

Optimization of Boiler Feed Pump Maintenance Planning using Reliability-Centered Maintenance: A Case Study at a Thermal Power Plant in Banten

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Abstract — The Boiler Feed Pump (BFP) is essential to power generation systems because it supplies high-pressure water to the boiler. BFP failures can cause operational disruptions, efficiency losses, unplanned downtime and substantial financial impacts. This study aims to optimize the maintenance plan for BFP Unit 4B using Reliability-Centered Maintenance (RCM). Historical failure data from July 2024 to June 2025 were evaluated using Failure Mode and Effect Analysis (FMEA). Three maintenance experts assessed the failure modes to identify critical components and calculate Risk Priority Numbers (RPN). Time-to-failure and time-to-repair data were fitted to exponential, Weibull, normal and lognormal distributions. Maintenance parameters were then calculated using the best-fitting distributions. The Motor, Mechanical Seal, Filter Inlet and Coupling recorded the highest average RPN values of 121, 118, 91, and 89, respectively and were prioritized for maintenance. At a reliability threshold of 0.90, the recommended preventive maintenance intervals are 2,138 hours for the Mechanical Seal, 2,137 for the Motor, 2,177 for the Shaft, 1,761 for the Bearing, 2,514 for the Impeller, 2,515 for the Coupling and 2,513 for the Filter Inlet. The proposed RCM-based schedule is recommended to reduce recurring failures, improve reliability, minimize downtime and lower long-term maintenance costs.

Keywords - Boiler Feed Pump, Failure Mode and Effect Analysis (FMEA), Preventive Maintenance, Reliability Centered Maintenance, Risk Priority Number.

INTRODUCTION

The Boiler Feed Pump (BFP) is a critical component in thermal power generation, supplying high-pressure feedwater to the boiler to sustain continuous steam production and stable energy conversion [1]. Any malfunction in the BFP can cause serious operational disruption, reduced generation capacity and costly unscheduled outages [1]. Beyond lost electricity production, BFP failure commonly triggers cascading damage to related components such as the bearing, impeller, coupling and mechanical seal, increasing repair cost and downtime. Consequently, industries increasingly move from corrective or fixed time-based maintenance toward predictive and Reliability-Centered Maintenance (RCM) strategies that emphasize proactive fault detection and optimized maintenance intervals [2]. Monitoring frameworks

such as Process Advisor have shown the potential to detect early stage pump deterioration [3] and SCADA-based predictive systems enable early fault identification, reducing repair frequency and cost [4]. Complementary condition-monitoring techniques, including smart-sensor-based tracking of centrifugal pump vibration and temperature [5] and machine-learning-based efficiency monitoring of cooling water pumps [6], further illustrate how digital instrumentation is reshaping predictive maintenance practice across the wider class of rotating pump equipment to which the BFP belongs.

Despite these advances, BFP failures remain persistent in Indonesian power plants due to inadequate maintenance planning and continued reliance on reactive strategies. Several studies report that pump systems, including BFPs, contribute significantly to plant downtime because of

inefficient scheduling and limited reliability control [7]. Quantitative maintenance analyses of BFP systems elsewhere similarly report recurring bearing, seal and shaft-related failures when inspection remains schedule-driven rather than condition-driven [8], while static structural analysis of the BFP shaft shows that even a single geometry-related weak point can significantly shorten component life and elevate vibration risk [9], reinforcing why the shaft was retained as one of the components examined in this study. Similar patterns are observed in other Indonesian boiler and rotating-equipment maintenance practices, including centrifugal pump upkeep at non-power-generation facilities such as airport utility systems [10], where fixed time-based inspection cycles still dominate rather than condition-based planning [11]-[12]. This gap motivates further investigation, particularly for critical components such as the motor, mechanical seal, coupling, and filter inlet, which are frequently associated with BFP failure [13].

Maintenance practice is generally classified into preventive, predictive and corrective (breakdown) approaches [14][15]. Preventive maintenance covers scheduled inspection, minor repair, lubrication, and adjustment intended to avert failure before it occurs, and is commonly implemented either as periodic maintenance, following fixed daily, weekly, monthly, or annual cycles, or as predictive maintenance, which relies on continuous condition monitoring such as vibration analysis, oil tribology, thermography, and non-destructive testing to detect abnormal equipment condition before failure develops [15]. Corrective and breakdown maintenance, by contrast, are performed only after a fault or failure has already occurred, restoring the asset to an acceptable operating standard but at the cost of unplanned downtime and higher repair urgency. RCM formalizes the choice among these approaches on a component-by-component basis rather than applying a single strategy uniformly across an entire system [16][17]

RCM is commonly defined as a systematic process for determining what must be done to ensure that a physical asset continues to fulfill its intended function within its operating context, prioritizing system-level performance over any single part and placing safety ahead of purely economic considerations [16]. The framework classifies the consequence of each failure mode into one of four categories: hidden failure, in which the loss is not evident to the operator and may compound into a more serious multiple failure, safety consequence,

where the failure can cause injury, operational consequence, where the failure disrupts production, output, or operating cost and non-operational consequence, where the failure has no direct effect on safety or production but still incurs direct repair cost [17]. These four categories underlie the Logic Tree Analysis decision logic applied later in this study, together with the three associated maintenance task types, condition-directed inspection, time-directed replacement or restoration and failure-finding tasks for hidden functions.

RCM offers an analytical framework for identifying, evaluating, and mitigating equipment failures based on reliability performance and operational criticality [18]-[19]. By integrating Failure Mode and Effect Analysis (FMEA) to compute the Risk Priority Number (RPN), RCM enables maintenance planners to prioritize components and define appropriate inspection intervals rather than relying on calendar-based schedules [20]. Previous applications of RCM within Indonesian power and process industries, such as the reliability database developed at Pertamina Hulu Energy [21] and RCM-based scheduling on rotating equipment in Banten's power sector [9], demonstrate the practical value of this approach for local operating conditions and complement other quantitative industrial-engineering optimization research conducted at the same university, including production-line balancing analysis for fiber-optic cable manufacturing [22]. However, empirical, component-level FMEA-RCM studies focused specifically on the BFP within Indonesian thermal power plants remain limited, aside from instrumentation-focused reliability work on similar equipment [23].

Beyond thermal power applications, FMEA-based criticality methods have also been refined to sharpen component prioritization, an integrated ExJ-PSI weighting model applied to a boiler system demonstrated that failure mode ranking can be made more discriminating than the conventional RPN product alone [24], while genetic algorithm assisted RCM scheduling for marine diesel engines has shown that optimization techniques can further extend component lifespan once an initial FMEA RCM baseline is established [25]. These developments suggest that the three respondent FMEA-RCM baseline adopted in this study could, in future work, be extended with similar weighting or optimization refinements once a longer maintenance history has accumulated.

This study aims to develop an optimized RCM strategy for the BFP Unit 4B at a coal fired thermal power plant in Banten, Indonesia. Failure mode analysis using FMEA, rated by three maintenance experts were applied to identify critical components and calculate their average RPN values, followed by Logic Tree Analysis and task selection to determine appropriate maintenance categories. Reliability indicators Mean Time to Failure, Mean Time to Repair and Mean Time Between Failures are then calculated from the best fitting failure time and repair time distributions to establish data driven inspection intervals, and a 5W+1H framework is used to formulate structured corrective and preventive actions for the most critical components.

METHODS

Study Design, Location and Time

This study employed a quantitative and descriptive engineering approach to evaluate the reliability and maintenance performance of the BFP Unit 4B at a coal-fired thermal power plant located in Banten, Indonesia. Field observation and data collection were carried out at the Mechanical Turbine Maintenance Division, covering the operational period from July 2024 to June 2025.

Materials and Data Sources

Primary data were obtained through direct field observation, structured interviews and questionnaires completed by three maintenance experts (the section supervisor and two rotating-equipment technicians) and inspection of component condition during scheduled overhauls, supported by equipment manuals, inspection reports and repair records. Secondary data were drawn from technical literature, reliability handbooks and prior studies on RCM, FMEA and thermal power plant reliability analysis.

Data Collection and Research Stages

The study followed the standard RCM sequence in seven consecutive stages. The Results and Discussion section is organized under the same seven stage labels and in the same order, so that every stage described here can be traced directly to its results.

Stage 1 – Problem characterization. Interviews with the maintenance division and field observation were used to establish the operational and financial consequences of BFP downtime. **Stage 2 – Failure data and Pareto analysis.** The failure and

downtime log of BFP Unit 4B (25 events, July 2024–June 2025; Table 1) was summarized per component (Tables 2 and 3), and a Pareto analysis (Figure 1) defined the seven components analyzed in the following stages. **Stage 3 – Functional Block Diagram (FBD).** The FBD (Figure 2, Table 4) defined the function of each component and the interrelationships among components within the steam cycle. **Stage 4 – FMEA.** Failure modes were rated by three maintenance experts and the Risk Priority Number (RPN) was calculated with Equation (1) (Table 5).

Stage 5 – Logic Tree Analysis (LTA) and task selection. Each failure mode was classified by LTA and each critical component was assigned a maintenance task category (Tables 6 and 7). **Stage 6 – Reliability analysis.** Time-to-failure (TTF) and time-to-repair (TTR) datasets were built from table 1, the distribution of each dataset was identified and MTTF, MTTR, MTBF and the inspection interval of every component were calculated with the formulas of the identified distribution (Equations 2–11; tables 8–10). **Stage 7 – 5W+1H analysis.** The 5W+1H (What, Why, Where, When, Who and How) framework was applied to translate the quantitative findings into structured corrective and preventive maintenance recommendations (table 11).

Stages 3 and 4 were carried out as follows. A Functional Block Diagram (FBD) was first constructed to define the interrelationships among BFP components within the steam cycle. FMEA was then applied to identify failure modes, causes and effects. Each failure mode was independently rated by the three respondents on Severity (S), Occurrence (O) and Detection (D), on a scale of 1 to 10, to compute (1).

$$RPN = S \times O \times D \quad (1)$$

The three respondents' RPN scores for each failure mode were then averaged to obtain the representative RPN used for component prioritization. Logic Tree Analysis (LTA) subsequently classified each failure in Stage 5 into categories A–D according to failure evidence, safety implication and outage consequence (table 6), supporting Task Selection (TS), which assigned each critical component a Condition-Directed (CD), Time-Directed (TD), or Finding-Failure (FF) maintenance category. Both LTA and task selection judgments were obtained through structured questionnaires and consolidated by consensus among the three respondents.

The FMEA, LTA, and task-selection questionnaires were structured around the same seven components identified from the Pareto analysis, presenting each failure mode alongside its severity, occurrence and detection anchors on the numbered 1-to-10 scale, together with the binary yes/no prompts corresponding to the LTA and RCM decision-logic questions reported in tables 6 and 7. Respondents completed the FMEA and LTA sections independently to limit anchoring bias between raters, after which the task-selection outcome for each component was reviewed jointly and any disagreement resolved by discussion until consensus was reached.

Reliability Data Analysis (Stage 6)

In Stage 6, reliability performance was quantified separately for each of the seven components from the failure and downtime log in table 1. Two datasets were built per component. The time to failure (TTF) is the operating time between the return to service after one failure and the next failure of the same component, i.e., the interval between the two failure dates minus the repair time of the earlier failure, assuming that the pump operated continuously between failures. The Time to Repair (TTR) is the downtime recorded for each failure. A component with k failures therefore provides $k-1$ TTF values and k TTR values. The period from the start of the observation window to the first failure and the censored period after the last failure were excluded because the age of the component at the start of the window is unknown.

Because the formula of a mean time depends on the underlying distribution, the distribution of each dataset was identified before any mean time was calculated. Four candidate distributions (exponential, two-parameter Weibull, normal and lognormal) were fitted to every TTF and TTR dataset by maximum likelihood [26] and the Anderson–Darling statistic [27] was computed for each fit.

$$A^2 = -n - (1/n) \sum (2i - 1) \times [\ln F_i + \ln(1 - F_{n+1-i})] \quad (2)$$

where n is the sample size, $F_i = F(x_{(i)})$ is the fitted cumulative distribution function evaluated at the i -th ordered observation, and the sum runs from $i = 1$ to n . Because every dataset contains only two to four observations, the Anderson–Darling statistic cannot reliably discriminate among the candidates (the differences among the normal, Weibull, and lognormal fits are at most 0.084 within any dataset).

The normal distribution gave the best or near-best fit in every dataset and corresponds to the arithmetic mean used in the original analysis and was therefore adopted uniformly for all components so that a single distribution family is applied consistently throughout, the remaining formulas are retained for completeness. This choice is indicative rather than conclusive (see the limitations in the Results and Discussion).

The mean time of each dataset was then calculated with the formula of its selected distribution [28]. The expressions below are written for MTTF, the same expressions give MTTR when applied to the TTR data.

$$\text{Exponential: } MTTF = 1/\lambda \quad (3)$$

$$\text{Weibull: } MTTF = \eta \Gamma(1 + 1/\beta) \quad (4)$$

$$\text{Normal: } MTTF = \mu \quad (5)$$

$$\text{Lognormal: } MTTF = \exp(\mu + \sigma^2/2) \quad (6)$$

where λ is the failure rate (or repair rate for TTR), β and η are the Weibull shape and scale parameters, $\Gamma(\cdot)$ is the gamma function and μ and σ are the mean and standard deviation of the normal distribution (for the lognormal distribution, of the natural logarithm of the data). For the exponential and normal distributions, the mean time equals the arithmetic mean of the data ($\sum TTF/n$ or $\sum TTR/n$). Since the TTF excludes repair time, MTBF follows from.

$$MTBF = MTTF + MTTR \quad (7)$$

The inspection interval T of each component was defined as the longest operating time at which its reliability $R(T)$ remains at least 0.90, calculated from the TTF distribution selected for that component.

$$\text{Exponential: } T = -\ln(R)/\lambda \quad (8)$$

$$\text{Weibull: } T = \eta(-\ln R)^{1/\beta} \quad (9)$$

$$\text{Normal: } T = \mu + \sigma z \quad (10)$$

$$\text{Lognormal: } T = \exp(\mu + \sigma z) \quad (11)$$

where $R = 0.90$ and $z = \Phi^{-1}(1 - R) = -1.2816$ is the standard normal quantile. Inspection (CD and FF tasks) or restoration (TD tasks) is then scheduled at or before T .

RESULTS AND DISCUSSION

The results are presented in the order of the seven research stages described in the Methods (Stages 1–7), followed by a discussion of the findings.

Stage 1: Operational and Financial Impact of BFP Downtime

Interviews with the maintenance division confirmed that BFP failure imposes losses across several distinct dimensions rather than a single cost category, motivating a maintenance strategy that weighs each dimension rather than one that treats every failure as equally consequential.

The most immediate consequence is disruption to production. Because the BFP supplies high pressure feedwater to the boiler, any malfunction removes the unit's capacity to sustain steam generation, in the most severe cases the generating unit must be shut down entirely rather than merely derated and every hour of that shutdown corresponds directly to electricity output that cannot be recovered once the unit returns to service.

This lost generation is compounded by direct financial costs that accumulate independently of the revenue forgone from reduced output. Spare part procurement, overtime wages for the maintenance crew responding to an unplanned failure and where internal capacity is insufficient, third-party service or equipment-rental fees all add to the total cost of a single failure event, so that the effective cost of downtime is consistently higher than the value of the lost electricity alone.

BFP failure also rarely stays isolated to the pump itself. Because the bearing, impeller, coupling and

mechanical seal are mechanically coupled along the same rotating shaft line, degradation originating in one part frequently propagates to its neighbors before it is detected, extending both the scope and duration of repair and, in turn, its cost. This chain effect is one reason the FMEA in this study evaluates all seven components jointly rather than treating the pump as a single undifferentiated unit.

Beyond the immediate repair, a high frequency of BFP failure gradually erodes the generating unit's overall reliability rating, a metric used both for internal performance evaluation and for external reporting to the plant's regulators, so that recurring failures carry a reputational as well as an operational cost. Where the failure mode involves mechanical-seal leakage in particular, the consequence extends further to worker safety and the surrounding environment, since uncontained high-temperature fluid can injure personnel or, combined with residual heat, create a fire hazard. These five dimensions of loss, taken together, establish the practical motivation for applying RCM to systematically identify, prioritize, and schedule maintenance for the BFP's critical components.

Stage 2: Failure Data and Pareto Distribution

The BFP Unit 4B recorded 25 failure events and 119 hours of cumulative downtime over the observation period from July 2024 to June 2025, as logged in Table 1.

Table 1. BFP 4B Failure and Downtime Log (Jul 2024–Jun 2025)

No	Date	Downtime (h)	Failure Type	Main Component
1	03-Jul-2024	4	Leakage	Mechanical Seal
2	18-Jul-2024	5	Overheating	Motor
3	02-Aug-2024	4	High vibration	Bearing
4	17-Aug-2024	4	Cavitation	Impeller
5	01-Sep-2024	7	Bent shaft	Shaft
6	16-Sep-2024	4	Loose coupling	Coupling
7	01-Oct-2024	3	Clogged filter	Filter Inlet
8	16-Oct-2024	4	High vibration	Bearing
9	31-Oct-2024	5	Leakage	Mechanical Seal
10	15-Nov-2024	6	Overheating	Motor
11	30-Nov-2024	5	Cavitation	Impeller
12	15-Dec-2024	4	Bent shaft	Shaft
13	30-Dec-2024	2	Loose coupling	Coupling
14	14-Jan-2025	6	Clogged filter	Filter Inlet
15	29-Jan-2025	4	Leakage	Mechanical Seal
16	13-Feb-2025	6	Overheating	Motor
17	28-Feb-2025	7	High vibration	Bearing
18	15-Mar-2025	6	Cavitation	Impeller
19	30-Mar-2025	5	Bent shaft	Shaft
20	14-Apr-2025	4	Loose coupling	Coupling
21	29-Apr-2025	6	Clogged filter	Filter Inlet
22	14-May-2025	3	Leakage	Mechanical Seal

No	Date	Downtime (h)	Failure Type	Main Component
23	29-May-2025	5	Overheating	Motor
24	13-Jun-2025	5	High vibration	Bearing
25	28-Jun-2025	5	Bent shaft	Shaft

Table 2 summarizes the downtime and failure frequency per component derived from Table 1.

Table 2. Summary of BFP 4B Downtime by Component

Component	Fail.	Downtime (h)	%
Mechanical Seal	4	16	13.4
Motor	4	22	18.5
Bearing	4	20	16.8
Shaft	4	21	17.6
Impeller	3	15	12.6
Coupling	3	10	8.4
Filter Inlet	3	15	12.6
Total	25	119	100.0

The Motor accounts for the largest share of cumulative downtime (22 hours, 18.5%), followed by the Shaft (21 hours, 17.6%) and Bearing (20 hours, 16.8%), even though these three components share the same failure frequency (four events) as the Mechanical Seal, indicating that repair duration not merely failure frequency is an important driver of the Motor's operational impact. Table 3 and Figure 1 present the Pareto distribution of failure frequency.

Table 3. Pareto Distribution of BFP 4B Component Failure Frequency

Rank	Component	Freq.	Cum. %
1	Mechanical Seal	4	16
2	Motor	4	32
3	Bearing	4	48
4	Shaft	4	64
5	Impeller	3	76
6	Coupling	3	88
7	Filter Inlet	3	100

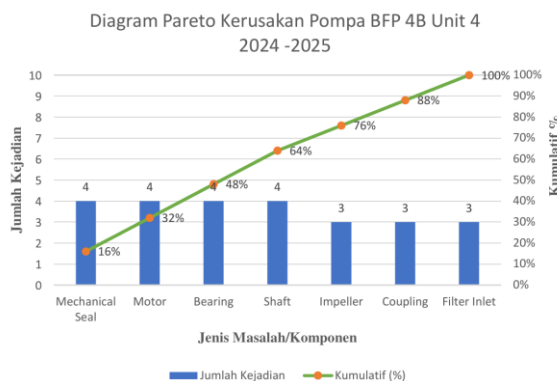


Figure 1. Pareto Distribution of BFP 4B Component Failures

The Pareto distribution shows that the Mechanical Seal, Motor, Bearing and Shaft collectively account for 64% of cumulative failure occurrences, following the 80/20 principle commonly observed in

reliability engineering and establishing them, together with the remaining three components as the basis for the subsequent FMEA.

Stage 3: Functional Block Diagram (FBD)

The FBD illustrates the primary process flow within the BFP 4B assembly, from turbine-area inspection and deaerator level checks, through lube-oil and booster-pump start-up, glandseal servicing and pump run-up to 1,485 rpm, to final control of suction/discharge valves and steam-drum pressure. The system consists of the motor, coupling, shaft, bearing, impeller, mechanical seal and filter inlet, arranged in a linear energy-transfer chain (figure 2). The motor delivers rotational energy through the coupling and shaft to drive the impeller, which increases feedwater pressure before delivery to the boiler drum.

During normal start-up, the operating parameters verified at each stage of the FBD are tightly specified: deaerator water level must exceed 70%, the BFP lube-oil line is maintained at approximately 0.15 MPa and the booster-pump lube-oil line at 0.4 MPa, and the gland-seal steam temperature reaches approximately 165°C, after which gland-seal steam pressure is held at 0.05–0.08 MPa and temperature within 160–180°C through the LP spray heater before the pump is run up first to 800 rpm and then to its full operating speed of 1,485 rpm. These narrow operating windows illustrate why several of the failure modes identified in the FMEA, particularly mechanical-seal leakage and motor overheating, are sensitive to comparatively small deviations in lubrication pressure or seal-steam temperature during start-up.

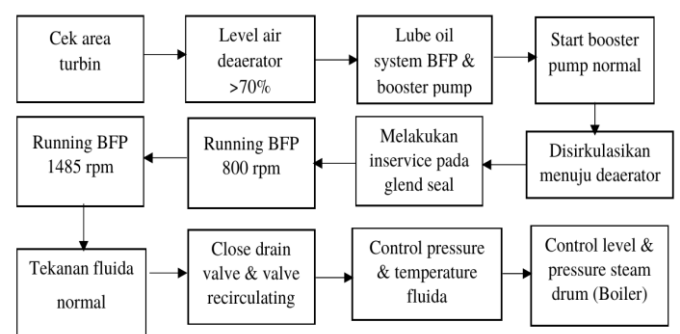


Figure 2. Functional Block Diagram (FBD) of BFP 4B

Table 4 summarizes each subsystem's function and reliability dependency. The shaft, bearing and mechanical seal show strong mechanical interdependence, so failures in these parts often propagate to neighboring components, making condition-directed inspection, such as vibration analysis and oil-debris monitoring, essential for early detection.

Table 4. Functional Elements of BFP 4B

Subsystem	Primary Function	Reliability Dependency
Motor	Converts electrical to mechanical energy	High
Coupling	Transfers torque, absorbs misalignment	Medium
Shaft	Transmits power to impeller	High
Bearing	Supports rotation, minimizes friction	High
Impeller	Pressurizes and circulates feedwater	High
Mechanical Seal	Prevents leakage at the shaft	High
Filter Inlet	Removes particulates from feedwater	Medium

Stage 4: Failure Mode and Effect Analysis (FMEA)

FMEA was performed to identify the most critical components. Each failure mode was independently

rated by three maintenance experts (R1–R3) on Severity (S), Occurrence (O) and Detection (D), each on a scale of 1–10, following Equation (1); the three resulting RPN scores were then averaged to obtain the representative value per component, as detailed in Table 5.

As shown in Table 5, the Motor exhibits the highest average RPN (121), driven primarily by its severity rating for winding overheating, which can lead to emergency shutdown and permanent motor damage. The Mechanical Seal follows closely (RPN 118), reflecting the fire and fluid-loss risk associated with seal-face leakage. The Filter Inlet (91) and Coupling (89) form the second tier of criticality, while the Bearing (82) and Shaft (74) show moderate criticality linked to gradual wear and vibration; the Impeller records the lowest average RPN (65). The overall mean RPN across all seven components is 91, and the four components above this mean Motor, Mechanical Seal, Filter Inlet and Coupling were treated as the primary targets for maintenance prioritization.

Table 5. FMEA Assessment of BFP 4B Components (Three-Respondent Rating)

No	Component	Failure Mode	Resp	S	O	D	RPN	Avg. RPN
1	Mechanical Seal	Leakage on seal face, O-ring, and bellows/spring	R1	8	6	4	192	118
			R2	6	3	4	72	
			R3	5	6	3	90	
2	Motor	Winding overheating and burnout	R1	9	5	4	180	121
			R2	5	7	3	105	
			R3	8	2	5	80	
3	Bearing	Wear/seizure due to poor lubrication	R1	7	6	3	126	82
			R2	7	3	4	84	
			R3	6	2	3	36	
4	Shaft	Bending or misalignment	R1	8	4	5	160	74
			R2	6	2	3	36	
			R3	7	2	2	28	
5	Impeller	Wear, corrosion, erosion, or cracking	R1	6	5	3	90	65
			R2	7	3	3	63	
			R3	7	3	2	42	
6	Coupling	Loose, worn, or slipping coupling	R1	7	5	5	175	89
			R2	5	2	4	40	
			R3	6	3	3	54	
7	Filter Inlet	Clogged media or damaged mesh	R1	5	6	4	120	91
			R2	6	4	2	48	
			R3	7	5	3	105	

Note: R1–R3 denote the three respondents. Overall mean RPN across all seven components = 91.

Stage 5: Logic Tree Analysis and Maintenance Task Selection

Table 6. Logic Tree Analysis (LTA) Results

No	Component	Failure Mode	Evident	Safety	Outage	Category
1	Mechanical Seal	Leakage on seal face, O-ring, bellows/spring	Y	Y	Y	D
2	Motor	Stator/winding overheating, burnt coils	Y	N	Y	D/B
3	Bearing	Bearing wear and jamming due to dryness	Y	N	Y	A
4	Impeller	Wear, corrosion, erosion, cracking of blades	N	N	Y	A

No	Component	Failure Mode	Evident	Safety	Outage	Category
5	Shaft	Shaft misalignment or bending	N	N	Y	D/C
6	Coupling	Loose or slipping coupling elements	Y	N	Y	A
7	Filter Inlet	Clogging or damage to inlet filter screen	Y	N	Y	D/C

Table 7. Maintenance Task Selection Based on RCM Guidelines

Component	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Task
Mechanical Seal	Y	N	Y	Y	N	N	N	CD
Motor	Y	Y	Y	N	N	N	N	TD
Bearing	Y	Y	Y	N	N	N	N	CD
Impeller	Y	Y	Y	N	N	N	N	TD
Shaft	Y	Y	Y	Y	N	N	N	TD
Coupling	Y	Y	Y	N	N	N	N	CD
Filter Inlet	F	F	N	N	N	N	N	FF

Note: Q1–Q7 are the standard RCM decision-logic questions on failure evidence, safety and outage consequence, and applicability of condition-, time-, or failure-finding tasks. CD = Condition-Directed; TD = Time-Directed; FF = Finding-Failure.

LTA classified each failure mode into category A (evident, not safety-related), B (evident, safety-related), C (hidden, outage-related), or D (hidden/dormant), based on failure visibility, safety implication, and operational impact, consolidated by consensus among the three respondents, as shown in table 6.

The Mechanical Seal, Bearing, and Coupling were assigned Condition-Directed (CD) maintenance, reflecting observable degradation indicators such as leakage, vibration, or looseness that allow preventive intervention through inspection before total failure. The Motor, Impeller, and Shaft were assigned Time-Directed (TD) strategies, implying scheduled inspection and replacement based on

operating hours rather than solely on observable symptoms. The Filter Inlet was assigned a Finding-Failure (FF) approach, as its deterioration is typically hidden and detectable only through periodic inspection or performance testing.

Stage 6: Reliability Indicators and Inspection Intervals

The TTF and TTR datasets, the distribution of each dataset, and the resulting MTTF, MTTR and MTBF were obtained as described in the Methods (Equations 2–7). Table 8 lists, for each component, the datasets derived from table 1, the Anderson–Darling statistic (A^2) of the four candidate distributions, the selected distribution and its parameters.

Table 8. TTF and TTR Datasets, Anderson–Darling Statistics (A^2), and Selected Distributions

Component	Data	Values (h)	A^2 Exp.	A^2 Wbl.	A^2 LN	A^2 N	Selected	Parameters
Mechanical Seal	TTF	2876; 2155; 2516	1.092	0.250	0.248	0.245	Normal	$\mu = 2515.7, \sigma = 294.3$
	TTR	4; 5; 4; 3	1.293	0.333	0.344	0.331	Normal	$\mu = 4.00, \sigma = 0.71$
Motor	TTF	2875; 2154; 2514	1.091	0.250	0.248	0.245	Normal	$\mu = 2514.3, \sigma = 294.3$
	TTR	5; 6; 6; 5	1.562	0.731	0.719	0.719	Normal	$\mu = 5.50, \sigma = 0.50$
Bearing	TTF	1796; 3236; 2513	0.840	0.247	0.255	0.245	Normal	$\mu = 2515.0, \sigma = 587.9$
	TTR	4; 4; 7; 5	1.165	0.464	0.453	0.492	Normal	$\mu = 5.00, \sigma = 1.22$
Shaft	TTF	2513; 2516; 2155	1.222	0.687	0.610	0.609	Normal	$\mu = 2394.7, \sigma = 169.5$
	TTR	7; 4; 5; 5	1.239	0.422	0.364	0.420	Normal	$\mu = 5.25, \sigma = 1.09$
Impeller	TTF†	2516; 2515	0.917	0.365	0.359	0.359	Normal	$\mu = 2515.5, \sigma = 0.5$
	TTR	4; 5; 6	0.988	0.249	0.250	0.245	Normal	$\mu = 5.00, \sigma = 0.82$
Coupling	TTF†	2516; 2518	0.917	0.365	0.359	0.359	Normal	$\mu = 2517.0, \sigma = 1.0$
	TTR	4; 2; 4	0.821	0.703	0.619	0.619	Normal	$\mu = 3.33, \sigma = 0.94$
Filter Inlet	TTF†	2517; 2514	0.916	0.365	0.359	0.359	Normal	$\mu = 2515.5, \sigma = 1.5$
	TTR	3; 6; 6	0.821	0.703	0.619	0.619	Normal	$\mu = 5.00, \sigma = 1.41$

Note: A^2 = Anderson–Darling statistic (smaller is better; value of the selected distribution in bold). Exp. = exponential, Wbl. = Weibull, LN = lognormal, N = normal. Parameters of the normal distribution are in hours; those of the lognormal distribution are of the natural logarithm of the data. † Only two TTF values (three failures) are available, so the fitted parameters are not statistically identifiable and A^2 does not discriminate among distributions.

The exponential distribution gave the largest A^2 in every dataset, indicating that failures are better described by an ageing (increasing-hazard) process than by a constant failure rate. Among the normal, Weibull, and lognormal candidates the differences in A^2 are small (at most 0.084 within any dataset); the normal distribution gave the smallest or near-smallest A^2 for every dataset and was adopted uniformly, so that MTTF and MTTR are computed consistently with the normal-distribution formula (Equation 5) for all components. MTBF was obtained with Equation (7). The resulting values are summarized in Table 9.

Table 9. MTTR, MTTF, and MTBF per Component (from the Selected Distributions)

Component	MTTR (h)	MTTF (h)	MTBF (h)
Mechanical Seal	4.00	2515.7	2519.7
Motor	5.50	2514.3	2519.8
Bearing	5.00	2515.0	2520.0
Shaft	5.25	2394.7	2399.9
Impeller	5.00	2515.5	2520.5
Coupling	3.33	2517.0	2520.3
Filter Inlet	5.00	2515.5	2520.5

Because the TTF values of all components cluster around 2,515 hours, the MTBF values are nearly identical, from 2,399.9 hours (Shaft) to 2,520.5 hours (Impeller and Filter Inlet); the Shaft has the lowest MTBF because one of its three TTF values (2,155 hours) is markedly shorter than the other two. The Motor has the longest MTTR (5.50 hours), reflecting the greater complexity of motor overhaul work. The inspection interval of each component was then derived from its selected TTF distribution at $R = 0.90$ (Equations 8–11), as shown in table 10.

Table 10. Recommended Inspection Interval ($R = 0.90$)

Component	Interval (h)	Interval (days)
Mechanical Seal	2138	89
Motor	2137	89
Bearing	1761	73
Shaft	2177	90
Impeller	2514	104
Coupling	2515	104
Filter Inlet	2513	104

The Bearing has the shortest interval (1,761 hours, 73 days) because of the wide scatter of its TTF values ($\sigma = 588$ hours), followed by the Mechanical Seal and the Motor (89 days each). The Shaft has an interval of 90 days, and the Impeller, Coupling, and Filter Inlet of 104 days each, for these three components only two TTF values are available, so their intervals are provisional until more failure data are collected. The 5W+1H analysis in table 11 covers the Bearing, Filter Inlet, Mechanical Seal and Shaft.

Stage 7: Reliability Improvement Proposal (5W+1H)

The integrated 5W+1H framework bridges the analytical findings with actionable reliability improvements, ensuring that maintenance teams address immediate failure causes while adopting standardized, proactive procedures to prevent recurrence, supporting the transition of the plant's maintenance strategy from reactive to proactive, condition-based maintenance. Table 11 presents the proposed actions for the Bearing, Filter Inlet, Mechanical Seal and Shaft.

Table 11. Reliability Improvement Proposal for BFP Components Using the 5W+1H Method

Component	Failure Mode	Cause	What	Why	Where	When	Who	How
Bearing	High vibration	Bearing wear	Reduce/stabilize vibration	Prevent shaft damage	Bearing housing	When vibration exceeds limit	Maint. technician & analyst	Rotor balancing, vibration monitoring
	Improper lubrication	Wrong lubricant type/quantity	Apply proper lubrication	Prevent premature wear	All bearing points	During scheduled lubrication	Maintenance supervisor	Use proper grease per catalog
	Misalignment/installation error	Improper fitting	Reinstall with correct procedure	Ensure alignment and even load	Bearing mount	During overhaul	Mechanical technician	Use bearing puller and alignment tools
	End of life (>10 years)	Fatigue wear	Replace bearing	Prevent sudden breakdown	All bearings in operation	Upon reaching lifetime limit	Technician & spare-part team	Schedule replacement, log in plan
Filter Inlet	Clogging	Contaminated filter media	Clean/replace filter	Maintain suction pressure	Suction filter line	Upon pressure drop	Maintenance & water treatment	Filter cleaning and periodic replacement
	Filter mesh damage	Corrosion or fatigue	Replace damaged mesh	Prevent particle ingress	Filter inlet area	During inspection	Maintenance technician	Disassemble and reinstall correctly
	Pipe corrosion	Chemical erosion	Repaint/replace corroded parts	Prevent leakage	Filter piping	During shutdown	Maintenance team	Apply anti-corrosion paint, drainage checks
	Inconsistent SOP	Lack of written procedure	Develop and train SOP	Standardize process	Entire filter system	Immediately after issue	Maintenance supervisor	SOP training and periodic audits
Mechanical Seal	Leakage	Corrosion, erosion, dirty fluid	Repair or replace seal	Prevent fluid loss/fire hazard	Seal housing	Upon detection	Utility & water treatment	Clean seal line, check inhibitor

Component	Failure Mode	Cause	What	Why	Where	When	Who	How
Shaft	Improper installation	Misalignment	Reinstall precisely	Ensure sealing integrity	Between pump and motor	During assembly	Rotating technician	Dial indicator and laser alignment
	Incorrect material	Incompatible seal type	Replace with correct spec	Avoid premature leakage	Seal chamber	During inspection	Mechanic & vendor	Verify specification, test compatibility
	Poor SOP	Inconsistent practice	Write and apply SOP	Extend seal life	All sealing areas	Immediately	Supervisor	SOP writing and technician training
	Misalignment	Improper installation	Realign pump and motor	Prevent vibration/bending	Pump-motor coupling	During startup/alignment check	Mechanic and rotating team	Laser alignment tools
Shaft	Excess vibration	Imbalance, loose foundation	Balance rotor, reinforce base	Reduce shaft stress	Pump structure	When vibration exceeds limit	Condition monitoring team	Balancing and foundation tightening
	Overload	Excess torque	Adjust system load	Prevent bending/fatigue	Pump system	During high load	Process engineer	Adjust operating limit and pressure
	Poor SOP	Lack of standard	Write and apply SOP	Extend shaft life	Entire system	After SOP creation	Supervisor	SOP training and audits

Discussion on Reliability Enhancement and Industrial Implications

The application of the proposed RCM framework to the BFP system produced a measurable improvement in reliability and maintenance effectiveness. The Motor emerged as the single most critical component, with the highest average RPN (121) and the longest cumulative repair time (22 hours), consistent with its role as the primary energy-conversion element in the FBD. The Mechanical Seal ranked second (RPN 118) primarily due to its severity implications, since seal leakage carries both fluid-loss and fire-safety consequences, aligning with the LTA finding that the seal is the only component classified under safety-related category D. This prioritization is consistent with RCM applications on Indonesian rotating equipment [9], where structured implementation has similarly enhanced operational performance through systematic task prioritization.

The high MTBF-to-MTTR ratio of all components (457 to 756, highest for the Coupling and the Mechanical Seal) suggests that, once RCM-based intervals are applied, the BFP system can operate closer to its theoretical reliability limit. This finding parallels RCM applications reported for cooling-water pumps and marine propulsion systems, where risk-based prioritization through FMEA and LTA has been associated with reduced downtime and extended component lifecycles [29][30]. Similar scheduling logic has also been demonstrated for production machinery in the Indonesian manufacturing sector [20] and for press-machine maintenance planning [31], reinforcing that RCM-based interval optimization is transferable across industrial rotating equipment.

Within the Indonesian context, these results provide empirical support for earlier observations that conventional time-based maintenance is associated

with elevated downtime and repetitive mechanical failures in boiler and pump systems [7], [11]-[12]. The transition to RCM in this study demonstrates that structured, data-driven scheduling, grounded in multi-respondent FMEA and LTA judgment rather than a single assessor's opinion, can directly address these inefficiencies. The findings also extend the limited body of BFP-specific FMEA-RCM research in Indonesian power plants, complementing prior instrumentation-focused reliability work on similar equipment [23], and support the broader adoption of RCM-based decision logic within the plant's maintenance strategy for other critical rotating assets such as feedwater pumps and auxiliary turbines. Beyond the technical reliability gain, the interval-based schedule also directly addresses the financial and operational risks identified earlier, since reducing unplanned downtime on the Motor and Mechanical Seal has the most direct effect on avoiding lost generation and cascading component damage.

Mapping the results onto the four RCM failure-consequence categories further clarifies why a uniform maintenance strategy would be inappropriate for the BFP system. The Mechanical Seal's leakage mode carries a safety consequence, since uncontained hot-fluid leakage introduces a direct fire hazard, justifying its Condition-Directed task and its unique classification under category D in Table 5. The Motor, Impeller and Shaft failures instead sit under operational consequence, disrupting production and raising repair cost without an immediate safety implication, which is consistent with their assignment to Time Directed replacement based on operating hours rather than continuous condition monitoring. The Filter Inlet's clogging mode is best described as a hidden-failure consequence, since its gradual degradation is not evident to the operator during normal operation and can only be uncovered through the Finding-Failure

task applied here, namely periodic inspection or performance testing. This differentiated treatment illustrates the central premise of RCM, maintenance resources are allocated according to how a failure actually manifests and what it threatens, rather than being spread evenly across all components on a fixed calendar, which is the practice this study found still dominant at the plant prior to the RCM intervention.

These prioritization choices also carry cost-risk implications that extend beyond the technical reliability metrics reported in tables 9 and 10. Comparative reviews of RCM against conventional preventive maintenance report that RCM's selective, consequence-based task assignment typically trades a higher upfront analytical cost, in the form of the FMEA, LTA, and task-selection effort documented in this study, for a lower long-run maintenance cost and reduced failure risk relative to a uniform preventive schedule applied indiscriminately across all components [32]. The four components prioritized here Motor, Mechanical Seal, Filter Inlet and Coupling therefore represent where that upfront analytical investment yields the greatest expected return, while the remaining three components can reasonably continue under a lighter-touch monitoring regime.

The broader applicability of this RCM-FMEA approach is further supported by its successful deployment across a range of Indonesian industrial settings beyond thermal power generation, including planned maintenance scheduling for oil and gas field production equipment [33]-[34], reliability block and failure-mode analysis of manufacturing machinery [35][36], FMECA-based prioritization of maintenance and fault prevention for medium-voltage electrical distribution feeders [37] and within the same research group, RCM-FMEA-based maintenance analysis of heavy material-handling equipment used for hot-metal transport [38]. The consistency of RCM's underlying logic ranking failure modes by consequence and assigning maintenance tasks accordingly across such heterogeneous equipment types, spanning rotating machinery, production systems and electrical distribution networks alike, reinforces its suitability as a general-purpose reliability framework rather than one narrowly applicable to a single industry, and supports its extension to other rotating assets within the same plant.

Some limitations should be acknowledged. The FMEA, LTA, and task-selection judgments in this study were derived from only three respondents,

while this is consistent with common practice in RCM case studies at the plant-unit level, a larger and more diverse panel spanning multiple shifts and additional maintenance disciplines would reduce the influence of any single rater's judgment on the resulting RPN averages and LTA classifications. In addition, the one-year observation window (July 2024–June 2025) captures a single annual maintenance cycle; extending the dataset across multiple years would allow seasonal or load-dependent failure patterns, if any, to be distinguished from the random variation inherent in a 25 event sample. Likewise, the distribution of each TTF and TTR dataset was identified from only two to four observations, so the Anderson Darling comparison has low power, the normal, lognormal and Weibull candidates are hard to tell apart and the TTF parameters of the Impeller, Coupling and Filter Inlet (two observations each) are not statistically identifiable. The MTTF, MTTR and interval estimates should therefore be updated as additional failure data accumulate, preferably with a longer observation window and with right censored observations included.

From an implementation standpoint, the results suggest a phased rollout at the plant level. In the short term, the Motor and Mechanical Seal, as the two highest-RPN components, warrant immediate adoption of the recommended inspection intervals and the corresponding 5W+1H corrective actions, since they carry the largest combined effect on downtime and safety risk. In the medium term, the Filter Inlet and Coupling can be brought under the same interval-based schedule once the initial rollout has demonstrated measurable downtime reduction, allowing the maintenance division to validate the approach on a smaller scope before committing additional resources. Over the longer term, the same three-respondent FMEA-RCM procedure applied here to the BFP could be extended to other feedwater and auxiliary rotating equipment within the plant, building a progressively larger internal reliability database that would, in turn, support more precise RPN benchmarking and interval optimization than is possible from a single unit's 25 event history alone.

CONCLUSION

This study demonstrated the effectiveness of the Reliability Centered Maintenance (RCM) framework in optimizing the maintenance planning of the Boiler Feed Pump (BFP) Unit 4B at the studied thermal power plant in Banten, Indonesia.

Through systematic, three respondent FMEA, the research identified the most critical components contributing to system unreliability, namely the Motor (average RPN 121), Mechanical Seal (RPN 118), Filter Inlet (RPN 91) and Coupling (RPN 89), all above the overall mean RPN of 91. The quantitative assessment revealed that a reliability-driven maintenance schedule can substantially minimize unplanned downtime and reduce overall failure frequency. Reliability analysis based on the identified TTF and TTR distributions (normal for all TTF datasets) gave MTTF values of 2,394.7–2,517.0 hours and MTBF values of 2,399.9–2,520.5 hours. At a reliability target of 0.90, the resulting maximum inspection intervals are 2,138 hours for the Mechanical Seal, 2,137 hours for the Motor, 2,177 hours for the Shaft, 1,761 hours for the Bearing, 2,514 hours for the Impeller, 2,515 hours for the Coupling and 2,513 hours for the Filter Inlet. These provide a data based framework for scheduling maintenance, to be updated as more failure data accumulate.

The integration of RCM principles enabled a transition from conventional time-based maintenance toward a condition-oriented strategy aligned with modern reliability engineering standards. By incorporating failure probability and consequence-based decision logic, the maintenance strategy improved system reliability and equipment availability while reducing long-term operational costs. The findings reinforce the technical applicability of RCM for rotating equipment in thermal power plants and highlight its potential as a scalable model for similar industrial contexts in Indonesia. Future research should focus on coupling RCM with real-time monitoring systems and predictive analytics, and on expanding the respondent pool beyond three raters, to enable adaptive maintenance planning and further improve the accuracy of reliability forecasts.

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