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The New Framework Maintenance Optimization Using Reliability Centered Maintenance-FMEA

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ABSTRACT

PT XYZ-Banten is the largest power generation company in Southeast Asia with a total output power of 3400 MW. The production process at PLTU XYZ is a continuous process. Of the 6 pumping machines that operate, if one of the machines or equipment is damaged or fails, the entire process will be stopped. Boiler Feed Pump (BFP) is the pump machine with the highest damage rate, with a percentage of 60% of all pumps located at PT XYZ-Banten. This research aims to optimize maintenance to increase reliability and minimize downtime on the BFP pump. The stages of the research with maintenance analysis using the Reliability Centered Maintenance (RCM)-FMEA method to identify the causes of failure, the impact caused, the category of damage, and the actions to be taken. The results with the Reliability Centered Maintenance (RCM)-FMEA method show that the most critical component is ARV with its task selection Condition Derect (CD) and the maintenance interval period for each component, including ARV 73 hours, Pipe 334 Hours, Mechanical Seal 960 hours, and Scooptube 1080 hours. Finally, the proposed improvements with 5W + 1H for more reliable and efficient maintenance optimization. Management implications are expected to help companies prevent machine failures and determine other factors that cause these failures.

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1. INTRODUCTION

In general, steam energy generation consists of seven main components, namely boilers, turbines, generators, transformers, water treatment, motors, and pumps. In the XYZ PLTU production process, the turbine is a very crucial component because it functions as a driving force that produces mechanical energy into kinetic energy (Chaudhuri *et al*., 2022). The Boiler Feedwater Pump (BFP) is one of the main equipment in the Turbine system, which plays a crucial role in the PLTU work cycle (Shokri & Fard, 2023). The function of the BFP is to send fill water, which is the raw material for the turbine to drive steam from the deaerator to the boiler (Moleda et al., 2020). BFP includes the pump machine with the highest damage rate, with a percentage of 60% of all pumps. Disruption in the BFP pump will cause the unit to experience derating, which can be caused by the formation of scale, corrosion, wear, leakage, as well as other losses derived from fluid flow in the BFP components.

Maintenance is the process of maintaining plant facilities and equipment and making necessary repairs, adjustments, and replacements to ensure satisfactory production operating conditions per the plan (George et al., 2022). Maintenance activities aim to ensure that assets run normally in the desired condition. The maintenance system can be observed to be a shadow of the production system (Tang et al., 2017). If the company's production system runs using a very high capacity, then the company's maintenance system will be better. System reliability can be improved through optimized required maintenance (Alvarez-Alvarado et al., 2022).

Maintenance activities are required for the BFP machine to function properly (de Jonge & Scarf, 2020). Preventive maintenance can be done before damage occurs (preventive maintenance) or after damage occurs (corrective maintenance) (Ullah et al., 2021). To reduce the downtime period and ensure the production process runs efficiently, preventive maintenance is very important to maintain the availability and reliability of equipment and systems (Prasetya et al., 2023).

Research (Sulistyo et al., 2022) obtained critical components of the wire feeder with an RPN value of 611, and the time interval for replacing wire feeder components was 10.1349 hours. Research by Eriksen et al. (2021) in the Sewing division with the Reliability Centered Maintenance (RCM) Method and Age Replacement obtained a critical component of the dynamo with an RPN value of 270, and the replacement time of the dynamo component when the component has operated for 16 days, and the component inspection time is 6 days. In research on the high frequency of machine breakdowns resulting in the cessation of the production process, it is necessary to apply machine maintenance using the RCM method to be more effective, as well as reduce the level of machine damage and the level of material loss (Suryana, 2021). From previous research, the results were obtained in the form of critical components and component replacement schedules (Pramesti and Susetyo, 2018; Rasindyo et al., 2015). Some of these studies focus on analyzing component replacement but do not analyze other factors that will cause the component to malfunction.

The application of the RCM-FMEA method for safety and environmental involvement will be the main priority (Kathiresan, 2021). This will result in better operational performance, lower operation and maintenance costs, increased equipment availability and reliability, components will last longer, and larger databases (Offshore & Matuszak, 2019). Increased individual motivation and better cooperation between parts of the installation. Through FMEA analysis to identify the most critical components that fail and the extent to which they affect system functionality, so that we can address critical components by performing appropriate maintenance (Sharma & Srivastava, 2018).

This study aims to plan maintenance policies using the reliability-centered maintenance (RCM) method and analyze other factors that will result in downtime on BFP machine components using the FMEA method. Managerial implications in company decision-making to prevent machine failures and determine other factors that cause these failures.

2. LITERATURE REVIEW

Reliability-Centered Maintenance (RCM)-FMEA is a systematic approach in industrial maintenance that aims to ensure equipment reliability by adjusting maintenance strategies based on risks and their impact on operations (Filz et al., 2021). The benefits of RCM-FMEA implementation in the industry are improving equipment reliability with more effective maintenance strategies, reducing maintenance costs by avoiding unnecessary maintenance, improving work safety by preventing critical failures that can cause accidents, extending equipment life with condition-based and predictive maintenance strategies, and improving operational efficiency by reducing unplanned downtime (Eriksen et al., 2021); (Krisnaningsih et al., 2022). RCM-FMEA is highly relevant in various industrial sectors such as manufacturing, energy, oil and gas, and transportation (Musthopa et al*.,* 2023). With proper implementation, industries can optimize their asset performance and improve competitiveness (Wari et al., 2023).

Reliability-Centered Maintenance-FMEA is a highly effective method to lower machine breakdown rates by optimizing reliability-based maintenance strategies (Dayo-Olupona et al., 2023). RCM-FMEA ensures that every maintenance action is performed based on risk and its impact on operations. Companies can ensure that maintenance is carried out proactively, not reactively, so that productivity remains optimal and emergency repair costs can be reduced to a minimum to support continuous improvement programs (Chan & Mo, 2017).

Furthermore, the application of RCM-FMEA can optimize the reliability of the boiler pump machine maintenance system with a systematic and risk-based approach. By applying RCM-FMEA, the boiler pump machine maintenance system becomes more efficient, cost-effective, and reliable. The main advantages of this approach are preventing sudden failures that can disrupt production, reducing downtime and emergency maintenance costs, improving energy efficiency and pump life, and ensuring boiler pumps always work at optimal conditions with a data-driven maintenance strategy (Ramere & Laseinde, 2021). RCM-FMEA allows the industry to maximize boiler pump reliability without having to perform excessive maintenance or ignore potential risks.

3. METHODS

The basis of physical maintenance and the techniques used to develop a scheduled preventive maintenance process. Based on the principles of reliability of equipment or machines and the performance structure of the design, and the quality of establishing effective preventive maintenance. The process of implementing reliability-centered maintenance is as follows:

a. Functional block diagram (FBD)

b. Failure mode and effect analysis (FMEA)
c. Logic tree analysis (LTA)
d. Task selestion map (selection of maintenance actions)

RCM-FMEA is a systematic approach to evaluate facilities and resources to produce cost-effective and highly reliable (Afefy et al., 2019), (Yang et al., 2020). The stages of RCM-FMEA implementation are:

3.1. Functional block diagram (FBD)

A diagram that explains the function of each component and the relationship between one component and another, so that the impact between components can be seen (Analog Devices, 2004). Information is used as the basis for making functional diagrams to identify the system in detail.

3.2. Failure Mode and Effect Analysis (FMEA)

Failure Mode and Effect (FMEA) is a method used to evaluate system designs by identifying failure modes for each system component, design, process, or service to develop maintenance measures (Li, 2024). Used to evaluate system designs by identifying failure modes for each system component, design, process, or service to develop maintenance measures. The RPN results show the level of components that are considered to have the highest level of risk, so they require special treatment through improvement (Huang et al., 2020). Determination of RPN value in equation (1).

$$RPN = Severity \text{ X } Occurrence \text{ X } Detection \quad (1)$$

RPN = Risk Priority Number

3.3. Logic tree analysis (LTA)

Prevention processes are needed to reduce the risk and likelihood of failure. LTA aims to classify failures to determine the priority level based on their category so that it can show the type of maintenance activities (maintenance tasks) that are feasible and optimal to overcome failure mode problems (Yazdi et al., 2023).

3.4. Boiler feedwater pump

The Boiler Feed Pump (BFP) or steam boiler filler water pump functions to pump filler water from the storage tank generator to the High-Pressure Heater. At PLTU Suralaya 1-4, each unit is equipped with 3 BFP pumps (Shokri & Fard, 2023).

3.5. Task selestion map

The process of selecting the right action for a particular failure mode (Fernandez et al., 2019). Maintenance actions on the action selection roadmap can be divided into: 1) Time directed (TD); 2) Condition Direct (CD 3). Finding Failure (FF) and Run to Failure (RTF). Determination of MTTF, MTTR, and MTBF values in equations (2)-(4).

$$MTTF = \frac{Total\ TTF/hour}{Total\ Number\ of\ Failures} \quad (2)$$

Calculation of Mean Time To Repair (MTTR)

$$MTTR = \frac{Total\ Repair\ Time}{Number\ of\ machine\ repairs} \quad (3)$$

Calculation of Mean Time Between Failure (MTBF)

$$MTBF = \frac{Total\ Time\ Between\ Failures}{Number\ of\ Failures} \quad (4)$$

3.6. 5W+1H

According to researchers (Ismail & Setiafindari, 2023)The 5W+1H elements can be used to understand and explain situations and events by asking six questions: what, why, where, when, who, and how. The purpose is to develop a detailed and systematic understanding of a particular event or situation (Jia et al., 2016). Proposed Improvements using the 5W+1H method in Table 1.

Table 1. Proposed Improvements 5W+1H

5W + 1H	
What	What improvements can be made?
Why	Why does the problem need to be solved?
Who	Who is responsible for carrying out repairs?
When	When will the repairs be carried out?
Where	Where are repairs made?
How	How are repairs carried out?

Aims to develop a detailed and systematic understanding of an event or situation using six questionnaires: what, why, where, when, who, and how. The research procedure starts from problem formulation, collecting research data from literature studies and field studies, to analyzing the results described in the research flow chart in Figure 1.

4. RESULTS AND DISCUSSIONS

4.1. Result

The study was conducted at PLTU XYZ-Banten, which is engaged in power generation. The research object is the Boiler Feed Pump (BFP) machine in the steam turbine system, which is used to transport make-up water from the deaerator to the boiler (steam drum), and the make-up water is the raw material for steam money to drive the turbine. Data on the amount of downtime of the BFP machine at unit 4C in 2024 is in Table 2.

Based on Table 2, the amount of downtime damage to the Boiler Feed Pump in 2024 is 175.45 hours, with ARV damage indicating leaks through on 26/08/2022, which is the largest downtime, with a downtime of 32 hours, while the smallest downtime is a dirty strainer with a downtime of 1.30 hours. A Pareto chart to determine the percentage rate of occurrence of the problem in Figure 2.

a. RCM data processing

The functional block diagram (FBD) in Figure 3 shows the function of the Boiler Feed Pump (BFP) system with the sequence of operations. The next step is to determine the failure modes. Then, the impact of each failure mode and the RPN value is identified. The Risk Priority Number value is determined by 3 factors, namely Severity, Occurrence, and Detection (Rajput et al., 2019). Based on equation (1), the Failure mode and effect analysis BFP pump is in Table 3.

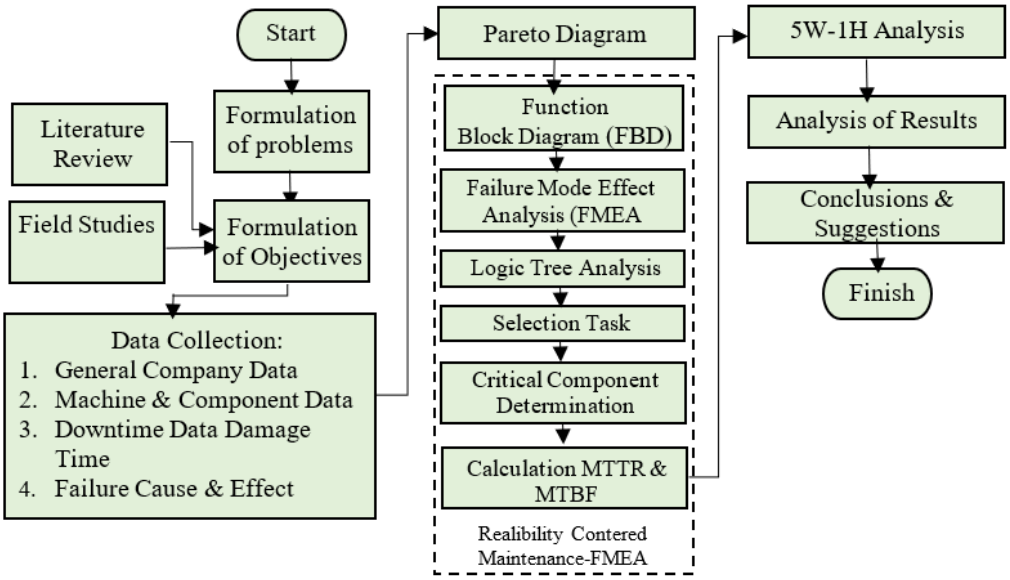

Figure 1. Flowchart of The Study

Table 2. Time Between Breakdown Data of BFP 4 C Machine

No.	Type of Damage	*Actual Start*	*Actual Finish*	*Downtime* (Hours)
1	ARV indication leaks through	17/03/2024 09.00	18/03/2024 18.00	16
2	Damage to the Variable speed coupling (VSC)	21/03/2024 08.00	21/03/2024 15.00	6
3	Pipe leaks out	22/03/2024 10.00	22/03/2024 16.00	2
4	ARV indication leaks through	24/03/2024 09.00	27/03/2024 15.30	29.30
5	ARV indication leaks through	04/04/2024 09.00	05/04/2024 11.00	12
6	BFP Mechanical Seal pump leak	12/04/2024 08.00	12/04/2024 15.00	6
7	Pipe leaks out	23/05/2024 09.00	23/05/2024 11.00	2
8	*Valve ARV has leaked out*	26/05/2024 09.00	27/05/2024 10.00	9
9	Pipe leaks out	09/06/2024 09.00	09/06/2024 16.00	6
10	Pipe leaks out	08/07/2024 08.00	08/07/2024 10.00	2
11	Pipe leaks out	02/08/2024 09.00	02/08/2024 14.00	4
12	ARV indication leaks through	09/08/2024 09.00	11/08/2024 17.00	23
13	Pipe leaks out	18/08/2024 09.00	18/08/2024 17.15	7.15
14	ARV indication leaks	26/08/2024 09.00	29/08/2024 18.00	32
15	Damage to the variable speed clutch (VSC)	28/09/2024 09.00	28/09/2024 16.00	6
16	BFP Mechanical Seal pump leak	19/10/2024 09.00	19/10/2024 12.00	3
17	Pipe leaks out	26/10/2024 09.00	26/10/2024 12.00	3
18	ARV indication leaks through	08/11/2024 09.00	10/11/2024 15.30	5.30
19	*Dirty and broken strainers*	24/11/2024 09.00	24/11/2024 10.30	1.30
	Amount			175.45

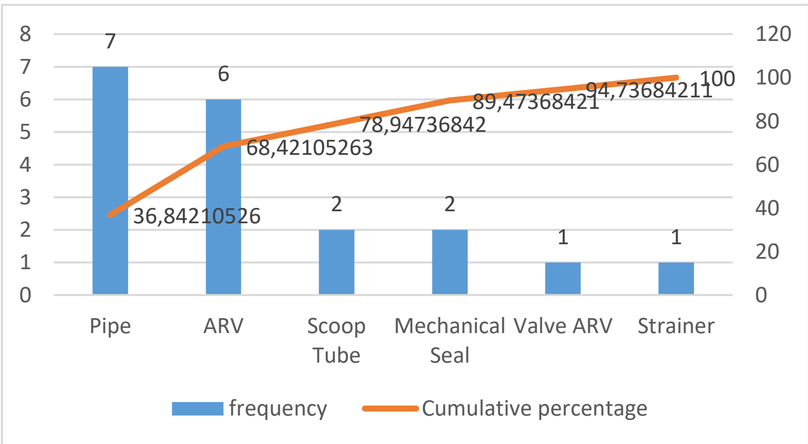

Figure 2. Pareto diagram types of damage

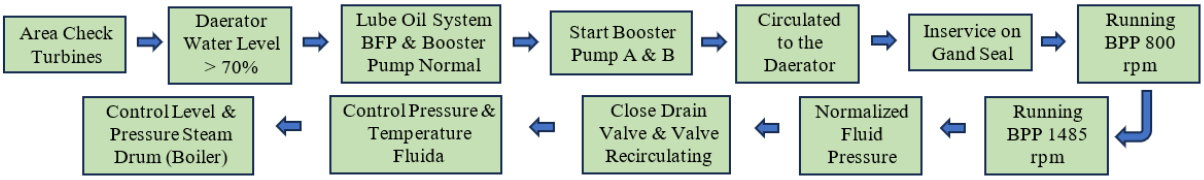

Figure 3. BFP Pump Functional Block Diagram

Table 3. Failure mode and effect analysis of the BFP pump

No.	Main Components	Failure	Effects of failure	R	S	O	D	RPN
1	Pipe	Leakage in the Suction venting line and the Drain line	Causes an increase in makeup water due to leakage. Harm to surrounding personnel and equipment.	1	7	4	4	112
				2	6	3	4	72
				3	6	5	3	90
				Amount				**91**
2	ARV	*The cascade piston bushing is broken*	This may cause unit trips due to low-level drums. Causes an increase in motor amperage, which can alarm or trip the motor.	1	8	6	3	144
				2	7	5	3	105
				3	8	5	2	80
				Amount				**109**
3	*Scoop tube*	The thread on the scoop tube control rod is damaged	This causes the need for filler water to be interrupted. Causes an increase in motor amperage, which can alarm or trip the motor.	1	7	2	4	56
				2	7	3	4	84
				3	6	2	3	36
				Amount				**58**
4	*Mechanical Seal*	Mechanical seal leakage	Fluid system flow and pressure are not met.	1	8	2	3	48
				2	6	3	2	36
				3	7	2	2	28
				Amount				**37**
5	*Valve* ARV	ARV valve leakage	This may cause the filler water demand to be interrupted This may cause the unit to trip	1	8	2	3	54
				2	7	3	3	63
				3	7	2	2	28
				Amount				**48**
6	*Strainer*	*dirty strainers*	This causes the need for filling water to be interrupted due to a lack of flow	1	6	2	2	24
				2	5	2	2	20
				3	6	2	3	36
				Amount				**26**

From Table 3, the ARV component is the Component with the highest RPN value of 109, and the smallest RPN value is the Strainer component with its RPN value of 26. So the Critical Component in the Boiler Feed Pump Unit 4 pump is the ARV Component with its RPN Value of 109; these results indicate that the ARV component experiences the most frequent failures and requires improvement. Next, classify failures to determine the priority level based on the category, so that it can show the type of maintenance activities (maintenance tasks) that are feasible and optimal to overcome each failure mode. There are four main categories of failure mode analysis. Logic Tree diagram in Figure 4.

LTA (Logic Tree Analysis) in Figure 4 is based on the results of questionnaires from 5 expert respondents. Critical analysis components consist of evidence, safety, outage, and Category components. LTA Identification Results in Table 4. Based on equation (1), the results of the calculation of the Risk Priority Number (RPN) value and the average value of each main component of failure are in Table 3.

LTA (Logic Tree Analysis) in Figure 4 is based on the results of questionnaires from 5 expert respondents. Critical analysis components consist of evidence, safety, outage, and Category components. LTA identification results in Table 4.

b. RCM-FMEA

Action selection is the final step in the RCM-FMEA method. This process is done by selecting the right action for a particular failure mode in Figure 5. Based on FMEA analysis, the most critical component is the ARV component. At this stage, calculations are made based on downtime data or data on the length of time to repair until the machine returns to normal (Time to Repair), while the calculation of the time interval of failure (Time to Failure) involves several components for calculating TTR and TTF, among others: 1) Automatic Recirculating valve; 2). Pipe; 3). Scooptube; 4). Mechanical Seal (Table 5). The total results of the calculation of TTR and TTF for each component are in Table 6.

Calculation of MTTR, MTBF, and MTTF

At this stage, the average failure, repair, and time between failures are calculated, based on the Time to Repair (TTR) and Time to Failure (TTF) calculation data and the total operating hours of the machine in 2022. Based on equations 2, 3, and 4, the results of the calculation of MTTR, MTTF, and MTBF are in Table 7.

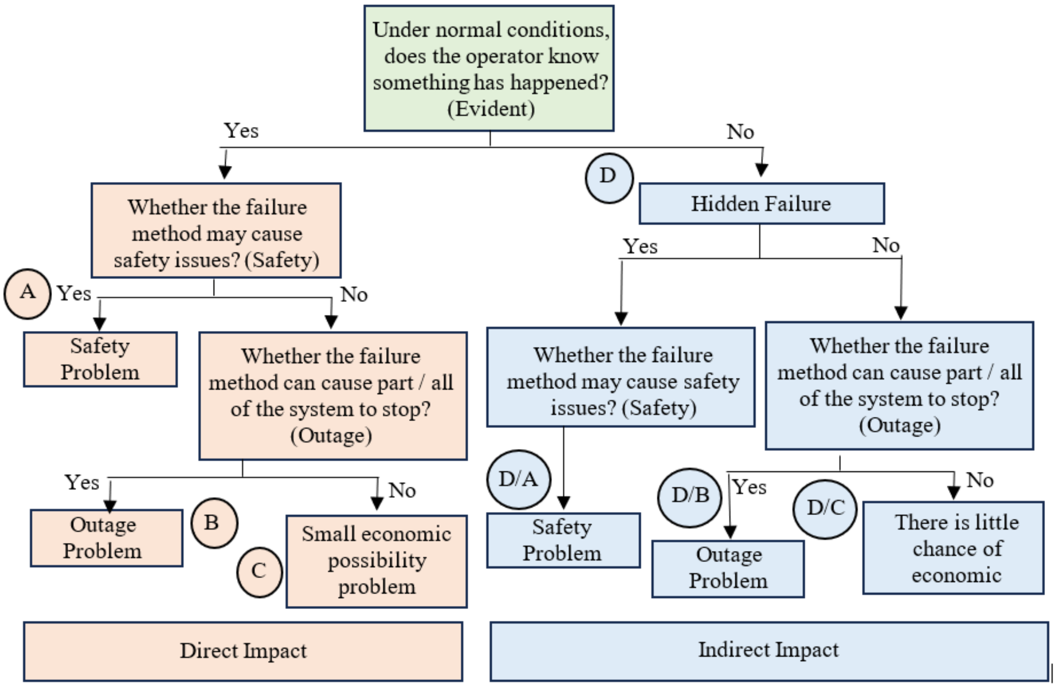

Figure 4. Logic Tree Diagrams

Table 4. LTA identification

No.	Main Components	Failure	Failure Effect	*Critical Analysis*			
				Evident	*Safety*	*Outage*	*Category*
1	Pipe	Leakage in the Suction venting line and the Drain line	Causes an increase in makeup water due to leakage Harm to surrounding personnel and equipment	Y	Y	N	A
2	ARV	*The cascade piston bushing is broken*	This may cause unit trips due to low drum level Causes an increase in motor amperage, which can alarm or trip the motor	Y	N	Y	B
3	*Scoop tube*	The thread on the scoop tube control rod is damaged	Causes the need for filler water to be interrupted Causes an increase in motor amperage, which can alarm or trip the motor.	Y	N	Y	B
4	*Mechanical Seal*	Leakage of the mechanical Seal	*Fluid system flow and pressure are not met*	Y	N	N	D/B
5	*Valve* ARV	ARV valve leakage	This may cause the filler water demand to be interrupted This may cause the unit to trip.	Y	N	Y	B
6	*Strainer*	*dirty strainers*	This causes the need for filling water to be interrupted due to a lack of flow.	Y	N	N	D/C

Table 5. Boiler Feed Pump Maintenance Task Selection

No.	Main Components	Failure	Effect of Failure	*Selection Guide*							
				1	2	3	4	5	6	7	*Task Selection*
1	Pipe	Leakage in the Suction venting line and the Drain line	Causes an increase in makeup water due to leakage. Harm to surrounding personnel and equipment	Y	Y						TD

Table 5. Boiler Feed Pump Maintenance Task Selection (Cont.')

No.	Main Components	Failure	Effect of Failure	*Selection Guide*							
				1	2	3	4	5	6	7	*Task Selection*
2	ARV	*Cascade piston bushing broken*	This may cause unit trips due to low drum levels. Causes an increase in motor amperage, which can alarm or trip the motor.	Y	N	Y					CD
3	*Scoop tube*	The thread on the scoop tube control rod is damaged	This causes the need for filler water to be interrupted. Causes an increase in motor amperage, which can alarm or trip the motor.	Y	N	Y					CD
4	*Mechanical Seal*	Leakage of the Mechanical Seal	*The fluid system flow and pressure are not met.*	Y	N	Y					CD
5	*Valve* ARV	Leak in the ARV valve	This can cause the need for filling water to be disrupted. This may cause the unit to trip.	Y	Y						TD
6	*Strainer*	*Dirty strainer*	This causes the need for filler water to be disrupted due to a lack of flow.	N	N	N	Y	Y			FF

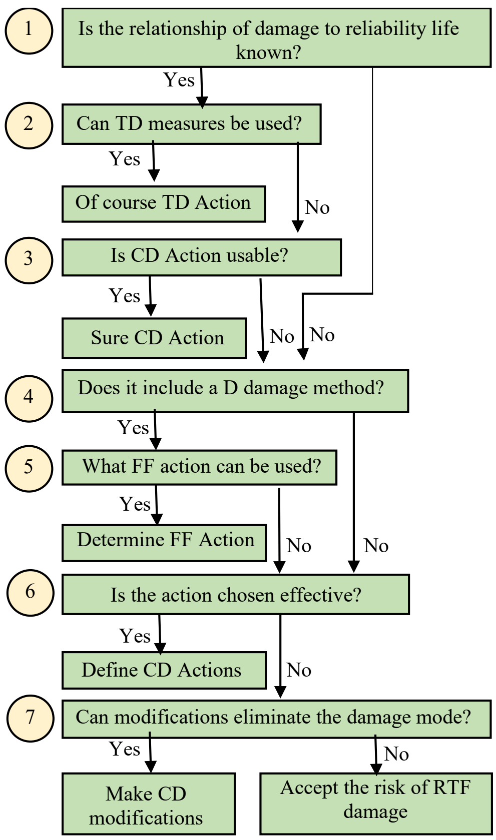

Figure 5. Task Selection Diagram

Table 6. Total results of all TTR and TTF calculations

No.	Component	Total TTR (Hours)	The time between failures (Hours)	Total TTF (Hours)	Frequency of Interference
1	ARV	118	5472	5437.3	6
2	Pipe	26.15	5496	5464.45	7
3	*Scooptube*	12	4584	4578	2
4	*Mechanical Seal*	9	4560	4554	2

Table 7. Calculation of MTTR, MTTF, and MTBF

No.	Component	MTTR (Hours)	MTTF (Hours)	MTBF (Hours)
1	ARV	19.6	906.2	912
2	Pipe	3.7	780.6	785.1
3	*Scooptube*	6	2289	2292
4	*Mechanical Seal*	4.5	2277	2280

Table 8. Recapitulation of Inspection Time Intervals

Number	Component	Inspection time interval	
		Hours	Day
1	ARV	73	3
2	Pipe	334	14
3	*Scooptube*	1080	45
4	*Mechanical Seal*	960	40

Calculation of inspection time intervals

Calculation of component inspection time intervals for each component. The calculation of the inspection time interval for ARV is as follows:

The time required by the company for inspection/preventive maintenance is 1 hour.

Average work per month

Working days per month = 30 days

Working hours per day = 24 hours

Average work per month = 30 x 24 = 720 (t)

Breakdown hours

Number of breakdowns for 1 year = 6 times

Average repair time

$$\frac{1}{\mu} = \frac{MTTR}{Average\ working\ hours\ per\ month} = \frac{19.6}{720} \quad (5)$$

$$\frac{1}{\mu} = 0.02722222$$

$$\mu = \frac{1}{1/\mu} = \frac{1}{0{,}02722222} = 36.7346969$$

Average inspection time

$$\frac{1}{i} = \frac{Average\ of\ 1\ inspection}{average\ work\ per\ month} = \frac{1}{720} = 0.00138889 \quad (6)$$

(Sharifi & Taghipour, 2021)

$$i = \frac{1}{\frac{1}{i}} = \frac{1}{0.00138889} = 719.999424$$

Average damage

$$k = \frac{Number\ of\ damages\ per\ period}{number\ of\ periods} = \frac{6}{12} = 0.5 \quad (7)$$

Optimal inspection frequency

$$n = \sqrt{\frac{k.i}{\mu}} = \sqrt{\frac{0.5\ x\ 719.999424}{36.7346969}} = 9.7999914 \quad (8)$$

Inspection time interval

$$\frac{t}{n} = \frac{average\ working\ hours}{n} \quad (9)$$

$$= \frac{720}{9.7999914} = 73.4694 = 73\ \text{Hours}$$

The results of the calculation of inspection time intervals for components are in Table 8.

4.2. Discussion

The advantages of our proposed research framework are:

1) Holistic and systematic approach
This framework integrates Reliability-Centered Maintenance (RCM) with Failure Mode and Effects Analysis (FMEA). Scientifically, this approach is holistic because it does not only focus on a single failure, but also considers: 1. The overall function of the system, 2. Critical failure modes, 3. The impact on reliability, safety, and costs. This differs from conventional preventive maintenance, which is often periodic without considering risk priorities.
2) Risk-based and reliability data-based
FMEA assesses failures through Risk Priority Number (RPN), while reliability analysis (MTBF, MTTR, failure distribution) provides a quantitative basis. The integration of the two makes this framework: 1. More scientific in determining maintenance priorities. 2. Ensures resources are focused on the most critical components. 3. Reduces over-maintenance and under-maintenance. In terms of risk management theory, this approach supports the principle of risk-based maintenance.
3) Multi-criteria optimization
This framework enables the optimization of maintenance strategies by considering multiple factors: cost, reliability, safety, availability, and downtime. Using a multi-criteria decision-making (MCDM) approach or mathematical optimization methods, the resulting decisions are more objective and rational than those based solely on the intuition or experience of technicians. This contributes scientifically to the literature on maintenance optimization.
4) Operational and economic efficiency
Scientifically, research shows that RCM + FMEA can: 1. Reduce downtime by >30% in the manufacturing industry. 2. Increase equipment availability to >90%. 3. Reduce maintenance costs due to more targeted maintenance intervals. These advantages support the life cycle cost (LCC) theory, where reliability-based maintenance is more economical than corrective maintenance.
5) Flexible for various industries
This framework can be applied in many sectors: energy, transportation, manufacturing, and mining. FMEA is universal in identifying risks. Reliability analysis can be tailored to the failure characteristics of each industry. Scientifically, this reinforces the value of generalization and replication of research.
6) Novelty in integration

The main advantage is its novelty: 1. It does not just apply FMEA or RCM separately, 2. But builds an integrated framework that produces an optimal maintenance strategy, based on risk and reliability data. This scientific contribution enriches the literature on modern maintenance management, which is shifting towards predictive and risk-based approaches.

5. CONCLUSIONS

Reliability-centered Maintenance (RCM) is an effective approach to optimizing BFP machine maintenance. With the application of RCM, the company focuses on the most effective and efficient maintenance to maintain machine reliability, minimize downtime, and reduce operating costs. Making a schedule of the Interval time of inspection of components and proposed improvements will make the Boiler Feed Pump downtime rate low.

Overall, the new approach with RCM-FMEA allows companies to focus on the most critical and effective maintenance. Minimize downtime, reduce costs, and increase machine life. This approach makes maintenance more strategic, measurable, and focused on long-term results.

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