failure against study interval, shows that both DT and failure increase as the study interval time increases. Data show that from the first year (2018) to the fifth year (2022) of production, there was a considerable rise in the number of bearing component failures.

Thus, DT will increase as well. The breakdown significantly reduced production capacity over the five years. It is also observed that the bearing component has a 0.5 annual repair rate, less than 40% reliability, and over 90% availability over a five-year period. This finding contributes to our comprehension of the pump's current state in light of MTBF and MTBR studies. These findings agree with previous studies [17], [20].

Fig. 3 shows the plot of the reliability of the bearing against the study time.

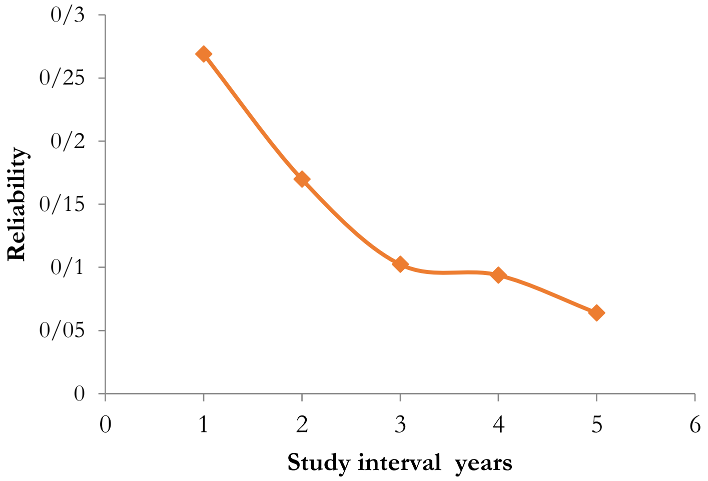


Fig. 3. Reliability against the study interval (5 years) for bearing.

Fig. 4 shows the plot of the unreliability of the bearing against the study time.

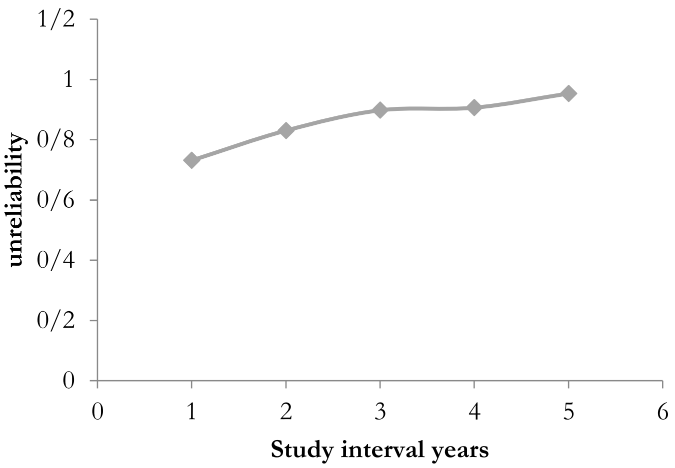


Fig. 4. Unreliability against the study interval (5 years) for bearing.

Fig. 3 shows that the centrifugal pump's bearing component is getting less and less dependable. It can be noticed that the reliability is decreasing as the study time is increasing. Aging of the bearing component is also increasing; obviously, aging comes with depreciation, and such unreliability, as seen in *Fig.* 4, should be expected. As shown in *Fig. 3*, the reliability of the bearing component drops sharply between years 1 and 2, from 0.2689 to 0.1698. There was a noticeable decline in the reliability curve between the first year, 0.2689 (26.89%), and the second year, 0.1698 (16.98%). For the next five years, this trend persisted. The impact of the unreliability graph is the opposite of that of the reliability graph, as *Fig. 4* illustrates.

This suggests that as the year went on, frequent maintenance and failure caused the centrifugal pump's bearing component to lose reliability. A suitable maintenance program has to be developed to increase the reliability or reduce the underperformance. According to prior research by Aggarwal et al. [17], data on the fertilizer plant subsystem's failure and repair rates were also collected in order to calculate the average interval between failures, reliability, and long-term availability. Their research focused on reliability analysis and Markov modeling of urea production systems in fertilizer plants. These researchers saw the same pattern as in *Fig. 3* and *Fig. 4*. Next, we analyze the shaft, another critical component of the pump, and its performance over the five-year period.

3.2 | Results of reliability analysis for the shaft

The results for the shaft component are summarized in *Table 2* below, which shows key reliability parameters such as uptime, MTBF, MTBR, failure rate, and availability over a five-year period.

Table 2. Result of shaft analysis.

Parameters	Period (Year)				
	1	2	3	4	5
Uptime (UT)*hrs*	2880	2592	2496	2304	2064
Study Interval (SI)(hrs)	8760	8760	8760	8760	8760
Meantime Between Failure (MTBF)*(hrs)*	576	518.4	277.3	230.4	172
Failure Rate (FR)	0.000570	0.000570	0.00102	0.00114	0.00136
DT	15	15	27	30	36
MTBR (hrs)	3	3	3	3	3
Repair rate	0.33	0.33	0.33	0.33	0.33
Reliability (R)	0.1936	0.2282	0.0784	0.0723	0.06038
Unreliability (UR)	0.8064	0.7718	0.9216	0.9277	0.9396
Availability (A)	0.9948	0.9953	0.9892	0.9871	0.9828
Unavailability (UA)	0.0052	0.0047	0.0108	0.0129	0.0172

Fig. 1 below shows the plot of the failure rate of the shaft against the study interval time.

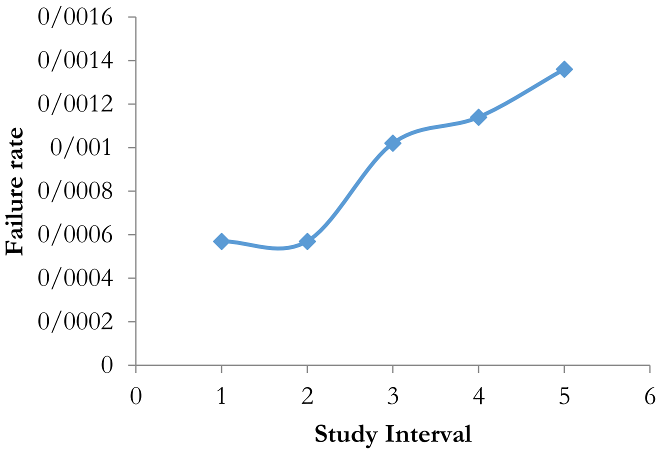


Fig. 5. Failure rate of shaft against study interval.

Fig. 5 visually depicts the centrifugal pump's shaft component failure rate. As the study interval time increases, the failure rate of the centrifugal pump shaft also increases. This trend has been observed by researchers like [1], [7], who equally observed that the failure rate of most components increases over time. According to computationally generated shaft sealing data, uptime, or operating time, decreases from year one to year five. Beyond that, the annual MTBF falls from 576 to 172 hours, while yearly DT rises from 15 to 36 hours between the first and fifth years.

Furthermore, the repair rate remains about 0.3 from the first to the fifth year of operation. Furthermore, *Fig. 5* shows that the failure rate increased from 0.000570 during the first year to 0.00136 in the fifth year. As manufacturing years pass, it is assumed that the shaft component's failure rate will grow, resulting in pump breakdown and a fall in output rate. The interpretation and findings acquired from this study are consistent with prior research done by Corvaro et al. [18].

The failure rate of reciprocating compressors increases from the first to the fifth year, according to the Reliability, Availability, and Maintainability (RAM) study. Furthermore, the findings are consistent with a recent study [20] that studied the operational availability of generators used in steam turbine power plants and observed that the failure rate rose from the first to the fourth year. *Fig. 6* shows the bar chart of the DT of the shaft against the study interval time.

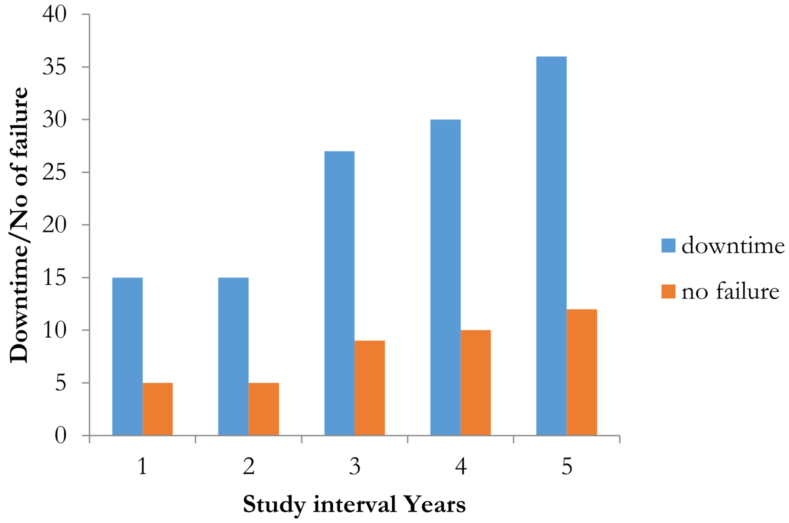


Fig. 6. Amount of failures/DT against study intervals (years) for Shaft.

Similar to what was seen in the bearing component, there is a noticeable rise in both the failure rate and DT over a five-year period (*Fig.* 6). Over the five years, there is more DT because replacing a broken shaft takes at least twenty-four hours, which is longer than replacing a bearing. Additionally, it was found that during a five-year period, the failed shaft sealing component had a reliability of less than 30% and an availability of over 90%. Following the research, a bar graph was created showing the correlation between the years and the total NF and DT recorded. The bar chart shows that DT and no failures increase with the study interval time. This pattern has been seen in virtually all of the components studied. *Fig. 7* shows the plot of the reliability of the shaft against the study time.

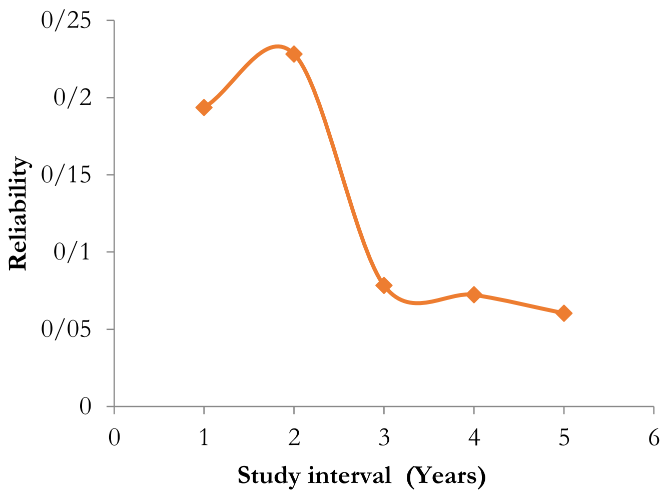
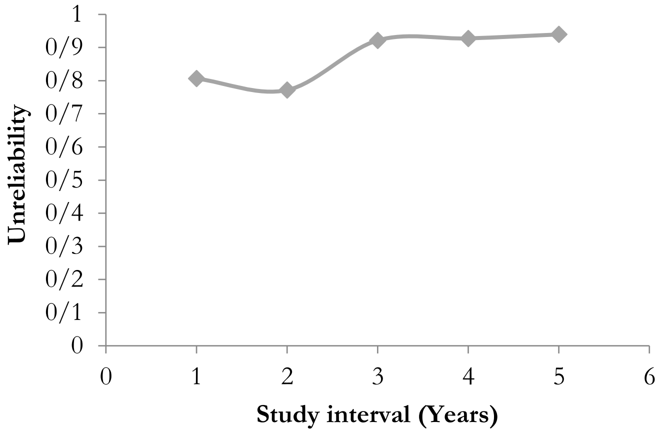


Fig. 7. Reliability analysis of the shaft sealing for a 5-year period.

Fig. 8 shows the plot of the unreliability of the shaft against the study time. *Fig. 7* shows that the reliability of the shaft rose to the highest peak in the second year and then assumed a descent as time increased. The shape



of the curve of *Fig. 7* depicts this. This still confirms earlier observations that the reliability of components of the pump decreases with the increase in time. As shown in *Fig. 7*, the value drops down quickly in the first year (0.1936), second year (0.2282), and fifth year (0.06038). Reliability rises after the first year.

Fig. 8.Unreliability analysis of the shaft for a 5-year period.

The state of the bearing component, as shown in *Fig. 8*, shows increasing unreliability. Reliability decreased as the frequency of unreliability rose along with the failure rate. This implies that the shaft was losing reliability due to fracture and continuous repair, as [21] observed earlier. As expected, reliability decreases with increased DT, indicating that frequent maintenance or replacement of components is required to maintain operational efficiency. Less dependable units should get greater attention overall, and a thorough maintenance plan should be devised to boost their reliability. Next, we analyze the ring, another critical component of the pump, and its performance over the five-year period.

3.3 | Results of Reliability Analysis for the Rings

The reliability analysis results for the ring component are summarized in *Table 3* below, which shows key reliability parameters such as uptime, MTBF, MTBR, failure rate, and availability over a five-year period.

Table 3. Result for ring analysis.

Parameters	Period (Year)				
	1	2	3	4	5
Uptime (UT)	2880	2592	2496	2304	2064
Study Interval (SI)(hrs)	8760	8760	8760	8760	8760
Meantime Between Failure (MTBF)(hrs)	576	324	249.6	209.4	172
Failure Rate (FR)	0.000570	0.000913	0.00114	0.00125	0.00136
DT	25	32	40	44	48
MTBR	5	4	4	4	4
Repair rate	0.2	0.25	0.25	0.25	0.25
Reliability (R)	0.1936	0.0936	0.0581	0.0723	0.0592
Unreliability (UR)	0.8064	0.9064	0.9419	0.9277	0.9408
Availability (A)	0.9913	0.9878	0.9856	0.9812	0.9772
Unavailability (UA)	0.0987	0.0122	0.0144	0.0188	0.0228

Fig. 9 below shows the plot of the failure rate of the ring against the study interval.

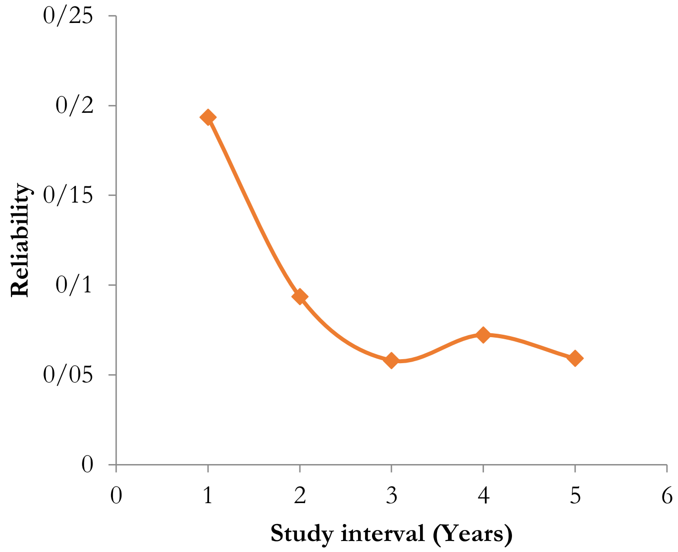


Fig. 9. Failure rate of ring against study interval.

A study into the centrifugal pump's rings showed a noticeable increase in the annual failure rate and DT during a 5-year period. These findings are also shown in *Table 3* computational figures. This study's import is that less reliable components should be monitored more frequently for preventive maintenance purposes.

Fig. 10 below shows the plot of the reliability of the ring against the study interval time.

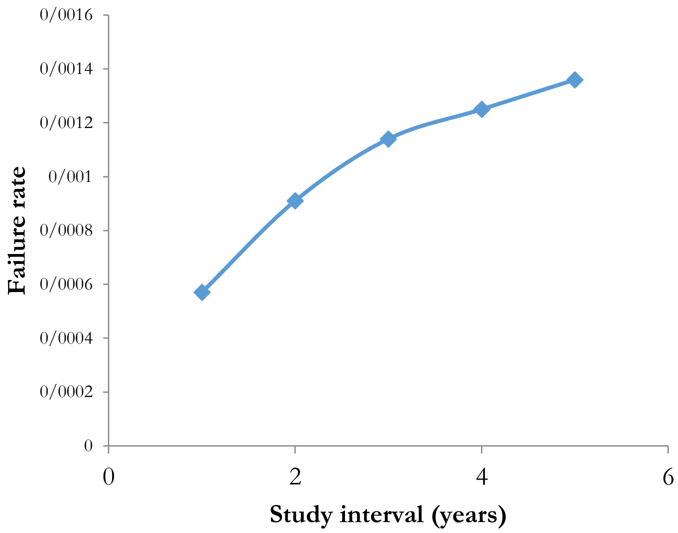


Fig. 10. Reliability analysis of the rings for a 5-year period.

Fig. 11 below shows the plot of the unreliability of the ring against the study interval.

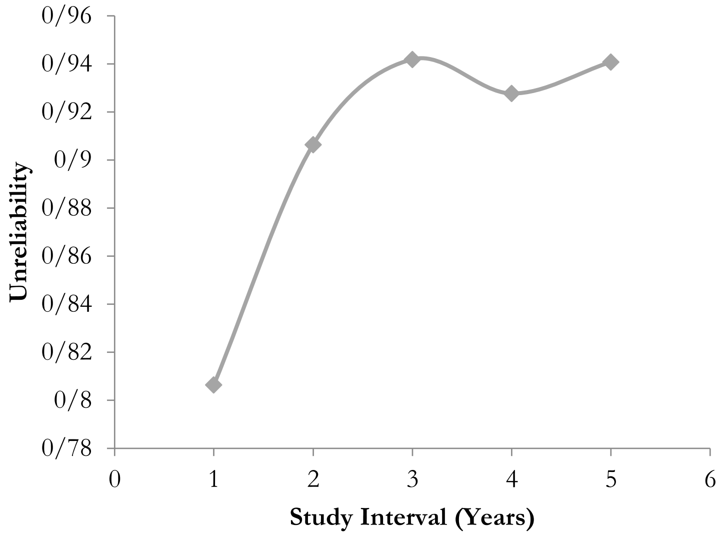


Fig. 11. Unreliability analysis of the rings for a 5-year period.

Fig. 10 shows the curve of the reliability analysis of the ring over a five-year period. The curve shows that the reliability is decreasing with time. This same pattern has been observed with the other components of the pump. *Fig. 11* shows the ring's unreliability analysis over a five-year period; the curve clearly shows that the unreliability increased to a peak of 0.94 and then decreased slightly to the fourth before commencing an upward rise again. In general, the unreliability increased over the five-year study period. Reliability declined, and unreliability rose as the failure rate rose. This illustrates how regular maintenance and breakage were causing the rings' yearly reliability to decline. It was discovered that the duration of operation, or uptime, also declined annually in addition to the period between failures.

Additionally, there is a similar pattern to the failure of maintenance and DT rates over a five-year period—that of the shaft and bearing sealing component. The ring's lengthier DT than the bearing is caused by its cumulative rise in DT over a five-year period since fixing a broken ring takes at least one day. Equipment that isn't functioning well should get more attention, and proper maintenance techniques should be used to make it more reliable.

Tsarouhas et al. [11] used a best-fit distribution of failure and repair rates to assess a strudel production line's availability, reliability, and maintainability; his findings agree with this work. Next, we analyze the volute, another critical component of the pump, and its performance over the five-year period.

3.4 | Results of Reliability Analysis for the Volute.

The results of the reliability analysis for the volute component are summarized in *Table 4* below, which shows key reliability parameters such as uptime, MTBF, MTBR, failure rate, and availability over a five-year period.

Table 4. Result for volute analysis.

Parameters	Period (Year)				
	1	**2**	**3**	**4**	**5**
Uptime (UT)	2880	2592	2496	2304	2064
Study Interval (SI)	8760	8760	8760	8760	8760
Meantime Between Failure (MTBF)(hrs)	960	864	624	329.1	229.4
Failure Rate (FR)	0.00034	0.00034	0.00045	0.00079	0.00102
DT	12	12	16	21	27
MTBR(hrs)	4	4	4	3	3
Repair rate	0.25	0.25	0.25	0.33	0.33
Reliability (R)	0.3756	0.4142	0.3252	0.1735	0.1218
Unreliability (UR)	0.6244	0.5858	0.6748	0.8265	0.8782
Availability (A)	0.9958	0.9953	0.9936	0.9909	0.9870
Unavailability (UA)	0.0042	0.0047	0.0064	0.0091	0.013

After investigating the volute of the centrifugal pumps, it was discovered that there was a considerable annual increase in DT and failure rate during a 5-year period, as seen in the computational results in *Table 4*. This is the benefit of reliability-based maintenance: the components with high failure rates and unreliability can be noted, and constant checks and attention can be given to such components to avoid equipment failure. This will reduce DT and increase uptime.

Fig. 12 below shows the plot of the reliability of the volute against the study interval.

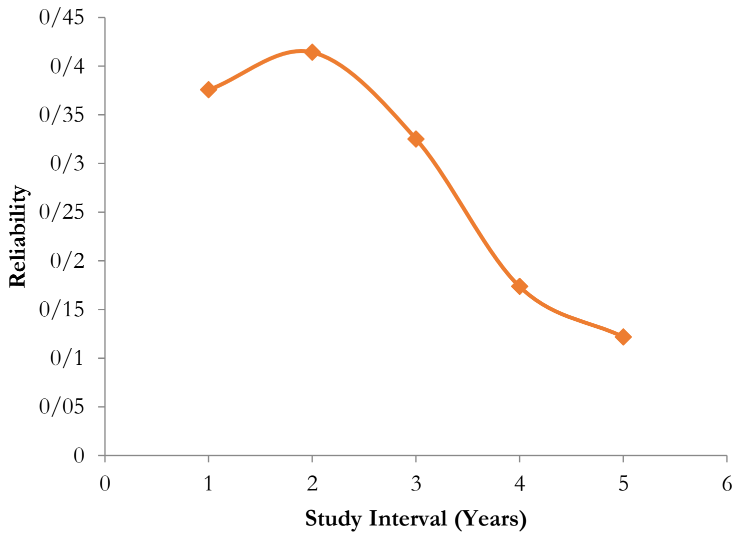


Fig. 12. Reliability analysis of the volute for a 5-year period.

Fig. 13 below shows the plot of the unreliability of the volute against study interval time.

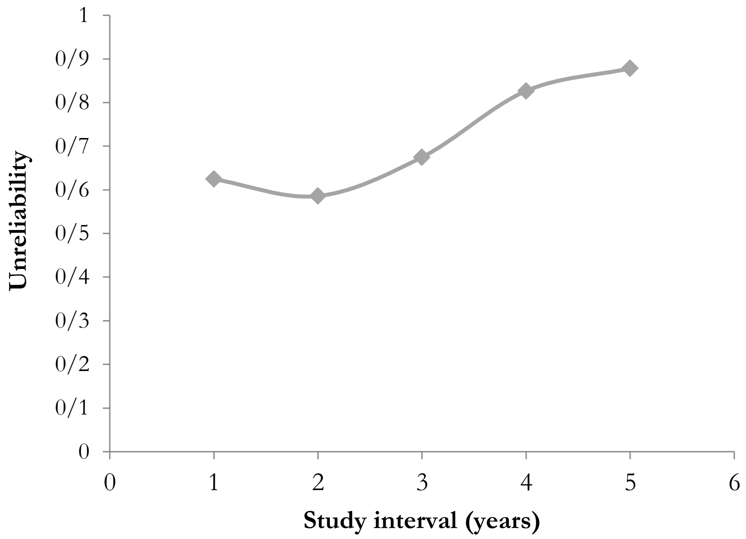


Fig. 13. Unreliability analysis of the volute for a 5-year period.

Fig. 12 and *Fig. 13* have very interesting shapes, *Fig. 12* shows that the reliability peaked above 0.4 during the second year and then continued to decrease with time over the five-year period. The same interesting observation is made in *Fig. 13*, the curve of the figure showed that the lowest unreliability (0.59) of the volute occurred during the second year, and thereafter, the unreliability continued to rise over the five-year period of the study time. This pattern is typical of every newly installed component, and monitoring is required as components age to avoid constant breakdown.

The reliability study's visual representation in *Fig. 12* shows that the centrifugal pump's volute component is becoming less reliable. The reliability curve illustrates this, with a noticeable fall starting in the first year at 0.3756 (37.56%) and continuing for the whole five years at 0.1218 (12.18%). The shift in focus from the reliability graph to the unreliability graph is seen in *Fig. 13*. Shaft sealing, rings, and bearings are less dependable than the volute, as *Fig. 11* further illustrates. Volute data calculation shows a drop in uptime or operating time from the first to the fifth year.

In contrast, the average annual DT increases from 12 hours in the first year to 26 hours in the fifth, while the mean interval between failures decreases from 960 hours to 229.4 hours. The failure rate in year one went from 0.00034 to 0.00102; then it climbed again in year five. The repair rate was constant at 0.25 from the first to the third year, increasing to 0.33 in the fourth and fifth years.

The volute, which fails less often than 40% of the time, and the availability, which exceeds 90% over a five-year period, should also be highlighted. It was also found that the MTBF exceeded the MTBF of the shaft sealing and the bearing. Yang and Hong's [23] paper, Reliability analysis of repairable systems with dependent component failures under partially perfect repair, reached a similar conclusion. Next, we analyze the impeller, another critical component of the pump, and its performance over the five-year period.

3.5 | Results of Reliability Analysis for the Impellers

The results of the reliability analysis for the impeller component are summarized in *Table 5* below, which shows key reliability parameters such as uptime, MTBF, MTBR, failure rate, and availability over a five-year period.

Table 5. Result for impeller analysis.

Parameters	Period (Year)				
	1	**2**	**3**	**4**	**5**
Uptime (UT)	2880	2592	2496	2304	2064
Study Interval (SI)	8760	8760	8760	8760	8760
Meantime Between Failure (MTBF)(hrs)	720	648	499.2	460.8	294.8
Failure Rate (FR)	0.00045	0.00045	0.00057	0.00057	0.00079
Dow45ntime (DT)	12	12	15	15	21
MTBR(hrs)	3	3	3	3	3
Repair rate	0.33	0.33	0.33	0.33	0,33
Reliability (R)	0.2736	0.3114	0.2410	0.2689	0.1958
Unreliability (UR)	0.7264	0.6886	0.7590	0.7311	0.8042
Availability (A)	0.9958	0.9953	0.9940	0.9935	0.9899
Unavailability (UA)	0.0042	0.0047	0.006	0.0065	0.0101

After being analyzed, the centrifugal pumps' impellers revealed that, as shown in the computational statistics in *Table 5*, there had been a significant increase in yearly DT and failure rate over the previous five years. This general trend has also been observed in the other components analyzed.

Fig. 14 below shows the plot of the reliability of the impeller against the study interval time.

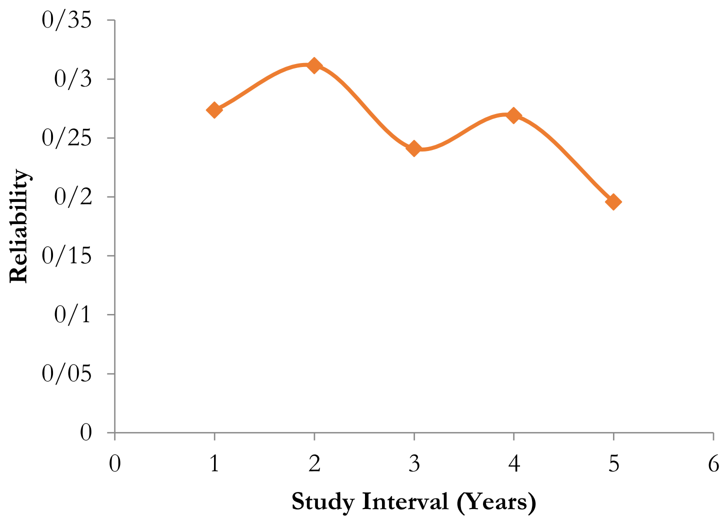


Fig. 14. Reliability analysis of the impeller for a 5-year period.

Fig. 15 below shows the unreliability of the impeller against the study interval.

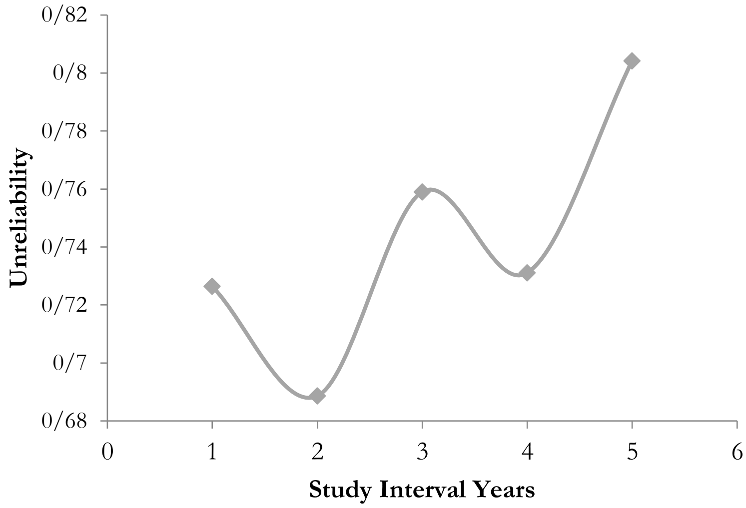


Fig. 15. Unreliability analysis of the impeller for a 5-year period.

Figs.14 and *15* have very unique curves. The curve of *Fig. 14* is rising and falling, indicating that the reliability of the impeller is rising and falling; two years are of particular interest; the second and the fourth year have all exhibited high reliability, and this high reliability corresponds to the lowest peaks of the curve of *Fig. 15* which indicates the lowest points of unreliability these points also occur at the second and fourth year. This means the impeller was at its best during the first two years, and with maintenance, its reliability improved in the fourth year, reducing DT.

The impeller's reliability fluctuates when the dependability analysis in *Fig. 14* is reviewed. As shown in *Fig. 15*, the unreliability graph has the opposite effect on the reliability graph. Empirical research suggests that the reliability curve peaked in the first year at 0.2736 (27.36%) and steadied at 0.3114 (31.14%) across the five-year period. It was also shown that the impeller was more reliable than the bearing, shaft sealing, and rings (*Fig. 13*). Based on projected impeller values, one may see a decrease in uptime, or operational time, from the first to the fifth year.

Furthermore, when DT grows, the MTBF reduces yearly, falling from 12 hours in the first year to 21 hours in the fifth. The MTBF ranges from 720 to 294.8 hours. The failure rate was 0.00045 in the first year and rose to 0.00079 in the fifth, resulting in a five-year repair rate of 0.33. The impeller's availability over a five-year period of more than 90% and best dependability of less than 40% are quite amazing. Again, as [20] noted, the MTBF is lower in the volute but higher in the bearing and shaft sealing.

Keeping in mind the previously mentioned outcomes. The indicators specified in the objectives are evaluated alongside the pump's effectiveness. The bearing, shaft, and ring components have been identified as the most significant sensitive, and particular care is needed if the pumps' reliability is to be increased. According to Gómez de León Hijes and Cartagena [24], regular maintenance monitoring will lower the failure rates of the bearing, shaft, and ring system, enhancing pump availability and productivity. Next, we analyze the different failure modes of the pump identified during the five-year study.

3.1.5 | Analysis of different failure modes identified and their occurrence

The results of the analysis of different failure modes identified and their occurrences for a period of five years are shown in *Table 6*.

Table 6. Failure modes identified and their occurrence in pump.

failure Modes	FM Code	Years					Total Occurrence
		1	2	3	4	5	
External leakage-process	ELP	8	10	13	15	16	62
Internal leakage	INL	4	8	6	8	11	37
Spurious stop	UST	3	4	7	8	16	38
Overheating	OHE	3	3	9	10	10	35
Total FO		18	25	35	41	53	

Fig. 16 below is the bar chart of the no of failures of the pump against the failure modes.

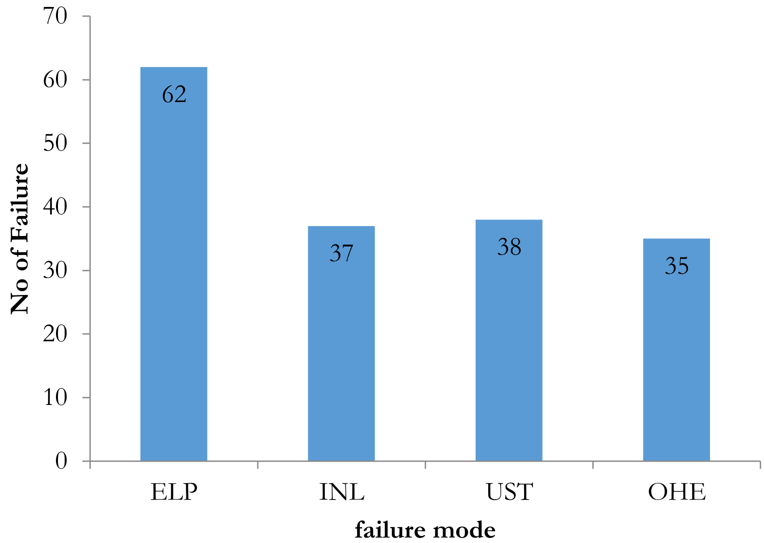


Fig. 16. Pump failure modes.

Based on the preliminary research, an estimated 172 centrifugal pump failures during the five-year period occurred, thanks to the explanatory findings. By documenting them, the ISO 14224 recommendations aided in the classification of the various failure types. According to the statistics, Spurious Stop (UST) (37), after External Leakage Process (ELP) medium (62), is the second most frequent failure mechanism. It was discovered that overheating (OHE) and internal leakage (INL) were additional reasons for the pump failure. These results agree with the work of Wang and Cheng [25], who published a paper on a technique for diagnosing faults in centrifugal pump systems using frequency-domain symptom characteristics. The frequency of various pump failure types is shown in *Table 6*. Studies showed that the External Leakage Process (ELP) medium has the highest occurrence [3].

4 | Conclusion

This study, improving the maintenance practice of pumps in crude oil production plant using reliability analysis, was successfully carried out. The research domain is Shell Petroleum Development Company (SPDC); the pump was located there, and a dependability analysis was carried out to examine the component elements. These components include the shaft, bearing, impeller, volute, and ring. The following conclusions were drawn from the study.

I. Every pump component had a sharp decline in uptime, or operational time, between the first and fifth years of use.

II. The bearing, shaft, and ring components have been identified as the most significant sensitive, and need particular care if the pumps' reliability is to be increased.

III. There were comparable shifts in the failure rate of the bearing component from their first year of 0.000456 to their fifth year of 0.001484. As the year progressed, the centrifugal pump's bearing component became less dependable, leading to an increase in unreliability.

IV. Throughout the course of the five years of study, the bearing components became more difficult to access since the failure rate of the bearing was increasing with time.

V. Furthermore, the shaft failed in the fifth year, with a failure rate of 0.00136, which was higher than 0.000570 in the first year. Less than 25% of the shaft proved to be constant throughout the course of the five years of investigation.

VI. The shaft had 96% accessibility and 96% unreliability for industrial applications.

VII. The study noted that the MTBF of the impeller was lower than that of the volute but higher than that of the bearing and shaft sealing.

VIII. As the failure rate increased, the ring component's dependability decreased and its unreliability increased. Since it takes at least twenty-four hours to repair a damaged ring, this ring experiences longer DT than a bearing; hence, the DT duration increases over the course of five years.

IX. Over a five-year period, the volute—the failing component—has an availability of over 90% and the lowest dependability of less than 40%.

X. The impeller's availability over a five-year period of more than 90% and best dependability of less than 40% are quite amazing.

XI. The study showed that the External Leakage-Process (ELP) medium has a higher occurrence rate as a mode of failure.

XII. The study has revealed components of pumps that require regular monitoring for maintenance to reduce DT and increase productivity.

XIII. The study has shown that reliability analysis can be used to improve the maintenance practice of pumps in crude oil production plants and, if adopted, will bring down the cost of maintenance and DT.

Author Contribution

This is to publicly declare that the five authors of this publication (names listed above) were involved in conceptualizing this research topic. Udo [3], the first author, was saddled with the responsibility of data curation and assisted by the other four authors with formal analysis. No outside funding was received for this project. The first author was the major financial contributor to this project. The five authors were jointly involved in the research project, playing various roles as supervisors, investigators, and resource providers to enable the project to go through the various stages of conceptualization, data curation, formal analysis, funding, investigation, methodology, project administration, resource provision, software provision, supervision, validation, writing the original draft and final report, and final paper for publication. All five members of the research team adopted this paper.

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The research team members wish to declare that this project was self-funded by team members publicly. SPDC only provides us with their data and research facilities.

Data Availability

The data used for this work is available in the University of Uyo, Uyo-Nigeria library, in the M.Eng.degree report submitted to the University, and can be obtained at SPDC PH-Nigeria. It is also available in journal publications made from the work. The references included in our journal publication are duly referenced. Every second-party data used in the publication is duly referenced, and credit is given to the source.

Conflict of Interests

The authors wish to declare no conflict of interest in this publication publicly; all five authors have agreed to submit their work for journal publication.

Financial Interests

We wish to publicly declare that this is a self-sponsored research work to which the research team members contributed.

Non-Financial Interests

This work is free of all encumbrances, whether financial or non-financial interests.

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