



Processing dates: received on 2026-4-06, reviewed on 2026-05-24, accepted on 2026-06-01 and online availability on 2026-06-30

Optimizing maintenance scheduling of water distribution pumps using reliability centered maintenance (RCM)

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Abstract

Water distribution pump systems are critical assets in public utility services, where failures can directly disrupt service continuity and increase operational costs. Empirical evidence from water utility operations indicates that conventional maintenance strategies are often unable to control downtime and reliability degradation effectively. This study aims to analyze maintenance scheduling for water distribution pumps using the Reliability Centered Maintenance (RCM) approach to improve system reliability and availability. A quantitative case study was conducted at a regional water utility using one year of historical operational and maintenance data from January to December 2025. The research methodology integrates Pareto analysis to identify critical assets, Failure Mode and Effect Analysis (FMEA) to prioritize dominant failure modes, and reliability analysis based on the Weibull distribution to estimate Mean Time to Failure (MTTF) and Mean Time to Repair (MTTR). The RCM Decision Worksheet was applied to determine appropriate maintenance actions and optimal preventive replacement intervals. The results showed that the distribution pump was the most critical asset, contributing the highest downtime (620 hours per year across 11 failures). The optimal preventive replacement interval was identified at 1,400 operating hours, reducing annual downtime to 12.7 hours (97.6% reduction) and increasing system availability to 99.78%. These findings confirm that RCM-based maintenance scheduling can improve the reliability, availability, and operational performance of water distribution pumping.

Keywords:

Water distribution pump, maintenance scheduling, RCM, FMEA, downtime reduction.

1 Introduction

In modern industrial systems, maintenance has evolved from a supporting activity into a strategic function that directly affects reliability, availability, safety, and operational costs of physical assets. Water distribution pump systems are considered critical assets because they operate continuously under high load conditions and are subject to vibration, cavitation, mechanical wear, and material degradation. Conventional maintenance practices, which are generally dominated by corrective maintenance and periodic preventive maintenance, are often unable to ensure long-term system reliability because they do not consider the actual failure behavior of each component [1], [2], [3]. As a result, industrial pump systems frequently experience unplanned downtime, high repair costs, and reduced operational availability, particularly in water utility industries that require continuous service operations [4], [5], [6].

These problems are reflected in the operational condition of the water distribution pump system investigated in this study. Maintenance data from 2025 indicate that the distribution pump experienced 11 breakdown events with a total downtime of 620 hours, while dosing and submersible pumps recorded 7 events (375 hours) and 4 events (155 hours), respectively. The high failure rate of the distribution pump indicates that several critical components, such as bearings, couplings, and electric motors, undergo progressive degradation that is not detected early. This condition not only increases corrective maintenance costs but also disrupts water distribution services and decreases service continuity. Previous studies have also reported that ineffective maintenance strategies and the limited use of historical failure data contribute significantly to industrial pump failures and operational inefficiencies [7].

Reliability Centered Maintenance (RCM) has been widely applied as a maintenance strategy that focuses on system functions, failure consequences, and reliability characteristics. RCM generally integrates Failure Mode and Effect Analysis (FMEA), reliability indicators such as Mean Time To Failure (MTTF) and Mean Time To Repair (MTTR), and maintenance decision logic to determine suitable maintenance actions [8], [9], [10]. Several studies have shown that RCM can reduce downtime, improve equipment availability, and optimize maintenance costs in manufacturing and energy industries [11], [12], [13]. However, most previous studies still have several limitations. Many studies focus solely on qualitative failure analysis using FMEA, without quantitatively identifying the dominant failure components through Pareto analysis. In addition, reliability analysis is commonly limited to general MTTF and MTTR calculations without applying Weibull distribution modeling to represent actual component failure behavior. Preventive replacement interval optimization is also often discussed separately from the RCM framework, resulting in less integrated maintenance scheduling decisions. Furthermore, studies specifically addressing water utility pump systems remain limited despite their critical role in public service operations.

Therefore, the novelty of this study lies in integrating Pareto analysis, FMEA, Weibull-based reliability analysis, and preventive replacement interval optimization within an RCM framework specifically for water distribution pump systems. This study combines actual operational downtime data with quantitative reliability modeling to identify critical components, evaluate failure risks, and determine optimal preventive replacement intervals. The proposed approach is expected to make both academic contributions to the development of integrated RCM methodologies and practical guidance for improving reliability, reducing downtime, and optimizing maintenance costs in the water utility industry.

2 Research methodology

2.1 Research design and approach

This study employs a quantitative-analytical approach using the Reliability Centered Maintenance (RCM) framework to develop maintenance scheduling for water distribution pump systems [14]; [15], [16]. The RCM approach was selected because it enables integrating historical failure data, failure analysis, and reliability parameters to generate optimal maintenance policies tailored to system functions and risk levels [17]. A case study was conducted on a water distribution pump system operated by a regional water utility company (Perumda), with an observation period covering one full year of operation from January to December 2025.

2.2 Data collection and characterization

The data used in this study consist of secondary data obtained from historical maintenance and failure records of water pump machines, including distribution, dosing, and submersible pumps [18], [19]. The dataset includes failure dates, repair start and completion times, downtime duration, and the number of failure occurrences. To ensure data accuracy and consistency, the records were validated through technical discussions with operation and maintenance personnel. The downtime summary indicates that the distribution pump contributes the highest proportion of total

downtime; therefore, it was selected as the primary object for further analysis [20], [21].

2.3 Critical component identification

Critical component identification was carried out using Pareto analysis based on the 80/20 principle, considering cumulative downtime contributions [22]. The Pareto analysis results reveal that the distribution pump accounts for more than 50% of the total annual downtime compared to other pump types. Accordingly, the RCM analysis focused on the distribution pump as a critical asset with a direct impact on the continuity of water distribution services.

2.4 Root cause analysis

To identify the underlying causes of failures, brainstorming and brainwriting methods were applied through structured interviews with branch managers, technical supervisors, and maintenance technicians. The identified causes were classified into four main categories: methods, man power, materials, and machines. The results were subsequently visualized using a fishbone (Ishikawa) diagram to map cause-effect relationships associated with downtime and to support the identification of failure modes in the subsequent analysis stage.

2.5 Failure mode and effect analysis (FMEA)

Failure Mode and Effect Analysis (FMEA) was conducted to identify potential failure modes, their causes, and their effects on the system [23]. Each failure mode was evaluated using three parameters: Severity (S), Occurrence (O), and Detection (D). The Risk Priority Number (RPN) was calculated as the product of these three parameters:

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

Failure modes with the highest RPN values were prioritized for determining the maintenance strategy. The FMEA results indicate that the distribution pump components exhibit the highest RPN values, highlighting the need for preventive maintenance policies and scheduled inspections to mitigate failure risks and reduce operational downtime.

2.6 Calculation of time to failure (TTF) and time to repair (TTR)

Historical downtime data was used to calculate Time to Failure (TTF) and Time to Repair (TTR) [3]. TTF is defined as the time interval between two consecutive failure events. At the same time, TTR represents the duration required to restore the equipment to its normal operating condition for each failure event. The calculated TTF and TTR values were then used as input for the reliability analysis.

The goodness-of-fit test results indicated that the TTF and TTR data were best represented by the Weibull distribution, characterized by a shape parameter (β) and a scale parameter (η) [17], [19]. The probability distributions were analyzed using Minitab software, with distributions selected based on the Anderson-Darling (AD) statistic and p-value, assuming that reliability and time to failure follow a specific statistical pattern. This distribution reflects the wear-related failure pattern commonly observed in mechanical components such as water distribution pump systems, where failure rates increase over time due to progressive degradation.

The Weibull distribution functions used in this study are described as follows:

- a. Probability Density Function (PDF)

$$f(t)=\frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1}e^{-\left(\frac{t}{\theta}\right)^{\beta}} \quad (2)$$

- b. Cumulative Distribution Function (CDF)

$$F(t)=1-e^{-\left(\frac{t}{\theta}\right)^{\beta}} \quad (3)$$

- c. Reliability Function

$$R(t)=e^{-\left(\frac{t}{\theta}\right)^{\beta}} \quad (4)$$

2.7 Estimation of reliability parameters

Based on the estimated Weibull distribution parameters, the Mean Time To Failure (MTTF) and Mean Time To Repair (MTTR) were calculated [15]. MTTF represents the average time to failure of the system, whereas MTTR represents the average time to repair the system and restore it to normal operating conditions. These parameters constitute the basis for evaluating system reliability and availability, as well as for designing optimal preventive maintenance intervals.

Mean Time To Failure (MTTF)

Mean Time To Failure (MTTF) is defined as the expected value of the time to failure and can be interpreted as the average operational lifetime of a component before failure. Mathematically, MTTF is expressed as the expected value of the random variable T.

$$MTTF = E(T) = \int_0^{\infty} t f(t) dt \quad (5)$$

$$f(t) = \frac{dF(t)}{dt}$$

sehingga;

$$MTTF = \int_0^{\infty} R(t) dt \quad (6)$$

Where

$f(t)$ = probability density function,

t = operating time

$R(t)$ = reliability function

For a system whose time-to-failure follows a Weibull distribution, the Mean Time To Failure can be calculated directly from the Weibull parameters as:

$$MTTF = \theta \Gamma \left(1 + \frac{1}{\beta} \right) \quad (7)$$

where:

$f(t)$ = probability density function

θ = scale parameter,

β = shape parameter,

$\Gamma(\cdot)$ = Gamma function.

This formulation enables efficient estimation of MTTF and provides insight into the failure behavior of distribution pump components, particularly in identifying wear-out failure patterns critical for preventive maintenance planning.

Mean Time To Repair (MTTR)

Mean Time To Repair (MTTR) is a performance metric that indicates how quickly the maintenance team can repair a failure and restore the system to its operational condition [25]. MTTR reflects the effectiveness of maintenance activities and directly impacts system availability and operational continuity.

For repair time data that follow a Weibull distribution, MTTR can be calculated using the following expression:

$$MTTR = E(T) = \int_0^{\infty} t f(t) dt$$

and,

$$MTTR \text{ Weibull} = \eta \cdot \Gamma \left(1 + \frac{1}{\beta} \right) \quad (8)$$

$f(t)$ = probability density function repair time

The calculated MTTR value represents the average duration required to complete repair actions. It serves as a critical input for availability analysis and preventive maintenance scheduling within the Reliability Centered Maintenance (RCM) framework.

2.8 Reliability parameters before and after preventive maintenance actions

Reliability analysis was conducted to evaluate system performance before and after the implementation of preventive maintenance actions [10]. Based on the estimated Weibull distribution parameters, the values of Mean Time To Failure (MTTF) and Mean Time To Repair (MTTR) were calculated. MTTF represents the average time to failure, while MTTR represents the average time to restore the system to operational condition. These parameters serve as the foundation for assessing system reliability, availability, and for designing optimal preventive maintenance intervals.

The reliability of the system at time t under a preventive maintenance policy is defined as follows:

$$R_m(t) = R(t), \quad 0 \leq t < T$$

$$R_m(t) = R(T) R(t-T), \quad T \leq t < 2T$$

where:

T = preventive replacement interval,
 $R_m(t)$ = reliability of the system with preventive maintenance,
 $R(t)$ = reliability of the system without preventive maintenance,
 $R(T)$ = reliability up to the first preventive maintenance action,
 $R(t-T)$ = reliability during the interval $t-T$ after the system has been restored to its initial condition at time T .

In general, the reliability function for a system subjected to periodic preventive maintenance can be expressed as:

$$R_m(t) = R(T)^n R(t-nT) \quad (9)$$

For $nT \leq t < (n+1)T$, where $n=0,1,2,\dots$

with:

n = number of preventive maintenance actions performed up to time t ,
 T = preventive maintenance interval,
 $R(T)^n$ = probability of survival through n preventive maintenance intervals,
 $R(t-nT)$ = reliability during the elapsed time since the most recent preventive maintenance action.

2.9 Determination of optimal preventive replacement interval

The preventive replacement interval was determined using the downtime ratio minimization approach [15], denoted as $D(tp)$. The optimal interval was determined through a trial-and-error procedure by evaluating several preventive-replacement candidates over the range of 600–1700 operating hours. This range was selected based on the historical failure characteristics of the critical components, particularly the Mean Time To Failure (MTTF) values derived from the Weibull distribution analysis, which were found to fall within this operational range. The lower limit of 600 hours represents an early replacement condition before the probability of failure increases significantly, while the upper limit of 1700 hours reflects operating conditions approaching the actual failure age observed from historical breakdown data. Therefore, the selected range was deemed sufficient to represent various maintenance scenarios, from highly conservative preventive replacement to conditions approaching corrective replacement.

For each preventive replacement candidate (tp), the reliability function $R(tp)$, failure probability $F(tp)$, mean failure time $M(tp)$, and downtime ratio $D(tp)$ were evaluated. The value of $D(tp)$ was calculated by considering both downtime caused by preventive replacement activities and downtime resulting from corrective replacement when component failure occurred before the planned replacement interval. The optimal preventive replacement interval was identified as the tp value that minimized $D(tp)$, indicating the best balance between preventive replacement frequency and the risk of unexpected component failure.

To improve the robustness of the obtained interval, a simple sensitivity analysis was also performed by comparing the variation in $D(tp)$ values around the optimal point. The results showed that the selected interval consistently provided the lowest downtime ratio and remained relatively stable compared to neighboring intervals. In addition, the trial-and-error approach was considered appropriate for representing actual operational conditions and offered practical advantages for maintenance scheduling implementation in water distribution pump systems.

The downtime ratio is defined as the ratio between the expected downtime per cycle and the expected cycle length, expressed as:

$$D(tp) = \frac{\text{Expected downtime per cycle}}{\text{Expected cycle length}}$$

The expected downtime per cycle is calculated as:

$$\text{Expected downtime per cycle} = T_p \cdot R(tp) + T_f \cdot [1 - R(tp)]$$

where:

T_p = downtime required for preventive replacement,
 T_f = downtime required for corrective repair following failure.

The expected cycle length is given by:

$$\text{Expected cycle length} = (tp + T_p) \cdot R(tp) + [M(tp) + T_f] \cdot [1 - R(tp)]$$

Accordingly, the downtime ratio function can be expressed as:

$$D(tp) = \frac{T_p \cdot R(tp) + T_f \cdot [1 - R(tp)]}{(tp + T_p) \cdot R(tp) + [M(tp) + T_f] \cdot [1 - R(tp)]} \quad (10)$$

2.10 Analysis of availability and downtime after RCM implementation

System availability was evaluated to assess the effectiveness of the Reliability Centered Maintenance (RCM) policy in reducing downtime and improving system performance [10], [14]. The availability of the system was first estimated based on the relationship between availability and the downtime ratio, expressed as:

$$A = 1 - D(tp)$$

where $D(tp)$ denotes the optimal downtime ratio corresponding to the preventive replacement interval tp . Annual downtime after RCM implementation was then calculated by multiplying the optimal downtime ratio by the total annual operating hours. This analysis provides a quantitative measure of the impact of RCM on system availability and downtime reduction.

In addition, availability was calculated using the conventional reliability-based formulation:

$$\text{Availability} = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR}} \quad (11)$$

where:

MTTF = mean time between machine failures,
 MTTR = mean time required to repair the machine.

To obtain a more comprehensive evaluation, availability was further analyzed based on inspection frequency and preventive replacement intervals. Availability based on inspection frequency is defined as:

$$D(n) = \frac{k}{m \cdot n} + \frac{1}{i}$$

$$A(n) = 1 - D(n) \quad (12)$$

where

k = average number of failures per year,
 m = average monthly operating hours,
 n = inspection frequency,
 i = inspection rate.

Availability based on the preventive replacement interval is expressed as:

$$A(tp) = 1 - D(tp) \quad (13)$$

where $D(tp)$ represents the total downtime per cycle corresponding to the preventive replacement policy.

Finally, the overall system availability was calculated by combining the availability contributions from inspection and preventive replacement strategies:

$$\text{Availability}_{\text{total}} = A(n) \times A(tp) \quad (14)$$

This comprehensive availability analysis enables a systematic evaluation of the effectiveness of RCM implementation in improving system availability and reducing operational downtime in water distribution pump systems.

2.11 Determination of inspection interval

The inspection frequency and interval were determined by considering the failure rate, inspection rate, and repair rate of the system [1]. These parameters were calculated to ensure inspections are conducted at optimal intervals to detect component degradation before functional failure.

The steps for calculating the optimal inspection interval are as follows.

The average repair rate is defined as:

$$\frac{1}{\mu} = \frac{MTTR}{\text{Average monthly operating hours}} \quad (15)$$

where μ represents the repair rate of the system.

The average inspection rate is calculated as:

$$\frac{1}{i} = \frac{\text{Average inspection time}}{\text{Monthly operating hours}} \quad (16)$$

where i denotes the inspection rate.

The average failure rate is expressed as:

$$k = \frac{\text{number of failures over 12 month}}{12 \text{ bulan}} \quad (17)$$

Based on these parameters, the **inspection frequency** is determined using:

$$n = \sqrt{\frac{k \cdot i}{\mu}} \quad (18)$$

Where,

n = inspection frequency

k = failure rate

i = inspection rate

μ = repair rate

Finally, the **inspection interval** is calculated as:

$$ti = \frac{\text{average monthly operating hours}}{n} \quad (19)$$

3 Result and discussion

3.1 Data collection

Historical maintenance and downtime data were collected from a regional water utility company (Perumda) over a one-year period, from January to December 2025. The data covered three types of water pump machines, namely distribution pumps, dosing pumps, and submersible pumps, all of which experienced breakdown maintenance events resulting in operational stoppages and downtime. The collected data represent actual operational records used as the empirical basis for reliability and maintenance analysis.

Table 1. Downtime of distribution pump

No	Date	Start (hours)	Finish (hours)	Number of repair (hours)
1	09-12 January	12:10	00:10	60
2	24-26 February	11:05	18:05	55
3	15-18 March	10:00	03:00	65
4	02-04 April	14:00	14:00	50
5	06-08 May	13:05	20:05	55
6	08-11 June	12:10	00:10	60
7	12-15 July	13:30	01:30	60
8	03-05 August	10:15	07:15	45
9	19-21 September	11:05	19:05	55
10	14-16 October	21:00	23:00	50
11	18-21 November	20:00	13:00	65
Total				620

Table 2. Downtime of the dosing pump

No	Date	Start (hours)	Finish (hours)	Number of repairs (hours)
1	06-08 January	10:10	17:10	55
2	18-20 March	11:05	13:05	50
3	10-13 May	21:00	09:00	60
4	20-22 July	14:00	16:00	50
5	15-17 August	13:15	10:05	45
6	28-01 Sept-Okt	14:25	02:25	60
7	02-04 December	10:55	17:55	55
Total				375

Table 3. Downtime of dosing pump

No	Date	Start (hours)	Finish (hours)	Number of repair (hours)
1	06-08 January	10:10	07:10	45
2	12-13 February	11:05	22:05	35
3	10-12 March	21:00	13:00	40
4	20-22 April	14:00	01:00	35
Total				155

The maintenance history data include failure dates, repair start and completion times, downtime duration, and the number of breakdown occurrences for each pump type. Table 1 presents the downtime records for the distribution pump, which experienced 11 breakdown events totaling 620 hours during the observation period. Table 2 summarizes the downtime of the dosing pump, which recorded 7 breakdown events with a total downtime of 375 hours, while Table 3 shows the downtime data of the submersible pump, which experienced 4 breakdown events with a total downtime of 155 hours.

3.2 Selection of critical components

Based on the accumulated downtime data, a Pareto analysis was conducted to identify the most critical pump contributing to overall system downtime, as illustrated in Fig. 1.

Water pump downtime Pareto diagram

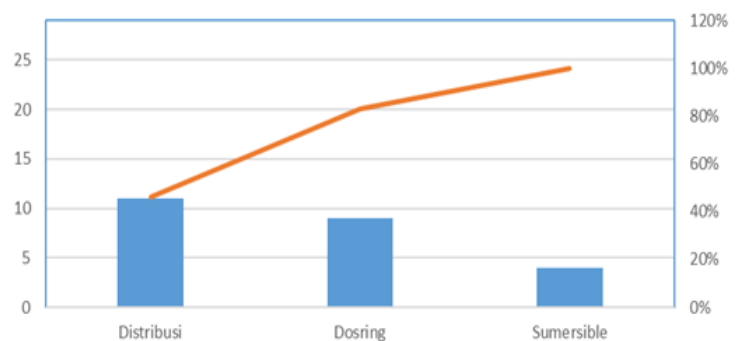


Fig. 1. Pareto diagram of the downtime of the pump

The Pareto diagram clearly indicates that the distribution pump is the dominant contributor to total downtime, accounting for the largest proportion compared to the dosing and submersible pumps. Therefore, the distribution pump was selected as the primary focus of further reliability and maintenance analysis.

3.3 Failure mode and effect analysis

In this calculation, Failure Mode and Effects Analysis (FMEA) is used to identify the causes and effects of failures in the water pump machine. This analysis applies rating values that describe the level

Table 4. Failure mode and effect analysis of the water pump machine.

No	Component	Potential Failure	Cause of Failure	Failure Effect	Severity	Occurance	Detection	RPN
1	Distribution	Excessive vibration and unstable water flow	Bearing wear and shaft misalignment	Water distribution decreases	7	8	8	448
2	Dosring	Incorrect chemical dosage	Coupling looseness and blockage	Water treatment quality decreases	6	8	7	336
3	Submersible	Pump fails to operate	Motor overheating and short	Water supply stops	8	5	7	280

From Table 4, it can be seen that the lack of a standard operating procedure (SOP) for inspecting the water pump machine before operation is the leading cause of failure, with an RPN of 448. This value is the highest and therefore the top priority for identifying the problem's root cause and providing recommendations for corrective actions or improvements.

3.4 Determination of failure data and repair data distribution

3.4.1 Distribution component

The distribution component is a unit that distributes or channels water into the production process. Based on the operational history, downtime events occurred in the distribution component as shown in Table 4.5 from January 2025 to December 2025, with a total of 11 (eleven) failure occurrences recorded. These failures caused the production line machine to experience a total downtime of 620 (six hundred and twenty) hours. The following are the data processing steps carried out for the distribution component.

3.4.2 Calculation of time to repair (TTR) and time to failure (TTF)

The Time To Repair (TTR) was calculated to determine the duration from the occurrence of component failure to the completion of the repair process. Time To Failure (TTF) was obtained as the time interval between consecutive component failure events.

Table 5. Results of time to repair and time to failure calculation in 2025

No	Date	Start (hours)	Finish (hours)	TTR (hours)	TTF (hours)
1	09 January	12:10	13:10	60	-
2	24 February	11:05	12:00	55	1.104
3	15 March	10:00	11:05	65	456
4	02 April	14:00	14:50	50	432
5	06 May	13:05	14:00	55	816
6	08 June	12:10	13:10	60	792
7	12 July	13:30	14:30	60	816
8	03 August	10:15	11:00	45	528
9	19 September	11:05	12:00	55	1.128
10	14 October	21:00	21:50	50	600
11	18 November	20:00	21:12	65	840

3.4.3 Identification of distribution for time to failure (TTF)

To determine the most appropriate distribution for Time To Failure (TTF) based on failure time data, a goodness-of-fit index was calculated for each selected distribution. The distribution selection was based on the smallest goodness-of-fit index for each component.

of damage and the causes of the effects occurring in the water pump machine. The rating values used to calculate the Risk Priority Number (RPN) consist of Severity, Occurrence, and Detection. For severity, a score of 1 indicates no significant impact on the damage, and a score of 10 indicates the failure will result in equipment malfunction and impact safety. For occurrence, a score of 1 indicates the failure can be controlled without impacting the equipment, and a score of 10 indicates a 50% frequency of the damage. For detection, a score of 1 indicates the damage can be quickly identified, and a score of 10 indicates the damage is almost undetectable.

The distributions evaluated in this analysis include the Exponential distribution, Weibull distribution, Normal distribution, and Lognormal distribution.

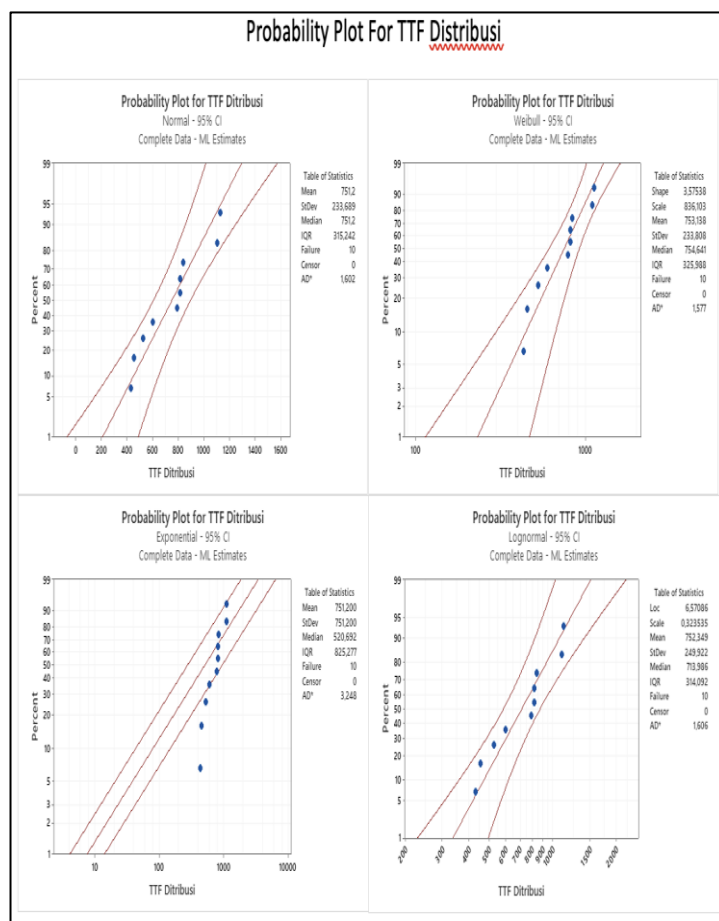


Fig.2. Probability plot for TTF distribution

Based on the results of the Time To Failure (TTF) distribution analysis for the water pump machine components, the distribution analysis was performed using Minitab 19. The selection criterion was based on the smallest Anderson–Darling (A–D) statistic value among the candidate distributions. After conducting the goodness-of-fit test, the results indicate that the Weibull distribution provides the best fit for the TTF data. The estimated Weibull parameters consist of a shape parameter (β) of 3,57538 and a scale parameter (η) of 836,10293, with an Anderson–Darling statistic value of A=1,577 for the Time To Failure (TTF) data.

Distribution Identification for TTF Distribution ID Plot for TTF

Descriptive Statistics

N	N*	Mean	StDev	Median	Minimum	Maximum	Skewness	Kurtosis
10	0	751,2	246,330	804	432	1128	0,240652	-0,976443

Goodness-of-Fit

Distribution	Anderson-Darling (adj)
Weibull	1,577
Lognormal	1,606
Exponential	3,248
Normal	1,602

ML Estimates of Distribution Parameters

Distribution	Location	Shape	Scale	Threshold
Normal*	751,20000		246,32986	
Exponential			751,19995	
Weibull		3,57538	836,10293	
Lognormal*	6,57086		0,34104	

* Scale: Adjusted ML estimate

Fig.3. Identification TTF distribution

3.4.4 Identification of Distribution for Time To Repair (TTR)

To determine the most appropriate distribution for Time To Repair (TTR) based on repair time data, a goodness-of-fit index was calculated for each selected distribution. The selection of the distribution was based on the smallest goodness-of-fit index value for each component.

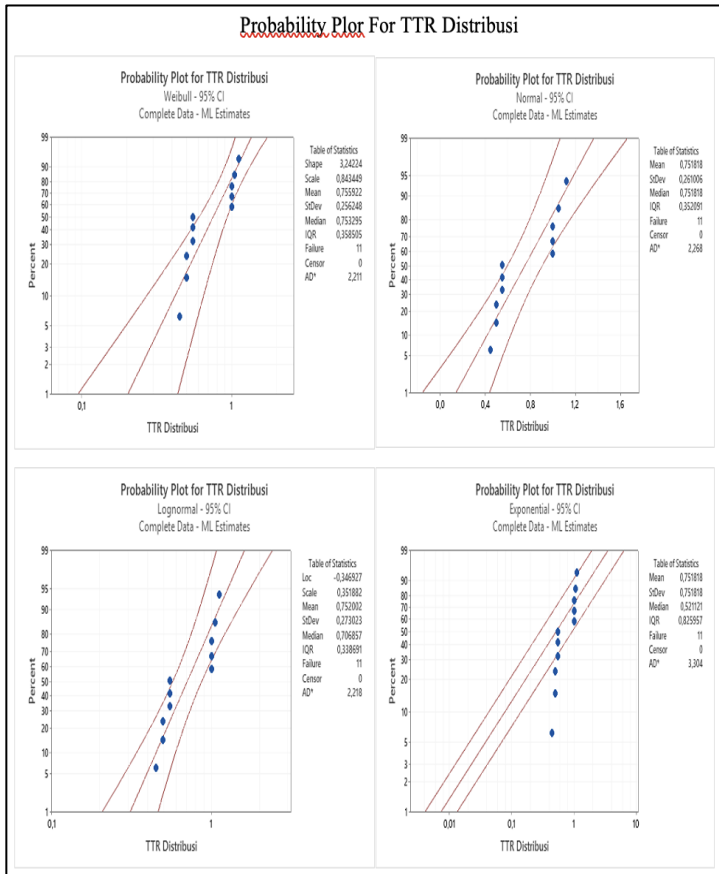


Fig.4. Probability plot for TTF distribution

Distribution Identification for TTR Distribution ID Plot for TTR

Descriptive Statistics

N	N*	Mean	StDev	Median	Minimum	Maximum	Skewness	Kurtosis
11	0	0,751818	0,273745	0,55	0,45	1,12	0,227545	-2,24108

Goodness-of-Fit

Distribution	Anderson-Darling (adj)
Weibull	2,211
Lognormal	2,218
Exponential	3,304
Normal	2,268

ML Estimates of Distribution Parameters

Distribution	Location	Shape	Scale	Threshold
Normal*	0,75182		0,27375	
Exponential			0,75182	
Weibull		3,24224	0,84345	
Lognormal*	-0,34693		0,36906	

* Scale: Adjusted ML estimate

Fig.5. Identification TTR distribution

Based on the selection criterion of the smallest Anderson–Darling statistic, the goodness-of-fit test results indicate that the Time To Repair (TTR) data are best represented by a Weibull distribution. The estimated Weibull parameters consist of a shape parameter (β) of 3.24224 and a scale parameter (η) of 0.84345, with an Anderson–Darling statistic value of $A=2.211$ for the Time To Repair (TTR) data.

3.4.5 Calculation of mean time to failure (MTTF) and mean time to repair (MTTR)

After conducting the goodness-of-fit test, the next step was to calculate the Mean Time To Failure (TTF) and, subsequently, the Mean Time To Failure (MTTF) for the distribution component. Using Equation (2.7), the MTTF value for the distribution component was obtained.

$$MTTF = \theta \Gamma \left(1 + \frac{1}{\beta} \right) = \Gamma. 1,786$$

Based on the value obtained from the Gamma (Γ) table, the calculation yields a Gamma value of.

Therefore, based on the above calculation, the Mean Time To Failure (MTTF) of the distribution component is 1,683 hours.

Using the same procedure and Equation (2.8), the Mean Time To Repair (MTTR) for the distribution component was calculated as 4.74 hours.

3.5 Reliability-centered maintenance decision worksheet

The Reliability Centered Maintenance (RCM) Decision Worksheet is used to determine the most appropriate maintenance process activities and to identify possible actions to address each failure mode. The selection of maintenance activities aims to achieve cost efficiency for each existing failure mode. The RCM Decision Worksheet is a systematic process within the RCM framework for determining the most suitable maintenance actions to effectively address identified problems [26].

Effectiveness in this context refers to a maintenance policy that selects activities capable of preventing, detecting, or identifying

hidden failures. In applying the RCM Decision Worksheet, it is necessary to define functional failures, failure modes, and failure impacts to determine appropriate maintenance actions. This approach enables efficient maintenance planning for water pump machines, allowing for optimal repair activities and restoring the machine to normal operating conditions.

The objectives of the Reliability Centered Maintenance Decision Worksheet are as follows:

1. To determine appropriate maintenance activities.
2. To analyze the consequences of failures.
3. To record important information related to failure occurrences.
4. To determine maintenance intervals.
5. To facilitate decision-making processes.

Table 6. RCM decision worksheet water pump machine

No	Component	Function	Functional Failure	Failure Mode	Failure Effect	Failure Consequences	Recommended Action	Maintenance Action Perform
1	Submersible	Lifting water from the source	Unable to deliver water	Motor burned	The water supply stops	Operation stopped	Routine inspection of the motor and cables	Bearing and motor check
2	Dosring	Adding chemical liquid precisely	Failure to add liquid	Pump clogged	Water treatment quality decreases	Process disrupted	Cleaning of chemical lines and pump inspection	Replacement of damaged pump components
3	Distribution	Delivering water to the output system	Bearing wear and shaft misalignment	Pump heat and leakage	Water flow stopped	Water distribution decreases	Bearing and shaft alignment	Check component vibration (CBM)

Based on the results of the Reliability Centered Maintenance (RCM) Decision Worksheet analysis.

1. Submersible

- a. Main function: The submersible component functions to lift water from the water source into the distribution system.
- b. Functional failure: Unable to lift water due to motor malfunction.
- c. Failure mode: The main cause of failure is a burned motor, which is usually caused by overloading or damage to the cable.
- d. Failure effect: No water flow occurs, causing pump operation to stop completely.
- e. Consequences: Operational consequences occur due to disruption of the water supply.
- f. Recommended action: Routine inspections of the motor and cables are carried out to detect potential problems before serious damage occurs.
- g. Maintenance action: If severe damage is found, the motor must be replaced to restore system functionality.

2. Dosing

- a. Main function: The dosing component functions to add chemical liquid precisely into the system according to process requirements.
- b. Functional failure: Failure to add chemical liquid accurately.
- c. Failure mode: The dosing pump becomes clogged due to the accumulation of residue or particles in the liquid line.
- d. Failure effect: The concentration of the chemical liquid does not meet the expected specifications, causing disturbances in the water treatment process.
- e. Consequences: The process is disrupted, which may affect the quality of the final output or the safety of the treated water.
- f. Recommended action: The liquid lines are cleaned routinely.
- g. Maintenance action: If the pump components suffer severe damage, the damaged parts must be replaced.

3. Distribution

- a. Main function: To deliver water from the pump system to the output system or end-user points.
- b. Functional failure: seal leakage causes ineffective water distribution.
- c. Failure mode: high vibration and unstable water flow are incorrect.
- d. Failure effect: water distribution decreases, preventing distribution from reaching the destination points.
- e. Consequences: water abnormal can be delivered to the output, disrupting processes or usage needs.

- f. Recommended action: Routine inspections and alignment of bearing and shaft.
- g. Maintenance action: maintenance scheduling, with CBM vibration analysis and heat.

3.6 Optimal replacement time

Furthermore, the MTTF and MTTR values for the distribution pump were obtained as 1,683 hours and 4.74 hours, respectively. Subsequently, the parameters and the distribution type for the time between failures were required. Based on the Goodness-of-Fit Test, the impeller component follows a Weibull distribution with a shape parameter (β) of 3.575 and a scale parameter (η) of 836.1. The optimal replacement interval for the distribution pump component was calculated using a trial-and-error approach, starting with a preventive replacement time t_{pt_ptp} of 600 hours and increasing to 1,700 hours.

Accordingly, the total downtime per unit time during preventive replacement can be determined using the following equation:

Table 7. Optimal component replacement calculation table

tp (jam)	R(tp)	F(tp)	M(tp) (jam)	D(tp)
600	0.7369	0.2631	6395.7	0.002226
650	0.6660	0.3340	5038.3	0.002235
700	0.5887	0.4113	4091.8	0.002257
750	0.5076	0.4924	3417.9	0.002292
800	0.4257	0.5743	2930.5	0.002337
850	0.3462	0.6538	2574.2	0.002392
900	0.2722	0.7278	2312.5	0.002452
950	0.2063	0.7937	2120.3	0.002516
1000	0.1501	0.8499	1980.3	0.002579
1050	0.1046	0.8954	1879.6	0.002637
1100	0.0695	0.9305	1808.7	0.002587
1150	0.0439	0.9561	1760.3	0.002727
1200	0.0263	0.9737	1728.4	0.002257
1250	0.0148	0.9852	1708.3	0.002278
1300	0.0079	0.9921	1696.3	0.002392
1350	0.0039	0.9961	1689.6	0.002400
1400	0.0018	0.9982	1686.1	0.002204
1450	0.0008	0.9992	1684.3	0.002207
1500	0.0003	0.9997	1683.5	0.002308
1550	0.0001	0.9999	1683.2	0.002308
1600	0.0000	1.0000	1683.1	0.002308
1650	~0	~1	1683.0	0.002308
1700	~0	~1	1683.0	0.002308

$D(tp)$ represents the minimum downtime probability value within the preventive replacement interval t_{pt_ptp} . Based on the trial-and-error calculation, the lowest value of $D(tp)$ occurs at $tp=1,400$ hours. Therefore, the preventive replacement interval for the component distribution pump is determined to be 1,400 hours.

3.7 Availability of distribution pump

The distribution pump availability analysis indicates that the minimum downtime ratio was achieved at an optimal preventive replacement interval of 1,400 operating hours. At this interval, the calculated downtime ratio was $D(1,400)=0.002204$, equivalent to 0.2204% of the total operating time (0.220%). Consequently, the resulting system availability reached 99.78%, indicating that the distribution pump system remained operational for nearly the entire operating period. According to engineering reliability standards, an availability level above 99% is considered a very high-availability system, demonstrating the effectiveness of the proposed Reliability Centered Maintenance (RCM) strategy in improving operational continuity and reducing unexpected interruptions.

The obtained availability result is consistent with previous RCM-based maintenance studies conducted in industrial systems. Dehghanian et al. [11] reported that implementing reliability-centered maintenance in power systems significantly improved system availability and operational reliability by optimizing preventive maintenance scheduling. Similarly, Sharma and Yadava [12] emphasized that maintenance optimization approaches based on reliability parameters can substantially reduce operational losses from unplanned failures. Compared with previous studies, the availability achieved in this research is relatively high because the proposed maintenance strategy integrates Pareto analysis, FMEA, Weibull-based reliability analysis, and preventive replacement interval optimization within a single RCM framework specifically for water distribution pump systems.

In addition, the Weibull distribution analysis revealed a wear-out failure pattern with a shape parameter $\beta > 1$, indicating that the probability of component failure increases with operating time. This finding supports the implementation of scheduled preventive replacement before the failure probability reaches a critical level. The preventive replacement interval of 1,400 hours therefore represents not only the minimum downtime condition but also a balance between excessive preventive maintenance and the risk of corrective maintenance caused by unexpected breakdowns.

From a practical perspective, the achieved improvement in availability has important implications for water utility operations, where service continuity is a critical performance indicator. Higher availability directly contributes to more stable water distribution services, fewer emergency repair activities, and better allocation of maintenance resources. Therefore, the proposed RCM-based maintenance policy can serve as a practical guideline for improving reliability performance in continuously operating water utility systems.

3.8 Downtime calculation before and after RCM

Prior to implementing Reliability Centered Maintenance (RCM), the distribution pump system experienced frequent operational downtime. Based on historical maintenance records, the total downtime reached 620 hours per year, reflecting frequent breakdowns and a maintenance strategy that relied predominantly on corrective maintenance actions. Such conditions reduced operational reliability, disrupted service continuity, and increased maintenance costs due to repeated emergency repairs. These findings confirm the limitations of conventional maintenance practices, which do not adequately account for component reliability characteristics and failure behavior.

After implementing the RCM approach with an optimized preventive replacement interval, the distribution pump's operational downtime decreased substantially. The reduction was determined based on the minimum downtime ratio ($D(tp)$) obtained from the

preventive replacement analysis: $D(tp)=0.002204$. Considering that the distribution pump operates for an average of 480 hours per month, the total annual operating time is 5,760 hours. By multiplying the downtime ratio by the annual operating time, the estimated annual downtime after RCM implementation was approximately 12.7 hours. This result indicates that the system experiences only a very small proportion of operational interruption compared with the total operating time. Compared with the pre-RCM condition, in which the annual downtime reached 620 hours, the proposed RCM strategy reduced downtime by approximately 97.6%. The substantial reduction demonstrates that the proposed maintenance scheduling strategy effectively minimizes unexpected failures and improves the operational stability of the distribution pump system.

The reduction achieved in this study is comparable to findings reported in previous RCM-related research. Bevilacqua et al. [10] demonstrated that maintenance optimization based on RCM and reliability analysis could significantly reduce operational interruptions and maintenance costs in industrial systems. Likewise, Rausand and Vatn [4] explained that reliability-centered maintenance improves system performance by shifting maintenance activities from reactive to preventive and condition-oriented actions. However, unlike many previous studies that focused mainly on manufacturing or power generation systems, this study specifically addresses water distribution pump systems using actual operational downtime data from the water utility sector. This sector has unique operational characteristics because failures directly affect the continuity of public services.

The Mean Time To Failure (MTTF) obtained in this study was 1,683 hours, while the Mean Time To Repair (MTTR) was 4.74 hours. The relatively high MTTF indicates that the distribution pump system can operate for a long time before failure, whereas the relatively low MTTR reflects an effective repair response once a failure occurs. Compared with reliability studies on industrial pumps reported by Zhang et al. [6] and Sinha and Mukhopadhyay [19], the obtained reliability parameters indicate that the implementation of preventive replacement and scheduled inspections successfully improved equipment operational performance [27].

Furthermore, the inspection interval analysis showed that inspections should be conducted every 229.7 operating hours, or approximately twice per month. This inspection interval enables early detection of component degradation before functional failure occurs, thereby supporting proactive maintenance planning. The combination of optimized preventive replacement intervals and periodic inspections forms an integrated maintenance strategy that not only reduces downtime but also improves system reliability, availability, and long-term operational efficiency in water distribution services.

4 Conclusion

This study demonstrates that the implementation of Reliability-Centered Maintenance (RCM) provides a systematic and effective framework for optimizing maintenance scheduling for water distribution pump systems. The integration of Pareto analysis, FMEA, and reliability analysis based on the Weibull distribution successfully identified the distribution pumps as the most critical asset, with an MTTF of 1,683 hours and an MTTR of 4.74 hours. Using the RCM Decision Worksheet and a downtime-ratio minimization approach, the optimal preventive replacement interval was determined to be 1,400 operating hours with an increased system availability to 99.78%, which is considered a very high level of availability by engineering reliability standards. From a practical perspective, the proposed maintenance strategy provides clear guidance for preventive replacements, inspection intervals, and prioritized corrective actions, enabling more efficient resource allocation and improved service continuity. Future research suggests integrating condition-based monitoring data, sensor-based diagnostics, or machine learning techniques to improve failure prediction accuracy and support dynamic maintenance scheduling.

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