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Implementation of Failure Mode and Effects Analysis in the Maintenance Strategy for the Main Engine Cooling Pump of Fishing Vessels

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Abstract

The performance of the main engine of a fishing vessel becomes less than optimal when its cooling system does not function properly. Centrifugal pumps, as an important component of the cooling system, require special attention in selecting maintenance methods to maintain stable performance. This is because centrifugal pumps are often used on fishing vessel, not marine pumps. This research aims to investigate the maintenance strategy of centrifugal pumps in the cooling system of the main engine of a fishing vessel. The Failure Mode and Effects Analysis (FMEA) method is used to analyze maintenance strategies based on RPN (Risk Priority Number) values. The resulting RPN value can indicate the maintenance strategy that needs to be carried out. The highest RPN value and the failure mode category that requires special attention are analyzed using a histogram diagram. While the root cause of failure is clarified with a fishbone diagram. The results show that the highest failure mode is damage to the pump impeller due to corrosion. The main cause of this failure is found in the selection of impeller materials that are less suitable for working conditions and the environment. Predictive maintenance strategies are considered as a solution to overcome pump impeller problems. This research provides insight into choosing the right maintenance strategy, especially for fishing vessel engines.

1. Introduction

The performance of the diesel engine on a fishing vessel directly impacts its propulsion system, as the engine operates continuously for 24 hours, often for weeks or even a month [1]. Generally, the diesel engines used on fishing vessels are not original marine engines, but are modified versions of commonly used diesel engines. To ensure optimal engine function, operators must closely monitor the engine's operational parameters. A decline in the main engine's performance can significantly affect the ship's propulsion system [2]. One key factor in maintaining engine performance is stabilizing the operating temperature, which relies on an effective cooling system. The main components of the cooling system are heat exchangers and pumps, which transfer heat within the system [3]. The centrifugal pump is crucial in circulating cold seawater to reduce water temperature in the engine cooling system [4]. If the pump fails during operation, the cooling circulation is disrupted, potentially causing the engine to overheat [5]. Pump failure can occur due to inadequate maintenance or reliability issues, with common causes being damage to the impeller, bearings, seals, or pump structure [6], [7], [8] Therefore, proper pump maintenance is essential to ensure uninterrupted vessel operations.

The operational reliability of machinery depends largely on maintenance activities designed to reduce the likelihood of unexpected failures [9]. Such failures can lead to unplanned downtime [10]. Machine maintenance often requires significant time, effort, and resources to ensure smooth operation. As machine reliability increases, so does the demand for maintenance resources [11]. Tan and Kramer [12] noted that maintenance costs can account for 20-30% of total operating budgets, highlighting the need for efficient maintenance strategies. Ineffective maintenance strategies can quickly lead to significant losses in performance [13]. Therefore, a well-planned and efficient maintenance strategy is critical. Many researchers argue that Reliability-Centered Maintenance (RCM) and Failure Modes and Effects Analysis (FMEA) are two of the most effective maintenance techniques for addressing various machine maintenance challenges [14]. FMEA, a structured method for preventing failure, is one of the most used techniques [15]. It has been widely applied to determine machine maintenance strategies [16], [17].

Several studies have applied the FMEA technique to develop maintenance strategies. For example, Siahaan et al. [9] used FMEA to determine a risk-based maintenance strategy for refrigeration systems on fishing vessels, prioritizing the highest-risk components. Similarly, FMEA has been applied to water distribution system pumps, where three categories of maintenance techniques were implemented based on RPN values [18]. FMEA has also been used in power distribution systems to develop reliability-based maintenance strategies, resulting in a 7% reduction in the maintenance budget [19]. Additionally, Scheu [20] used the FME(C)A framework to identify critical failure modes in wind turbine systems, leading to improved prevention and optimized industrial operations. Centrifugal pump failure can originate from the impeller component due to inappropriate use of pump loads [5]. The use of FMEA-based maintenance in overcoming and preventing repeated failures in centrifugal pumps can be implemented in the centrifugal pump operating system [18]. These studies demonstrate that FMEA is a widely used and effective technique for determining engine maintenance strategies.

However, despite numerous studies on the use of FMEA for engine maintenance strategies, research on centrifugal pump maintenance in the diesel engine cooling systems of fishing vessels remains limited. Additionally, few studies have focused on engine maintenance strategies for fishing vessels, despite their significance for further development. This article aims to investigate suitable maintenance strategies for centrifugal pumps in the main engine cooling systems of fishing vessels. The research also classifies critical failures using a histogram to identify key components in pump operations. This research provides valuable insights into the development of maintenance strategies for centrifugal pumps.

2. Methods

FMEA is an engineering technique used to analyze and identify problems and causes of failures based on known and potential events of a system or item. FMEA is an important tool that is widely used in analyzing the reliability of a system or item [21]. The main advantage of this method is increasing user satisfaction through increased reliability and reducing the occurrence of failures. By reducing the chances of failure, this method can also improve workplace safety by minimizing the risk of injury and negative impacts on the work environment. In the last decade, FMEA has become the most used technique to analyze the risk of system or item failure [22]. Historically, FMEA was first published as FME(C) A in the US Armed Forces Military Procedure document. In the 1960s, NASA began implementing FMEA with the names of different aircraft components [23].

2.1. The FMEA Procedure

The implementation of FMEA begins with selecting the system or item to be analyzed. This selection can involve a machine based on various events or its operational history. It is crucial to clearly understand the relationship between the machine and its working environment to determine the potential impacts and causes of failures. The procedure for implementing FMEA in analysis is illustrated in Figure 1 [13], [24]. Once the scope of FMEA has been defined, the subsequent investigation plan is as follows:

1. Initiating the Machine: Begin the analysis with the main engine cooling system of the fishing vessel, which is deemed important and critical based on its operational history.
2. Categorization and Classification: Categorize and classify the components found within the machine being analyzed.
3. Functional Identification and Failure Mode: Identify the function and potential failure modes of each categorized component. Each component's function should be described based on its characteristics.
4. Analysis of Causes and Mechanisms of Failure Modes: Analyze the causes and mechanisms behind each failure mode in the selected machine components. Determine the impact and influence of each failure mode on the machine and its environment. The assessment of failure impacts should be based on the level of hazard identified.
5. Failure Potential Determination: Evaluate the potential risks associated with each machine component's failure mode. Develop a detection control design to identify the failure modes and their impacts. Assess the feasibility of each arrangement by analyzing the rankings provided.
6. General Hazard Assessment: Conduct a general hazard assessment of the failure modes using the Risk Priority Number (RPN), which is calculated by multiplying the severity, occurrence, and detection parameters. A high RPN value indicates a greater hazard associated with the failure mode.
7. Recovery Procedure Recommendation: Recommend recovery procedures aimed at reducing the identified hazards.

This process aids in identifying potential risks while prioritizing and formulating the necessary corrective actions to enhance the reliability of the system or machine.

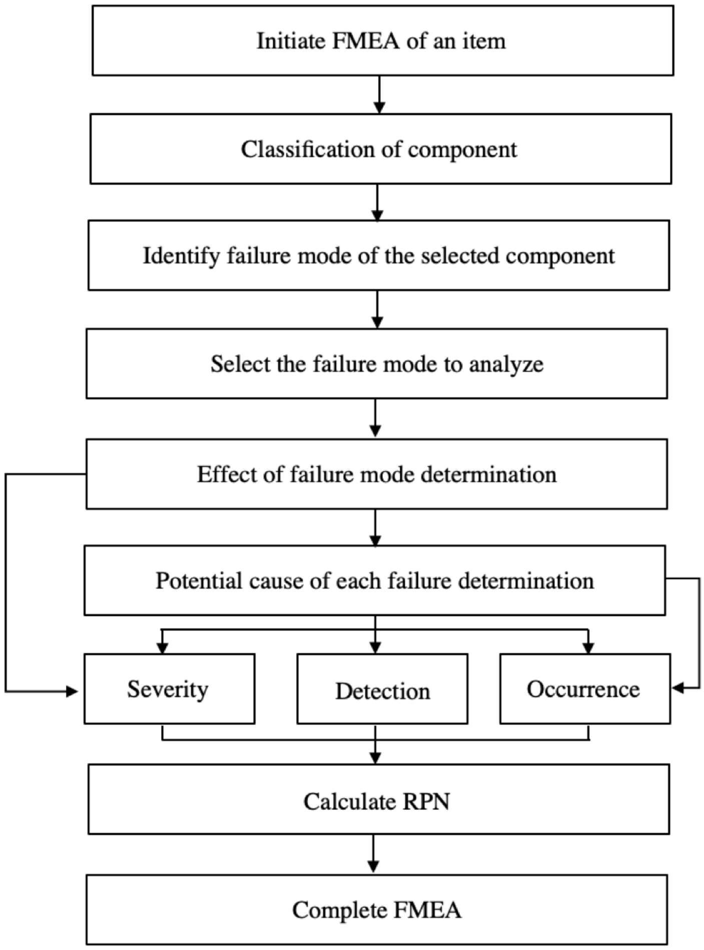

Figure 1. Flow chart for the procedure of FMEA

Table 1. Ranking of parameter indices (S, O, and D) for RPN estimation

Effect	Severity Level (S)	Probability of Occurrence (O)	Detection Criteria (D)	Rating/ Scale
Hazardous	The effects of failure are hazardous to user safety	Extremely high: failure is nearly inevitable (1-2 times in operation)	Impossible to detect failure	10
Very high	The effects of failure are harmful to user safety	Very high: failure is nearly inevitable (3-4 times in operation)	It is very difficult to detect the failure	9
High	Component not suitable for operation	High: recurrent failures, a process that has failed frequently (5-8 times in operation)	It is difficult to detect the failure in detail	8
Moderately High	High degradation from non-functioning components	High: frequent failures, a process that has failed multiple times (9-20 times in operation)	It is difficult to detect the failure directly	7
Moderately Low	The user must replace damaged components	Moderate: rare failures that have a minor impact (21-80 times in operation)	There are ways to detect failures	6
Low	Damaged components must be replaced by the user	Moderate: occasional failures with minimal impact (81-400 times in operation)	There is an opportunity to detect failures	5
Very Low	Failures can be noticed by the user in detail	Low: similar processes have a relatively low incidence of failure (401-2000 times in operation)	Quite a high chance of detecting failure	4
Very Remote	Failures can be noticed by users immediately	Low: only a small number of failures occur in similar processes (2001-15000 times in operation)	It may be possible to detect failures with the naked eye	3
Remote	A failure has occurred that has no effect	Remote: failure is nearly impossible (More 15001 times in operation)	It is possible to detect failures with the naked eye	2
None	The failure is tiny and does not affect performance	Failure is unlikely	Can immediately detect failures with the naked eye	1

2.2. Data Collection

Primary data used for the assessments of Severity, Occurrence, and Detection includes information about engine components that are critical to engine operations, as well as data on component failure modes, severity level assessments, potential frequencies of failure occurrences, and detection capabilities for these failure modes. Data collection on the main engine components of the ship and their operational mechanisms was conducted directly on the cooling system of a fishing vessel located in the Batam area, Indonesia. The assessments of Severity, Occurrence, and Detection levels for engine component failure modes were performed through interviews with three experts involved in repairing and diagnosing engine failures. The positions of the experts and coding for FMEA assessment are the chief engineer (N1), the head of the engine workshop (N2) and the assistant head of the engine workshop (N3). The results of the qualitative assessment are converted into quantitative based on the parameter index in the next section. To conduct these interviews using a questionnaire, ethical clearance was necessary. This research has obtained ethical approval from KEP UAD (Komite Etik Penelitian Universitas Ahmad Dahlan) under the number 022407090. Ethical clarity is used to ensure the safety, rights and welfare of research subjects, reduce the risk of refinement in the research process and ensure the research process runs well, based on integrity and ethics. This is used because in current research, humans are used as research subjects as sources and materials for data collection.

2.3. Indexed Parameters

FMEA techniques are utilized not only to identify potential failure modes but also to prioritize these modes based on expert assessments using specific index parameters. Generally, the most critical failure priorities can be determined and calculated through the Risk Priority Number (RPN). This is achieved by multiplying the Severity (S), Occurrence (O), and Detection (D) indices of each failure mode associated with the machine component.

i. Severity (S)
Severity assesses the level of criticality regarding the impact of potential hazards that may arise. The S score is evaluated based on the consequences caused by the failure mode.
ii. Occurrence (O)
Occurrence pertains to the frequency of potential failures under specific conditions or frameworks. The likelihood score is determined by evaluating how probable it is for the failure mode to occur.
iii. Detection (D)
Detection ability refers to the likelihood of identifying failures before their adverse impacts manifest in the evaluated procedure or framework. The D score is assessed based on the capacity to recognize the outcomes of the failure mode.
iv. Risk Priority Number (RPN)
RPN is derived from ranking three input data sources (Severity, Occurrence, and Detection) and is instrumental in assessing the risk of failure.

$$RPN = Severity\ (S) \times Occurrence\ (O) \times Detection\ (D) \tag{1}$$

RPN serves as a guide for ranking potential failures and identifying recommended actions for modifying maintenance strategies to reduce the severity or frequency of failures. The parameter index rankings used for RPN estimation are detailed in Table 1.

2.4. Determining maintenance strategy

The results of the RPN estimation are presented in the form of a bar chart (histogram) and analyzed against critical limits. The objective of this critical RPN analysis is to identify which components should be prioritized for maintenance actions. The calculation of critical RPN values can be performed using Equation 2 [25].

$$RPN_{Critical} = \frac{Total\ RPN}{Number\ of\ failure\ modes} \tag{2}$$

Data processing for RPN estimation is conducted using a Pareto diagram. This type of histogram is utilized to analyze critical areas or components by identifying that 20% of failure types contribute to 80% of all failure modes. Consequently, the Pareto diagram helps in pinpointing critical points within the system. Once the causes of component failure are identified, the next step is to establish a maintenance strategy for each failure mode or component. This maintenance strategy is based on the RPN estimation value. The classification of RPN estimation values, along with the recommended maintenance strategies, is presented in Table 2 [26].

Table 2. Strategic Maintenance based of RPN criteria

Rank	Strategic Maintenance	Criteria
1	Predictive Maintenance	RPN > 300
2	Preventive Maintenance	200<RPN<300
3	Corrective Maintenance	RPN <200

2.5. Root Cause and Failure Analysis (RCFA)

Root Cause Failure Analysis (RCFA) is a method commonly employed to identify potential root causes of failures in a system or machine component. Typically, the cause of a failure is not attributable to a single factor but rather to a combination of various interrelated factors. In this study, the Ishikawa or fishbone diagram is utilized as an analytical tool. This diagram is a comprehensive method for examining all possible causes of failure along with the influencing factors, earning it the alternative name of a cause-and-effect diagram. This approach aids designers and process planners in anticipating future failures. The fishbone diagram considers several key factors when identifying the cause of failure, including humans, materials, methods, and machines [27] these factors are interrelated, and each identified cause is analyzed to determine the root cause of failure, based on observations and discussions with field experts.

3. Results and Discussion

3.1. Case Study

The subject of this research is a purse seine fishing vessel operating in the waters of Natuna, Indonesia. This fishing boat is powered by a 350 PS diesel engine (Nissan RD 10). The main engine operates with a cooling system that includes a heat exchanger, a centrifugal pump, and a sea chest. Figure 2 illustrates the block diagram of the cooling system for the main engine of the fishing vessel, which functions by circulating freshwater that is cooled by seawater. Figure 3 shows the centrifugal pump utilized in the cooling system of the main engine. The centrifugal pump is a critical component of the engine cooling system, responsible for dissipating excess heat to ensure optimal engine performance [5]. It circulates water to cool the engine [28]. Recently, the centrifugal pump has exhibited a significant decrease in performance when delivering coolant fluid. Failures in the centrifugal pump may manifest as issues such as bearing failures, seal failures, and other structural problems. The most common failure encountered is the pump's inability to transfer water for cooling the main engine. Given the importance of the pump in the cooling system, it requires careful attention in maintenance practices. Based on the case study conducted, further investigation and maintenance recommendations for the centrifugal pump are essential to prevent future failures. Crucial components within the centrifugal pump–such as the casing, impeller, seal, shaft, pulley, belting, and bearing–were identified through direct observation and interviews, supported by existing literature.

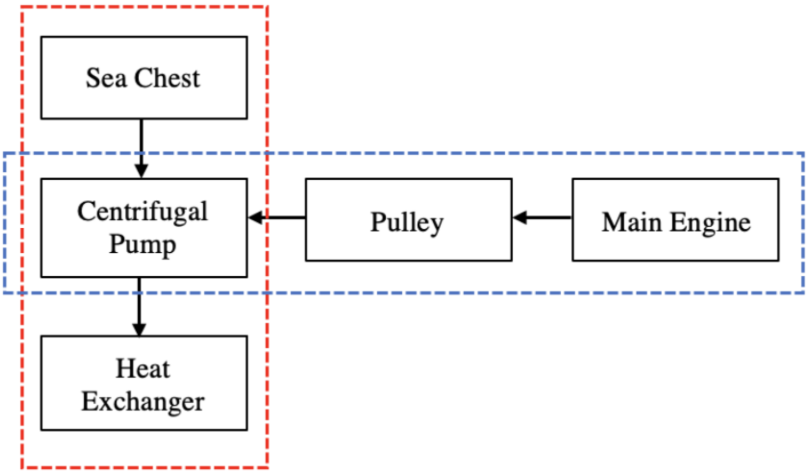

Figure 2. Block diagram cooling system of fishing vessel main engine

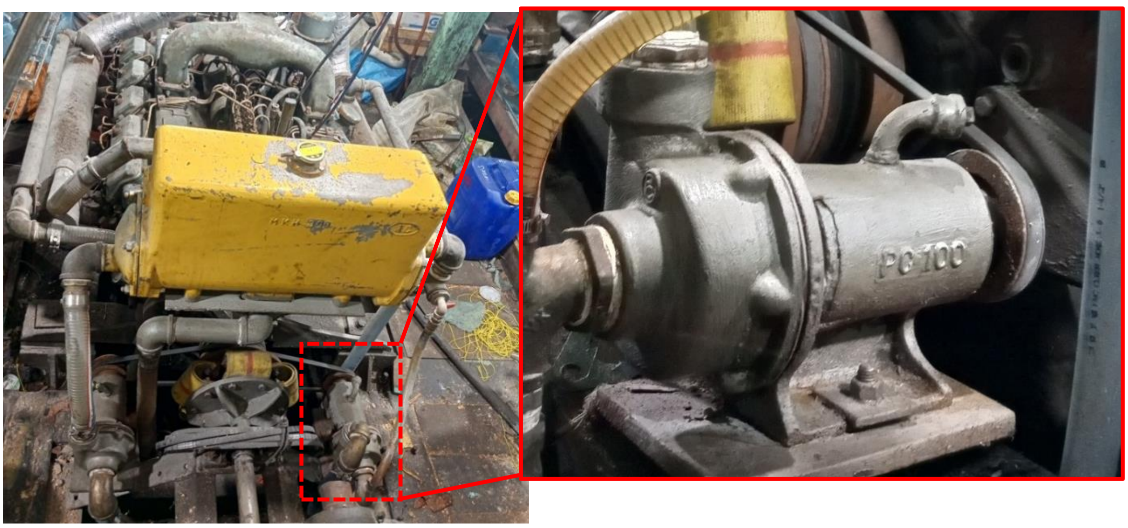

Figure 3. Centrifugal pump on fishing vessel main engine

3.2. Failure Mode and Effect Analysis (FMEA)

In this investigation, the centrifugal pump is analyzed as a means of transferring fluid within the cooling system of the main engine. The centrifugal pump examined is a common type used in these systems. Based on interviews and direct observations, seven main components of the centrifugal pump were identified. Through this analysis, eleven potential failure modes were detected, some of which could lead to severe damage to the pump and result in a shutdown of the main engine. Consequently, a detailed analysis was conducted to identify all functions, potential failures, causes of these failures, impacts, and detection methods. All failures in the pump components were further studied to prioritize maintenance efforts [29] Table 3 presents the types of failures and their classifications, including causes and detection methods, in the form of an FMEA table. This table serves as a basis for assessing the Risk Priority Number (RPN) established in previous sections. Among the seven components, eleven failures were identified and labeled from F1 to F11.

The evaluation results were based on the indices provided by three different experts, utilizing their opinions and experiences. Table 4 displays the results of the evaluations, which include the parameters of Severity (S), Occurrence (O), and Detection (D). The RPN value is obtained from the average of the three experts' (N1, N2 and N3) assessments of the parameter index. The three values are then averaged, which were validated through field observations [30]. The highest RPN values recorded were as follows: F3 with a value of 327.4, F4 with 314.8, and F6 with 272.9. Conversely, the three lowest RPN values were F8 at 3.6, F1 at 4.7, and F2 also at 4.7. The highest RPN values indicate that these failure modes are critical [18], [31]. In this research, the highest potential failure modes are associated with the impeller, which exhibited the two highest failure modes, F3 and F4. The impeller is a crucial component for the proper functioning of the pump [32]. It is responsible for converting the torque applied to the pump shaft into pressure and kinetic energy in the fluid being pumped. The highest RPN for F3 (327.4) consists of the following parameter values: S = 6.7, O = 5.7, and D = 8.7. The Severity (S) indicates that failure mode F3 could significantly impair pump performance, necessitating component replacement during a failure event. The Occurrence (O) suggests a moderate frequency of this failure during pump operation. Meanwhile, the Detection (D) indicates that a complete disassembly is required to inspect for failure. This failure mode leads to a decline in pump quality, potentially causing a drop in pressure or failure to transfer fluid effectively [5].

Table 3. FMEA for centrifugal pump

Component	Function	Potential Failure Mode	Reason for Potential Failure Mode	Effect of Potential Failure Mode	Detection of Failure mode
Cover	The housing for all pump components.	Crack/ Leak (F1)	The impact is caused by other work and seawater corrosion	The pump can still operate, but it needs to be closely monitored	Direct Observation or NDT Inspection
		The thick cover is becoming thinner (F2)	Corrosion caused by seawater and atmospheric conditions	The pump is operational, but it is not performing optimally	Directly view and measure
Impeller	The blade creates centrifugal force, allowing the water to be pumped	Surface corrosion (F3)	Erosion corrosion caused by corrosive fluids	A low-powered pump can still move water	Disassemble the entire pump and examine the components.
		Cavitation (F4)	High pressure caused by the inlet filter, which can become clogged	The pump is unable to pump or draw water.	Disassemble the entire pump
Seal	The border bearing between the shaft, impeller, and pulley	Leakage (F5)	The seal is torn due to improper installation	The pump is unstable, turning on and off	Disassemble part of the side for inspection.
		Rigid Seal (F6)	Seal fatigue	The pump operates but does not draw or push water.	Disassemble a portion of the side for inspection
Poros	The component that transmits energy from the motor's rotation to the impeller	Vibrations are occurring in the pump (F7)	Misalignment in the installation of the pump shaft	The pump is vibrating and noisy	Measure vibrations using a measuring instrument
Pulley	The connector that transmits rotation from the dynamo to the pump shaft.	Stuck / unable to move (F8)	Wear on the spi section within the pulley	The pump is not operating at maximum efficiency	Visually inspect

Belting	The rubber connector from the dynamo to the pulley.	The belt is broken (F9)	Misaligned belting causes the belt to wear out	The pump is not functioning	Visually inspect
Bearing	The wheels that rotates the shaft in place	The shaft rotation is heavy and noisy (F10)	Vibrations occurring in the pump	The pump vibrates and is noisy	Disassemble part of the component's side
		The rolling component is worn out. (F11)	Bearing fatigue	The pump is moving slowly	Disassemble part of the component's side

3.3. Pareto Diagram′s

Critical components that contribute to failures in a system can be identified using the Risk Priority Number (RPN) threshold, based on the average RPN value across all components. Figure 4 illustrates the failure modes of the centrifugal pump along with their critical RPN limits. According to the Figure 4, the critical RPN threshold is set at 135.5. Several failure modes, including F3, F4, F5, F6, and F11, exceed this threshold, indicating they require special attention in maintenance strategies [18] consequently, specific components warranting focus for maintenance include the impeller, mechanical seal, and bearing, all of which have surpassed the standard maintenance priority threshold based on the calculation results [33].

Table 4. Estimated value of index parameter and RPN metrics

Component	Failure Mode	Severity				Occurrence				Detection				RPN
		N1	N2	N3	Average	N1	N2	N3	Average	N1	N2	N3	Average	
Casing	F1	2	3	2	2,3	2	3	1	2,0	1	1	1	1,0	4,7
	F2	2	2	2	2,0	2	3	2	2,3	1	1	1	1,0	4,7
Impeller	F3	7	7	6	6,7	5	6	6	5,7	9	9	8	8,7	327,4
	F4	7	7	6	6,7	5	6	6	5,7	9	8	8	8,3	314,8
Mechanical Seal	F5	7	7	6	6,7	6	4	6	5,3	7	8	6	7,0	248,9
	F6	7	7	6	6,7	6	4	6	5,3	8	8	7	7,7	272,6
Poros	F7	4	3	3	3,3	4	3	2	3,0	5	6	6	5,7	56,7
Pulley	F8	2	2	2	2,0	2	1	1	1,3	1	1	2	1,3	3,6
Belting	F9	7	8	8	7,7	2	2	1	1,7	1	1	2	1,3	17,0
Bearing	F10	4	4	3	3,7	5	2	2	3,0	7	8	8	7,7	84,3
	F11	7	6	7	6,7	5	2	3	3,3	7	7	7	7,0	155,6

In addition to the standard maintenance priority threshold, the Pareto diagram is utilized to identify the dominant types of failures in the pump by examining the cumulative RPN values for each failure mode. The Pareto principle asserts that 80% of problems stem from 20% of the primary causes of overall machine failures [34]. Figure 5 presents the Pareto diagram for the failure modes of the centrifugal pump in the main engine cooling system. The diagram indicates that the failure modes requiring attention are F3, F4, F5, and F6, which are related to the impeller and mechanical seal components. This highlights the need for targeted maintenance actions to ensure effective pump operation. From the analysis of both the RPN threshold and the Pareto diagram, the intersecting failure modes that require attention are F3, F4, F5, and F6.

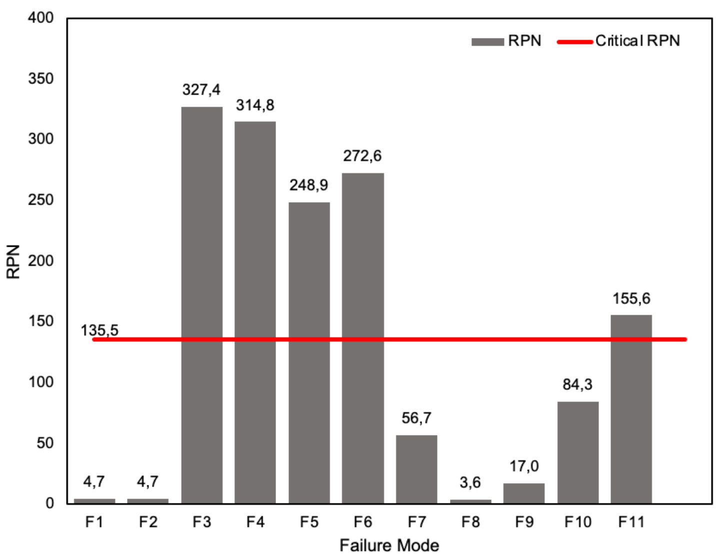

Figure 4. Classification of RPN diagram of failure mode on centrifugal pump

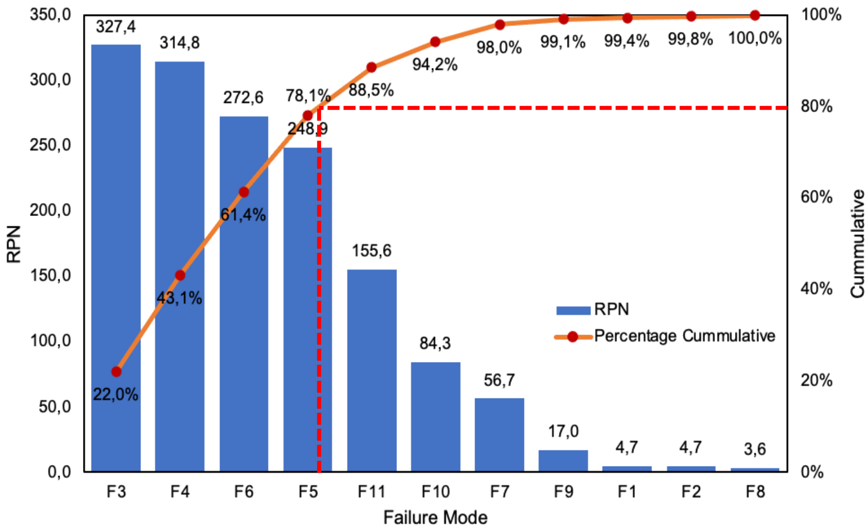

Figure 5. Pareto chart of failure mode on centrifugal pump

3.4. Cause and effect

After obtaining the RPN values and analyzing all failure modes of the centrifugal pump, the highest value is associated with mode F3, indicating issues with the impeller. Mode F3 is indicated as the highest failure mode and is of concern according to the assessment of experienced experts working on the research object. The failure of the impeller is fundamentally influenced by several contributing factors. To analyze the root causes of component failures related to the pump in the cooling system of the fish-catching vessel, a fishbone diagram is employed. The factors considered in this analysis include Machine, Man, Method, and Material [35]. Figure 6 illustrates the failure analysis of the impeller, showing how each category is interconnected and breaking down into sublevels to identify root problems. Based on interviews with experts, eight root causes of failure have been identified. Among these, the primary issue arises from material selection. The use of incorrect materials in the operation of the main engine cooling pump leads to suboptimal pump performance, ultimately contributing to the main engine's failure during operation. Impeller failure is a common occurrence in pump operations [36].

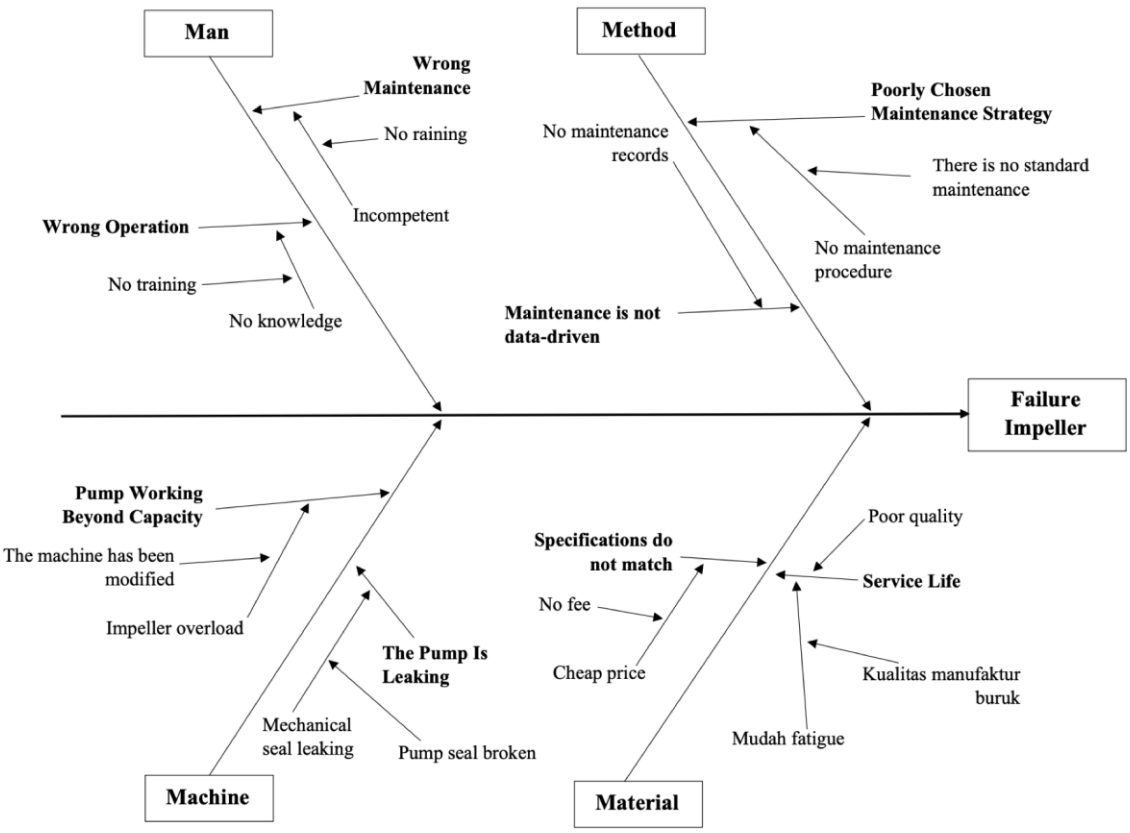

Figure 6. Fishbone diagram of failure impeller pump

Figure 7. Visual of the impeller component (personal documentation) that a) failed b) change material

Detailed observation and visual analysis are employed to investigate the causes of impeller failure. Prior research has indicated that impeller failure can be preceded by corrosion and cavitation [8]. Visual inspections revealed that the impeller suffers from uniform corrosion across its entire surface, as shown in Figure 7a. This figure illustrates that corrosion affects both the impeller blades and the outer surface, appearing as a foamy layer. Additionally, brass metals typically develop a residue layer due to corrosion products [37]. Another contributing factor may be cavitation within the pump, which can trap air and accelerate corrosion processes [5]. This analysis serves as an initial investigation into the visual indications of impeller failure.

3.5. Recommendation

Based on the RPN analysis for determining maintenance priorities, we have developed a maintenance action plan for the centrifugal pump. Figure 8 displays the RPN values for each failure mode along with the recommended maintenance actions, which are determined according to the RPN values [18]. Predictive maintenance is recommended for failure modes F3 and F4, while preventive maintenance is applicable to failure modes F5 and F6. Corrective maintenance is necessary for failure modes F1, F2, F7, F8, F9, F10, and F11. For predictive maintenance, it is crucial to replace materials in the components to prevent future failures, as indicated by the cause-and-effect analysis. The material replacement for the impeller, illustrated in Figure 7b, shows a transition from brass to stainless steel. This change is essential due to the significant impact of environmental and operational conditions on the impeller's performance. Additionally, to address cavitation, operational adjustments are required to ensure optimal pump functionality. For preventive maintenance, regular inspections, and adjustments to the alignment of the shaft during pump operation should be conducted to maintain efficiency.

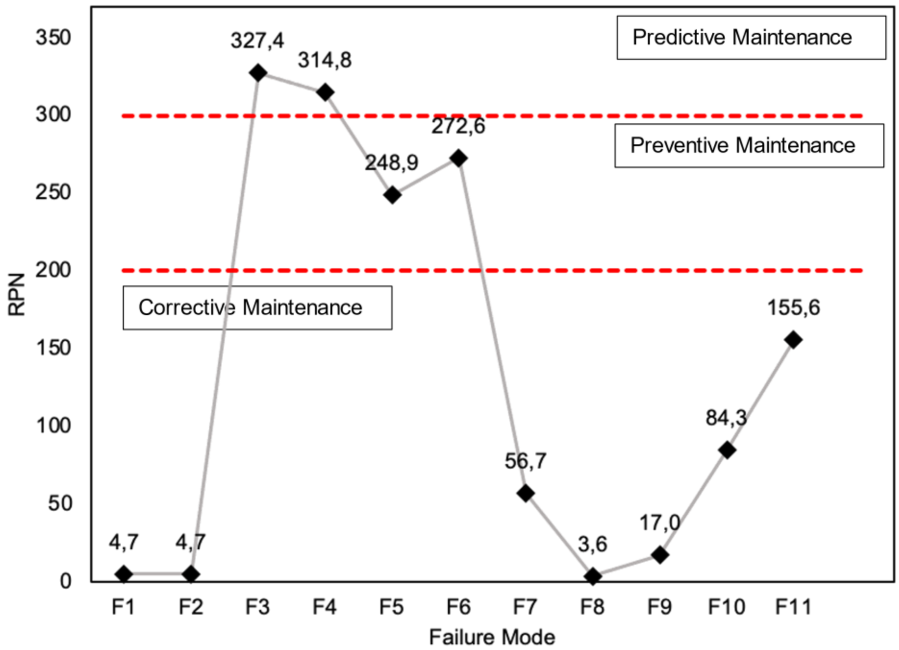

Figure 8. RPN classification based on maintenance strategy

4. Conclusion

The application of the FMEA method in analyzing maintenance strategies for centrifugal pumps in the cooling systems of fishing vessels has been investigated. The failure mode with the highest RPN value was identified as corrosion on the impeller surface (F3), followed closely by cavitation on the impeller (F4), with RPN values of 327.4 and 314.8, respectively. In total, there are four failure modes associated with two key components (the impeller and the mechanical seal) that require special attention in the maintenance process. The root cause of these high-priority failure modes has been determined to be the unsuitable material design for the operational conditions and environment. As a result, predictive maintenance is recommended for the impeller, while preventive maintenance should be applied to the mechanical seal. Selecting the appropriate maintenance strategy is crucial for enhancing the operational efficiency of the centrifugal pump. Future research should focus on improving material analysis for the impeller, considering the specific operational conditions and environmental factors.

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