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Centrifugal Pump Reliability Improvement in the Pulp and Paper Industry

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Abstract

South African pulp and paper mills have encountered frequent breakdowns of centrifugal pumps, resulting in considerable production losses. A case study was conducted to determine the factors contributing to these failures and devise ways to enhance pump reliability. Data were collected through questionnaires and operational records. The study revealed that inadequate maintenance, misalignment of pump components, lack of lubrication, improper baseplate installation, subpar sealing arrangements, inadequate design of the pumping system, and foreign materials entering the system were the primary causes of pump failure. To improve reliability, this study suggests employing machine learning methods to select the optimal maintenance strategy and provide internal maintenance personnel with training in condition monitoring systems. This will enable both pulp and paper mills and pump manufacturers to identify blind spots and improve the dependability of centrifugal pumps.

Keywords
South Africa, Centrifugal Pump, Case Study, Pump System, and Paper Mill.

1. Introduction
South Africa is one of the world's largest pulp and paper producers, making the pulp and paper industry a major contributor to the South African economy (Chamberlain *et al.*, 2005). A pulp-and-paper company based in South Africa has hundreds of centrifugal pumps installed in their production plants. Every papermaking process relies heavily on pumping, and pulping, bleaching, refining, and stock preparation involve large pumps and complex multiphase flows (Lindsay, 1992). This South African pulp and paper mill has experienced centrifugal pump breakdowns. A study (Maverengo, 2017) was conducted to discover ways to reduce energy use in South African pulp and paper mills, highlighting that the industry spends a lot of money on pumping systems, one of which is insufficient maintenance programs, which also result in significant energy loss. Traditionally, centrifugal pumps have been designed to have an average lifespan of approximately 30 years (Al-Obaidi, 2018). However, a pulp and paper company in South Africa has raised concerns that they are experiencing centrifugal pump breakdowns that occur unexpectedly before the manufacturers' recommended useful life. When these pumps fail, the company loses millions of rands in revenue owing to production loss, and the pumps' life cycle costs become massive as well. In South Africa, there are few to no studies conducted in this area on the pulp and paper industry; therefore, the causes of centrifugal pump breakdowns are unclear or unknown.

1.1 Objectives
The primary goal of this study is to 1) determine the underlying reasons for the breakdown of centrifugal pumps in South African pulp and paper companies. Furthermore, 2) to give engineering managers the techniques and approaches they need to properly oversee the dependability of centrifugal pumps in the pulp and paper sector.

2. Literature Review

Centrifugal pump operating problems may be either hydraulic or mechanical. Azadeh et al. (2010) identified mechanical seal damage, misalignment, cavitation, bearing, and shaft-related problems as the mechanical and hydraulic reasons for pump failures. ALTobi et al., (2019) identified an artificial intelligence method for pump fault diagnosis between multilayer perception (MLP) and (SVM), the authors used five mechanical faults namely misalignment, imbalance, faulty bearing, faulty impeller, and mechanical looseness as well as cavitation as a hydraulic fault, to help compare the two methods. The following section discusses these different mechanical and hydraulic failures.

2.1 Impeller Failures

Impeller failure can have a substantial impact on the impeller, which is an essential component of centrifugal pumps. According to a study conducted in China (Cao et al., 2017), asymmetric geometry, machining accuracy, assembly errors, casting asymmetry, and manufacturing processes can result in hydraulic imbalance, which can destroy flow structures and reduce efficiency, vibration, noise, bearing wear, stability, reliability, shortened pump service lives, and even catastrophic accidents. Yu et al. (2022) investigated the effects of eccentricity on centrifugal pumps. They discovered that pressure fluctuations, deteriorating performance, and decreased pump efficiency resulted from an increase in the eccentricity ratio caused by a parallel misalignment of the coupling. The significance of considering impeller eccentricity during pump design and maintenance was emphasized in both studies.

2.2 Shaft Failures

The centrifugal pump shaft is a crucial component that supports the impeller and other rotating parts during start-up and operation, while transmitting torque (Mohamed *et al.*, 2022). Failure of the pump shaft can lead to complete damage to other components. Studies have shown that several centrifugal pump shaft failures occur owing to the inability to model the optimal stress on the shaft during operation. There have been instances where the pump shaft's actual design lifetime was 40 years, but it only lasted for a year, resulting in premature shaft failure, as observed in a nuclear power plant in China (Sob and Pita, 2020). Impellers also contribute to the shaft failure. In a study conducted in Poland, shaft fractures occurred in four pumps owing to cavitation, leading to mass imbalance and uneven distribution. This caused fractures in the impeller keyed joint section and coupling hub attachment section, as well as failure in the keyway walls at the shaft and impeller joint. Shaft failures can result from poor design or manufacturing (Padasale *et al.* 2022). In India, a pump shaft failed within 4.5 days of operation owing to improper material and a square-ended key used in the round-ended keyway. Poor maintenance also plays a significant role in shaft failure. In Indonesia, a broken shaft was found because of previous repairs, incorrect shaft materials, and foreign materials such as sand and bolts in the pump chamber.

2.3 Sealing Failures

Sealing is crucial for sealing the shaft of a centrifugal pump in order to prevent fluid leakage (Gavade and Sawant, 2020). Seal failures are a major cause of pump breakdowns, with up to 70% of failures due to seal failures (Shihab et al., 2020; Shihab *et al.*, 2021). The problem arises from uniform particle mixing, worn parts, or uneven sealing surfaces (Hao *et al.*, 2022). Contamination in fluids, including solid particles and chemically reactive substances, damages seals and other components (Kumar and Kumar, 2017). Studies using failure mode effects and criticality analysis (FMECA) have identified mechanical seals as critical components in pump failures (Singh and Suhane, 2013). Cavitation, poor lubrication, and bearing vibrations are the main causes of mechanical seal failure (Chittora, 2018). Stuffing box seals are often used because of their simplicity and low cost; however, they have larger leaks and limited service life. The pump industry faces challenges in reducing leakage. A platinum mine in South Africa faces a problem with improper seal design, leading to improper slurry pumping (Mphahlele *et al.*, 2022). The authors used finite element analysis and CFD simulations to improve seal design.

2.4 Bearing Failures

Bearings are critical mechanical components that significantly impact pump performance (Omri *et al.*, 2022). Unexpected breakdowns and catastrophic accidents can result in failures (Daraz *et al.*, 2018). According to an Indian study (Mishra et al., 2022), misalignment of the baseplate and concrete foundation is the primary cause of frequent bearing failures. Mechanical stresses on bearing balls, misalignment, corrosion, and a damaged inner or outer raceway are all factors to consider (Sinha and Rao, 2006). To maintain an optimal bearing life, bearings must be fitted correctly and carefully to avoid looseness between housing, support, and misalignment.

2.5 Motor Failures
Pump dependability is greatly dependent on motors, and the primary reason for electric motor failures in centrifugal pumps is rotor eccentricity caused by roller-bearing wear (Bekchanov *et al.*, 2022). In a study conducted in the UK, bearing faults, broken rotor bars, stator winding, and impeller imbalance were found to be the primary causes of induction motor faults when diagnosed using motor current signature analysis (MCSA). Chakravarthy et al. (2019) used a machine learning algorithm to identify three different types of faults in induction motors: electrical faults (unbalanced supply voltage or current, single phasing, under or over voltage, overload, and internal faults), mechanical faults (broken rotor bar, mass imbalance, air gap eccentricity, bearing, and impeller damage), and environmental faults (vibration and foundation defects).

2.6 Cavitation
Cavitation occurs when the local pressure is less than the vapor pressure of a liquid, either due to gas entering the fluid, insufficient available net positive suction head (NPSHa), or internal recirculation (George, 2016; Glovatsky *et al.*, 2020). It occurs on the impeller and is an essential problem in pumps, causing noise, vibration, fatigue, and sometimes, fracture (Jaiswal *et al.*, 2019). Cavitation also damages the shaft, bearing, and motor performance owing to erosion, leading to head and efficiency losses, increased input power, noise, and vibration generation. A study in Iraq (Al-Obaidi, 2020) found that cavitation in a centrifugal pump is caused by vaporization, entry of outside air, reduced fluid on the suction side, and leakage on the suction side. The study found that as the flow rate increased, the pressure head decreased and cavitation developed. The results also showed that cavitation occurs when the available net positive suction head (NPSHa) becomes smaller than the required net positive suction head (NPSHa). A similar experiment was conducted in Iraq, using various suction valve openings to detect cavitation. The results indicate that a decrease in NPSHa results in cavitation, as the occurrence depends on the operating conditions.

3. Methods
This study employed a mixed research method that collected both qualitative and quantitative data. The explanatory case study is a research strategy used to identify the causes of centrifugal pump failure, investigate the failure trend, and develop strategies to improve pump reliability. This study employs a cross-sectional time horizon. A questionnaire was sent to ten identified maintenance personnel at a case study pulp and paper mill to determine their experiences with centrifugal pumps. Qualitative data were obtained from the centrifugal pump operating data obtained from a service center used by the pulp and paper mill for inspections and repairs. This study used a questionnaire as the primary data collection method and the existing centrifugal pump operational data as a secondary data collection method.

4. Results and Discussion
4.1. Numerical Results
Ten maintenance personnel from pulp and paper mills were identified and sent to the questionnaire, all of whom agreed to participate in the study. The questionnaire included questions on study-related topics and demographics. Two questions on the study were: 1) What are the reasons behind centrifugal pump failures, and 2) What are the tactics and procedures employed to guarantee pump dependability?

4.1.1. Demographic Information
The majority (30%) of the participants were engineers, with the majority (40%) having 1–5 years of experience (see Table 1).

Table 1. Demographic information

Participants	Experience				
	Less than 1	**1 - 5**	**6 - 10**	**More than 10**	**Total**
Engineer (n = 3)		20%	10%		**30%**
Technician (n = 2)		20%			**20%**
Manager (n = 2)			10%	10%	**20%**
Foreman (n = 2)				20%	**20%**
Process Controller (n = 1)			10%		**10%**
Total		**40%**	**30%**	**30%**	**100%**

4.1.2. Causes of Centrifugal Pump Failures

A Likert scale and open-ended questions were used in the study-related questions. On a Likert scale, participants were asked to rate their level of agreement or disagreement with the component's causes of failure. A score of 1 – 5 was used, where 1 = strongly disagree (SD), 2 = disagree (D), 3 = neutral (N), 4 = agree (A), and 5 = strongly agree (SA). A relative importance index (RII) was used to determine the level of importance of each cause of failure.

Using the Relative Importance Index equation, $RII = {}^{\sum W}/_{A^{*}N} = \frac{5n_5+4n_4+3n_3+2n_2+1n_1}{5*N}$

W = Weight, A = Highest weight, N = Total number of samples.

4.1.2.1. Impeller Failures

Hydraulic imbalance (RII=0,74), cavitation (RII=0,66), and vibration (RII=0,6) were identified as the root causes of the impeller failures (see Table 2). The results did not provide sufficient evidence that assembly errors (RII=0,58) were a cause of impeller failure.

Table 2. Descriptive statistics for impeller failure causes

Failure Cause	SD (1)	D (2)	N (3)	A (4)	SA (5)	Total Number (N)	RII	Ranks
Hydraulic imbalance	0	0	15	12	10	10	0,74	**1**
Cavitation	2	0	6	20	5	10	0,66	**2**
Vibration	1	6	9	4	10	10	0,6	**3**
Assembly errors	2	4	6	12	5	10	0,58	**4**

Respondents were asked to provide additional causes of the impeller failures they experienced, and six failures were identified. Table 3 indicates that most participants (n=4) stated that foreign objects caused the impeller failure.

Table 3. Identified impeller failure causes

Failure Causes	*Eng*	*Eng*	*Techni*	*Eng*	*Man*	*Techni*	*Fore.*	*Fore.*	*Pro Contr.*	*Man*	*Total*
Foreign objects			1				1	1	1		4
Wrong material for construction	1										**1**
Wrong impeller size			1								**1**
Type of medium used					1	1					**2**
Misalignment										1	**1**
Bearing failure							1				**1**

4.1.2.2. Shaft Failures

The results demonstrated that the stress load on the shaft (RII=0,84), and poor maintenance (RII=0,82) were the dominant root causes of shaft failure (see Table 4). These results did not provide sufficient evidence to claim that cavitation is one of the root causes of shaft failure.

Table 4. Descriptive statistics for shaft failure causes

Failure Cause	SD (1)	D (2)	N (3)	A (4)	SA (5)	Total Number (N)	RII	Ranks
Stress loads on the shaft	1	0	0	16	25	10	0,84	**1**
Poor maintenance	1	0	3	12	25	10	0,82	**2**
Poor shaft design	1	0	9	4	25	10	0,78	**3**
Poor shaft material	2	0	3	8	25	10	0,76	**4**
Surface defects	2	0	12	12	5	10	0,62	**5**
Cavitation	2	0	18	4	5	10	0,58	**6**

The respondents were asked to provide the additional causes of shaft failures that they experienced. Approximately seven failures (Table 5) were identified, and most participants (n=5) mentioned that misalignment is a cause of shaft failure.

Table 5. Identified shaft failure causes

Failure Causes	*Eng*	*Eng*	*Techni*	*Eng*	*Man*	*Techni*	*Fore.*	*Fore.*	*Pro Contr.*	*Man*	*Total*
Misalignment	1	1					1	1	1		**5**
Incorrect pump use/ application			1								**1**
Motor start/stop control					1						**1**
Materials solidifying around the impeller						1					**1**
Incorrect oil seal used								1	1		**2**
Poor maintenance							1				**1**
Stress due to loads							1				**1**

4.1.2.3. Sealing Failures

Particles in the sealing cavity (RII=0,82) are the main root cause of sealing failures (see Table 6), followed by poor lubrication and poor seal design (RII=0,78).

Table 6. Descriptive statistics for sealing failure causes

Failure Cause	SA (1)	D (2)	N (3)	A (4)	SA (5)	Total Number (N)	RII	Ranks
Particles in the sealing cavity	1	0	3	12	25	10	0,82	**1**
Poor lubrication	1	2	3	8	25	10	0,78	**2**
Poor seal design	1	2	3	8	25	10	0,78	**2**
Ununiform sealing surface	2	0	3	12	20	10	0,74	**3**
Cavitation	2	4	9	0	15	10	0,6	**4**

The respondents were asked to provide additional causes of seal failures experienced by them. About nine failures were identified, and most participants (n=4) in Table 7 believed that improper installation of seals was a cause of failure.

Table 7. Identified sealing failure causes

Failure Causes	*Eng*	*Eng*	*Techni*	*Eng*	*Man*	*Techni*	*Fore.*	*Fore.*	*Pro Contr.*	*Man*	*Total*
Improper seal installation/assembly		1					1	1	1		**4**
Chemical corrosion		1									**1**
Fluids of high pulp consistency			1								**1**
Poor maintenance					1						**1**
Vibration due to misalignment							1				**1**
Unstable seal/cooling water supply								1	1	1	**3**
Dry running								1	1		**2**
Seal pipeline blockage									1		**1**
Foreign material on the seal chamber									1		**1**

4.1.2.4. Bearing Failures

The results in Table 8 indicate a lack of lubrication (RII=0,86) as the main cause of bearing failure, followed by mechanical stress with RII=0,84.

Table 8. Descriptive statistics for bearing failure causes

Failure Cause	SD (1)	D (2)	N (3)	A (4)	SA (5)	Total Number (N)	RII	Ranks
Lack of lubrication	1	0	0	12	30	10	0,86	**1**
Mechanical stresses	0	0	6	16	20	10	0,84	**2**
Damaged inner & outer race	0	2	3	20	15	10	0,8	**3**
Misalignment of baseplate & concrete	2	0	3	12	20	10	0,74	**4**
Water ingress from the seals	2	0	3	12	20	10	0,74	**4**
Corrosion	0	4	9	16	5	10	0,68	**5**

The respondents were asked to provide the additional causes of bearing failures that they experienced. Approximately twelve failures were identified. Most participants (n=3) in Table 9 stated that poor maintenance caused bearing failure.

Table 9. Identified bearing failure causes

Failure Causes	*Eng*	*Eng*	*Techni*	*Eng*	*Man*	*Techni*	*Fore.*	*Fore.*	*Pro Contr.*	*Man*	*Total*
Overheating		1									1
Overloading		1									**1**
Pumping highly corrosive fluids			1								**1**
Poor maintenance					1			1	1		**3**
Poor lubrication							1				**1**
Incorrect bearing assembly							1				**1**
Misalignment							1		1		**2**
Fretting								1	1		**2**
Thrust								1	1		**2**
Loose base bolt								1			**1**
Excessive leak of glands								1	1		**2**
Bearing housing wear/damage		1							1		**2**

4.1.2.5. Motor Failures

Table 10 lists the root causes associated with motor failure. The results indicated that the foundation defect was leading (RII=0,9). All the other elements had an RII=0,78 except for impeller imbalance, which had a slightly lower RII of 0,74.

Table 10. Descriptive statistics for motor failure causes

Failure Cause	SA (1)	D (2)	N (3)	A (4)	SA (5)	Total Number (N)	RII	Ranks
Foundation defects	0	0	6	24	10	10	0,8	**1**
Wear in bearings	1	2	0	16	20	10	0,78	**2**
Broken rotor bar	0	2	3	24	10	10	0,78	**2**
Stator winding	1	2	3	8	25	10	0,78	**2**
Electric faults	1	0	6	12	20	10	0,78	**2**
Vibration	1	0	6	12	20	10	0,78	**2**
Impeller imbalance	2	0	3	12	20	10	0,74	**3**

The respondents were asked to provide the additional causes of motor failures that they experienced. Approximately 11 failures were identified, and most participants (n=2) in Table 11 mentioned that water ingress to the motor, overheating, overloading, and short circuits were the reasons for motor failures.

Table 11. Identified motor failure causes

Failure Causes	***Eng***	***Eng***	***Techni***	***Eng***	***Man***	***Techni***	***Fore.***	**Fore.**	***Pro Contr.***	***Man***	***Total***
Misalignment		1									1
Shaft imbalance		1									**1**
Oversized impeller		1									**1**
Mech breakdown due to cross-motor stress			1								**1**
Poor motor selection				1							**1**
Seized bearings					1						**1**
Overloaded processes					1						**1**
Water ingress to motor						1	1				**2**
Overheating due to dry pulp blocking ventilation								1	1		**2**
Overloading								1	1		**2**
Short circuit								1	1		**2**

4.1.2.5. Cavitation

Insufficient NPSH availability (RII=0,92) is indicated as the main root cause of cavitation (see Table 12). All other elements had an RII of 0,86.

Table 12. Descriptive statistics for cavitation causes

Failure Cause	**SD (1)**	**D (2)**	**N (3)**	**A (4)**	**SA (5)**	**Total Number (N)**	**RII**	**Ranks**
Insufficient NPSHa	0	0	3	8	35	10	0,92	**1**
Vaporization	0	0	6	12	25	10	0,86	**2**
Entry of outside air into the system	0	0	9	4	30	10	0,86	**2**
Leakage on the suction side	0	0	3	20	20	10	0,86	**2**
NPSHa < NPSHr	0	0	6	12	25	10	0,86	**2**

The respondents were asked to provide the additional causes of cavitation that they experienced. Eight failures were identified, and most participants (n=3) mentioned that poor pump design was the main cause of cavitation (Table 13).

Table 13. Identified cavitation causes

Failure Causes	***Eng***	***Eng***	***Techni***	***Eng***	***Man***	***Techni***	***Fore.***	**Fore.**	***Pro Contr.***	***Man***	***Total***
Restricted suction flow		1									1
Pipe blockage on the suction side		1									**1**
Selection of undersized pump			1								**1**
Poor design consideration				1				1	1		**3**
Improper priming							1	1			**2**
Blocked suction strainer							1				**1**
Low level of pulp tank									1		**1**
No non-return valve									1		**1**

4.2 Graphical Results

4.2.1 Maintenance Strategies

Most participants (80%) in Figure 1 indicated that a preventative (scheduled) maintenance strategy was used in the pulp and paper mill.

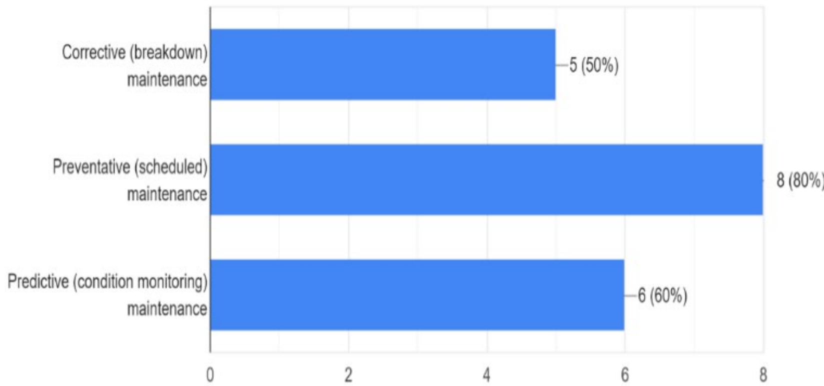

Figure 1. Maintenance strategies

4.2.2 Machine Learning Methods to Select Optimum Maintenance Strategy

Figure 2 shows that 60% of the participants indicated that the pulp paper mill used the analytic hierarchy process(AHP).

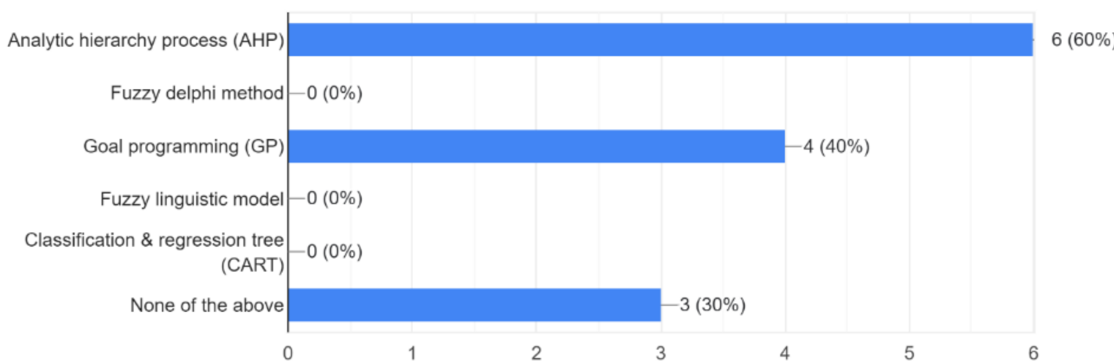

Figure 2. Machine learning methods to select optimum maintenance strategy

4.2.3 Machine Learning Methods for Failure Detection

As shown in Figure 3, the majority of the participants (70%) indicated that vibration signals and smart sensors were used for failure detection.

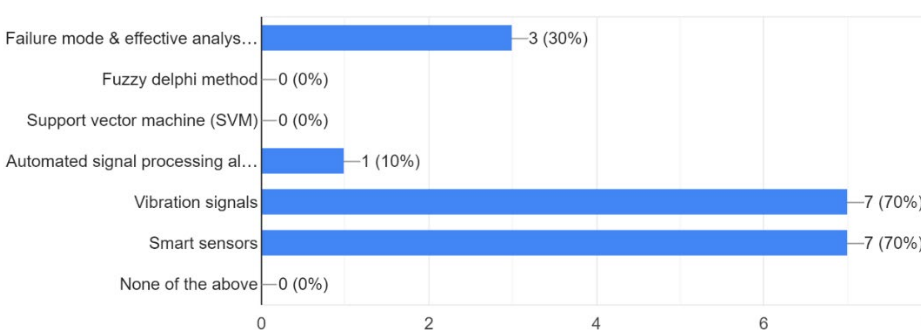

Figure 3. Machine learning methods for failure detection

4.3 Operational Data Analysis
For this study, historical data on 14 centrifugal pumps that experienced malfunctions or failed during the previous five years, from 2019 to 2023, were used. There were nine single-stage centrifugal pumps and five multistage pumps among the 14 pumps. The following section presents the results of the statistical analysis and identification of failure modes from historical data.

4.3.1 Trend Analysis Plot
The trend analysis plot in Figure 4 shows that the life of the pump decreased with time. Pumps 1 and 2 were installed in 2020 and failed after 122 days, whereas pump 6, installed in 2007, failed after 5936 days, as shown in Figure 4.

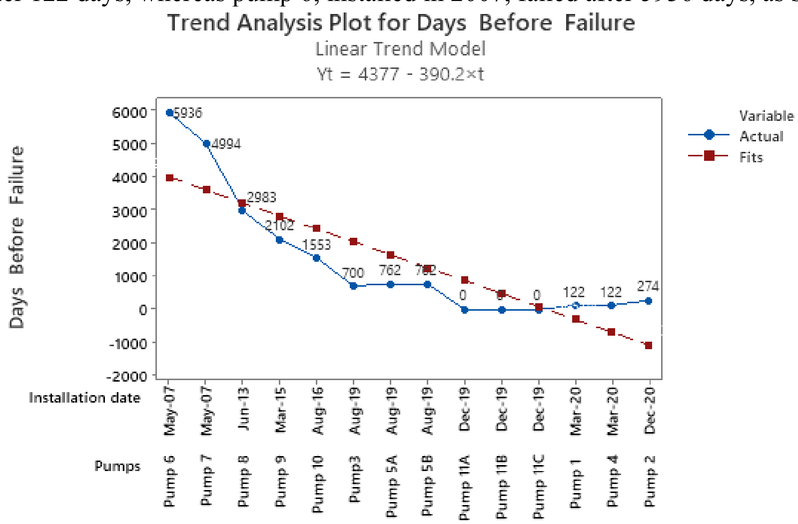

Figure 4. Trend analysis plot

4.3.2 Goodness of Fit Test
The study obtained the smallest Anderson-Darling (AD) number of 1,474 on the loglogistic distribution, indicating that this was the best model for the selected data. However, practitioners frequently use the Weibull distribution to model failure times in reliability analysis because it is highly flexible and allows for the modelling of multiple types of failure with a single distribution (Olteanu and Freeman, 2010). As a result, a Weibull distribution with an AD number of 1,516 was chosen and used in this study.

4.3.3 Weibull Distribution Analysis
The pumps under study have been identified to have a decreasing life span over time, with a shape parameter of 0.947, scale parameter of 1929.42, and mean life of 1977.79 (see Figure 5).

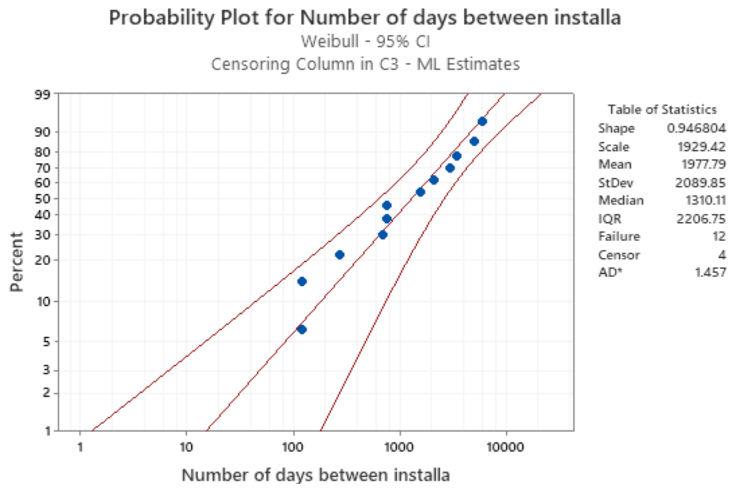

Figure 5. Probability plot

4.3.4 Failure Modes

Figure 6 shows a Pareto chart depicting all the failure modes discovered in these pumps. A mechanical seal (n=6) is a failure mode or subsystem responsible for the majority of centrifugal pump failures.

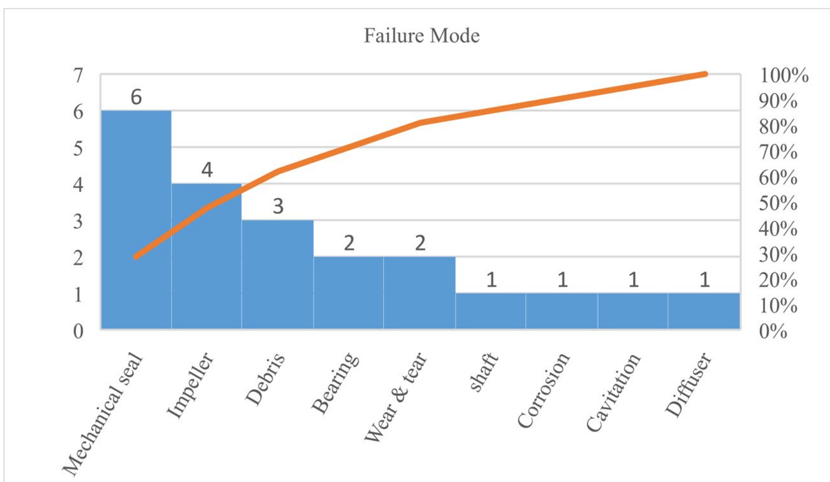

Figure 6. Pump failure mode

4.4 Proposed Improvements

The study examined the operational data of a pulp and paper mill and found that the average lifespan of centrifugal pumps is 4.5 years, with some failing even sooner. Although machine learning methods are not commonly used in mills, similar issues have been identified using neural networks and failure mode and effective analysis (FMEA) for failure diagnosis. The study discovered that mechanical seals were the primary cause of pump failure, primarily owing to incorrect sealing system design. To improve seal design, the study recommends using finite element analysis and simulations. The main causes of pumping system failures include misaligned components, poor lubrication, wear and tear owing to inadequate maintenance, and foreign objects. The study found that 80% of the participants utilized scheduled maintenance, while 60% and 50% used condition monitoring and breakdown maintenance, respectively. The mill should aim to minimize breakdown maintenance because it is not effective and can cause delays during repair processes. The study recommends considering machine-learning methods for selecting a suitable maintenance strategy.

4.5 Validation

The reliability and validity of the terms were used to assess the research quality. Validity is concerned with a measure's precision, whereas reliability is concerned with its consistency (Hasan *et al.*, 2021). This study used triangulation to ensure reliability and validity. Triangulation is used to assess and improve the validity of research findings (Ghrayeb et al. 2011). It helps improve the credibility and validity of the study, making use of multiple data sources reduce the research biases in sampling, procedural bias, and researcher biases, thus increasing validity and credibility (Bans-Akutey and Tiimub, 2021). Findings from the literature review were used to populate the questionnaire. The results from the questionnaire, operational data, and literature review were compared to make sound conclusions and recommendations.

5. Conclusion

This study investigated centrifugal pump failures using three sources: literature review, questionnaire, and operational data. This study also examined the strategies and methods used to ensure pump reliability. The results showed that there is little to no use of machine-learning methods for selecting optimal strategies and fault detection. The study helped identify the blind spots of both pump manufacturers and users, that is, pulp and paper mills, and made the necessary recommendations to improve the reliability of centrifugal pumps. Poor maintenance, misalignment of CP components, lack of lubrication of bearings and seals, poor installation of the base plate, use of incorrect seal arrangement, poor design of the pump system and its components, and ingress of foreign objects into the pump system are the main causes of CP failure. The study was based on a single paper mill. Future research should include more companies and benchmark strategies to improve CP reliability in the global market.

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