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Optimization of preventive maintenance on critical machines at the Sabiz 1 plant using Reliability-Centered Maintenance method

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Abstract
Maintenance planning is the first step in an industry, especially when it comes to the trade-off between cost and reliability, which is the reason for this research's aim. The Reliability Centered Maintenance (RCM) method will be used in this research to optimize maintenance activity in critical machines at the Sabiz 1 plant to minimize downtime, costs incurred for machine repairs, and production losses. The tools of RCM that will be used such as FMEA to determine critical machines as the focus of analysis, a Fishbone Diagram to determine the causes of failure, an RCM worksheet to get preventive activities, and a statistical distribution approach to obtain appropriate preventive activity intervals. The result of data processing shows that all data has a lognormal distribution and can be continued using the lognormal distribution method. The results of this analysis are the preventive maintenance activities proposal and their intervals as a reference for Sabiz 1 plant maintenance planning. The preventive maintenance plan for three critical machines is the high-pressure pump is four days of inspection activities and two days for replacement activities; for the powder, base conveyor is four days of checking activities and 17 days for replacement activities; and for the extraction tower fan for inspection, activities is seven days. The prediction of the implementation impact of this maintenance planning will save maintenance costs around 70% compared to historical costs.

Keywords:
Downtime;
FMEA;
Preventive Maintenance;
RCM;
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INTRODUCTION

Maintenance is considered to reach aims that crucially contribute to the company's important goals such as productivity and customer satisfaction [1]. Based on research, maintenance is also closely related to machine consumption patterns. A machine that is not properly maintained will consume more electricity between 10%-60.81%, which will increase production costs [2]. This is the reason why finding an optimal solution in maintenance strategy to achieve that objective is a continuing concern for decision-makers. Almost all modern companies are seeking ways to uplift maintenance at an advanced level by applying different strategies and techniques. Among the strategies, Reliability Centered Maintenance (RCM) has been around for decades to provide maintenance to various organizations [3].

Reliability is the possibility of a machine performing its optimal function within a specific period under a given set of conditions. The concluded strategy must balance maintenance cost and plant reliability [4]. The reliability system applies to various products, subsystems, equipment, components, and parts. When a product or system no longer performs its intended function, it is considered a failure. This can be a complete cessation of function, such as a machine shutting down or a structure collapsing, or it can be more subtle. To measure failure accurately, it is often necessary to define it quantitatively [5].

Reliability-centered maintenance (RCM) is a strategic framework designed to evaluate a system's maintenance requirements. While some industries rely on Preventive Maintenance (PM) and predictive maintenance strategies, these can often lead to increased production costs. By combining these strategies, RCM aims to optimize maintenance costs while ensuring the system remains available [6]. Reliability-centered Maintenance can be carried out by selecting effective maintenance strategies to ensure the reliability of spare parts. Product quality is better maintained because the production process goes according to plan. However, if a machine has low reliability or frequently breaks down, this will cause downtime, and the production process will be hampered [7].

In addition, this research conducted a comprehensive root cause analysis to identify all potential factors that could cause losses. This process involves using tools such as Failure Mode and Effects Analysis (FMEA). FMEA is expanding and has applications across different industries, such as manufacturing and services. This approach employs the Risk Priority Number (RPN) method and language-based terms to evaluate potential risks' severity, occurrence, and detection[8].

The fast-moving consumer goods (FMCG) industry produces goods in high market demand. These products meet the basic needs of society, such as food, body care, clothing, hygiene, etc. To meet market needs that are increasing every day, the FMCG industry must optimize the efficiency of their production plants so that they can produce products according to the specified targets. The decrease in plant efficiency can be affected by the occurrence of downtime. One of the factors' causing downtime is decreased machine reliability.

PT X is one of the FMCG industries that produces powder detergent products with various variants. The company has three primary plants in its production process to produce finished products. One of the plants that have a vital role is the Sabiz plant, which processes raw materials into detergent powder, ready to be transferred to the packing plant for packaging.

The production team compiles downtime recording reports to obtain factory efficiency values and a CMMS designed to assist with the planning, management, and administration functions required to maintain and record equipment failures [9] effectively.

The Sabiz plant is split into three segments: Sabiz 1, Sabiz 2, and Sabiz 3. The area of focus is determined based on the plant with the highest percentage of downtime. In 2022, Sabiz 1 demonstrated the lowest efficiency percentage, at 84.08%, and the highest percentage of recorded downtime, at 15.92%, compared to the other Sabiz plants. Thus, Sabiz 1 was selected as the primary research subject because it exhibited poor efficiency values, and reducing the recorded downtime is essential. The efficiency percentages for each Sabiz plant are shown in Figure 1.

In a global era, the competitive global market is very high, so it is crucial to have effective strategies for ensuring productivity and efficient production. To address issues related to production problems and breakdowns in manufacturing companies, it is essential to conduct regular maintenance on machines [10]. Research conducted by [11] presents an optimal reliability-centered maintenance (RCM) strategy in power distribution systems. The study approach involved selecting the best strategy to optimize energy losses from the power supply and considering factors such as maintenance costs, safety and outage costs, and failure risks. This method tests effectiveness by analyzing various scenarios and examining the impact of variables such as maintenance time, safety costs, and practical limitations. The results show that implementing our approach can reduce total maintenance costs by at least 7% compared to applying the proposed method.

According to [12], RCM guarantees that an asset can continue to perform its function according to its current operating situation.

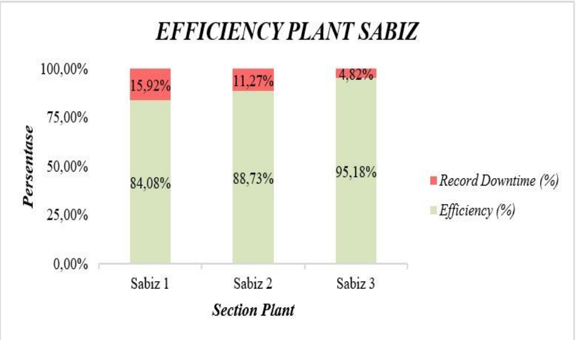

Figure 1. Efficiency Percentage for Sabiz Plant

This is achieved by identifying the asset's function potential failure modes that may prevent the asset from performing its intended function, prioritizing those failure modes, and determining practical preventive maintenance tasks that can be implemented cost-effectively and efficiently to reduce the likelihood of failure. Furthermore, the reliability of railway systems is crucial, and FMEA analysis is a widely used technique to ensure it. In a study by [13], researchers explored methodshat efficiently apply FMEA to RCM procedures. This paper selected the AF Track circuit system as the target system, applied FMEA to ensure its reliability, and compared the results of using FMEA for system reliability and maintenance reliability. The analysis showed that using an approach based on maintenance reliability was more efficient in establishing a railway system maintenance system.

In addition, research was conducted by [14] using the FMEA maintenance optimization method for electric drive compressors. In order to maintain the compressor's performance at an optimal level, it is essential to strike a balance between achieving economic benefits and ensuring its reliability and availability. Neglecting maintenance can lead to costly repairs, while excessive maintenance can result in unnecessary expenses. Therefore, it is crucial to evaluate maintenance needs and perform only what is necessary to ensure the compressor functions efficiently and safely.

In preventing downtime, the purpose of maintenance is needed, where it has the function of monitoring and maintaining all the equipment by designing, organizing, handling, and inspecting work to ensure the function of the unit during uptime and minimize downtime caused by damage or repairs, so it can extend the usage time of equipment and reduce the cost of sudden repairs, start-up costs due to engine failure, and the cost of product defects due to engine damage [15].

Based on the problems described previously, this study optimizes preventive maintenance planning through analysis using a reliability-centered maintenance and FMEA method at Sabiz 1 Plant. By applying this method, the final result will be obtained in the form of proposed preventive maintenance activities that are right on target and at appropriate time intervals based on data processing and a statistical distribution approach as a reference. The Weibull, Exponential, Lognormal, and Normal distributions are selected to determine the probabilistic characteristics of the preventive maintenance interval for each piece of equipment.

Based on statistical data, damaged equipment causes increased maintenance costs. Using statistical distribution analysis can improve reliability, help uncover the causes and mechanisms behind failures, and identify corrective actions to prevent critical secondary failures or damage. These findings have provided the basis for creating quantitative models that assist in selecting and optimizing maintenance strategies [16].

The application of RCM allows for the selection of critical equipment through FMEA. The RCM program's operator involvement increases control and equipment operational requirements. RCM is a proven methodology that helps companies achieve their goals. Training and certification of maintenance staff is essential to measure their performance. Furthermore, RCM optimizes the availability of spare parts, thereby reducing costs. It also enables the planning of all tasks, reducing overtime [17].

METHOD

For this study, we are utilizing the reliability-centered maintenance (RCM) approach, which focuses on enhancing the reliability and maintainability value. RCM is an essential and highly effective approach utilized to assess and optimize the maintenance needs of plants and equipment during operation. Its primary goal is to minimize equipment failures and enhance preventive maintenance strategies, allowing industrial plants to maintain their equipment efficiently and effectively [6].

The following is a brief overview of the RCM implementation process: Firstly, data is collected to determine the probability of occurrence and criticality assessment. In this case, it is important to record every machine defect in detail to obtain valid data for analysis. Second, it is important to identify which machines have an important role and need to be the focus of maintenance. It is imperative to consider a range of factors when evaluating critical components. These factors consist of the frequency of damage, the impact of damage on the system, the assembly process's complexity, and the components' cost [7]. In addition, a thorough root cause analysis is conducted to identify all potential factors that may lead to harm. This process involves utilizing tools like Failure Modes and Effects Analysis (FMEA), which considers three parameters: severity (S), likelihood of occurrence (O), and probability of detection failure (detectability - D). The resulting Risk Priority

Number (RPN) helps to prioritize risks. The fishbone diagram is also employed, which outlines the six leading causes of problems, including machine malfunction, methods utilized, materials used, measurement processes, human resources, and environmental factors [18]. Third is the development of preventive maintenance activities using the RCM Decision Worksheet, which is then classified as preventive maintenance by calculating the accurate time intervals through a statistical approach to analyzing data distribution.

Analyze the damage data of components by calculating the time to failure (TTF) and time to repair (TTR) of important machines. Additionally, process the Index of Fit data on TTF and TTR data, using distribution approaches such as Weibull, exponential, lognormal, and normal exponential. The Weibull distribution is frequently utilized to assess the dependability of a system or component and determine its useful lifespan. The Weibull distribution has two key parameters: the characteristic life (θ) and the shape factor (β) values. The value of Beta (β) determines the shape of the distribution. If β > 1, the failure rate increases. If β < 1, the failure rate decreases. If β = 1, the failure rate remains constant [19]. The cumulative distribution function of the two-parameter Weibull distribution, as in (1). Reliability refers to the likelihood of an object or entity functioning as intended under specific conditions for a certain duration. The reliability function for the two-parameter Weibull distribution can be expressed as in (2).

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

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

Equation (3) displays the Weibull failure rate function, which is the expected number of failures per unit of time for a given product.

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

where β is shape parameter and θ is scale parameter.

Exponential distribution is commonly used in modeling reliability data due to its simplicity. The most used method for estimating the parameter of this distribution is the classical estimator, such as the maximum likelihood estimator, which is known for its efficiency. The exponential distribution implies that the likelihood of damage remains constant over time and is not affected by the age of the tool. The exponential distribution may be considered the specific case of the Weibull distribution with shape factor β = 1 and characteristic life θ = $1/\lambda$. The cumulative distribution function, reliability function, and failure rate function of exponential distribution are shown in (4), (5), and (6) respectively [20][21].

$$F(t) = 1 - e^{-\lambda t} \quad (4)$$

$$R(t) = e^{-\lambda t} \quad (5)$$

$$h(t) = \lambda \quad (6)$$

The lognormal distribution has many vital economic, biological, and reliability engineering applications. In practical problems, the lognormal distribution is more suitable for data modeling than the normal distribution, especially in small samples [22]. A lognormal distribution is a type of continuous probability distribution for a random variable, in which the logarithm follows a normal distribution. This type of distribution is commonly used to describe fatigue failure, failure rates, and other phenomena that involve a wide range of data [23]. The density function of the lognormal distribution is given as (7).

$$f(t) = \frac{1}{\sigma t\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\ln(t)-\mu}{\sigma}\right)^2} \quad (7)$$

The formula for the cumulative distribution function of the lognormal distribution is as follows (8).

$$F(t) = \Phi\left(\frac{\ln(t)}{\sigma}\right) \quad (8)$$

where $\boldsymbol{\Phi}$ is the cumulative distribution function of the normal distribution.

The reliability of items that experience wear out failures can be modeled using the normal distribution. To determine the reliability at a specific point in time (t), the mean life (μ) and standard deviation (σ) are required. The probability density function and reliability function of normal distribution are given as (9) and (10) respectively [24].

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2} \quad (9)$$

$$R(t) = \int_t^{\infty} f(t)\, dt \quad (10)$$

The distribution calculation results should be identified based on the largest fit value index to obtain a value that can be used for Mean Time to Failure (MTTF) and Mean Time to Repair (MTTR) calculations. Afterward, the results should be tested for goodness of fit. Calculating the level of damage or repairs required for a component and estimating the duration of the repairs utilize the least square curve fitting method [25]. Equation

(11) displays the least squares curve fitting formula.

$$r = \frac{n\sum_{i=1}^{n} x_i y_i - (\sum_{i=1}^{n} x_i)(\sum_{i=1}^{n} y_i)}{\sqrt{\{(n\sum_{i=1}^{n} x_i^2) - (\sum_{i=1}^{n} x_i)^2\}\{n\sum_{i=1}^{n} y_i^2 - (\sum_{i=1}^{n} y_i)^2\}}} \quad (11)$$

The MTTF refers to the average duration of time it takes for damage to occur. It represents the working period of a component from its initial use or activation to the point where it becomes damaged. Depending on the type of damage distribution, MTTF is calculated differently for each instance of damage data [26]. The calculation for each distribution is as follows:

1. Weibull Distribution

$$\text{MTTF} = \theta\Gamma\left(1 + \frac{1}{\beta}\right) \quad (12)$$

where θ is the scale parameter and β is the shape parameter; Γ obtained from the Gamma function.

2. Exponential Distribution

$$\text{MTTF} = \frac{1}{\lambda} \quad (13)$$

where λ is the failure rate.

3. Lognormal Distribution

$$\text{MTTF} = t_{med} \cdot e^{\frac{s^2}{2}} \quad (14)$$

where t_{med} is median (a scale parameter) and s is the shape parameter.

4. Normal Distribution

$$\text{MTTF} = \mu \quad (15)$$

where μ is the mean value.

MTTR is the average value or average time needed to repair a damaged component (breakdown). MTTR affects system availability by impacting downtime. A lower MTTR means faster repairs and recovery [26]. The MTTR calculation for each distribution is as follows:

1. Weibull Distribution

$$\text{MTTR} = \theta\Gamma\left(1 + \frac{1}{\beta}\right) \quad (16)$$

where θ is the scale parameter and β is the shape parameter; Γ obtained from the Gamma function.

2. Exponential Distribution

$$\text{MTTR} = \frac{1}{\lambda} \quad (17)$$

where λ is failure rate.

3. Lognormal Distribution

$$\text{MTTR} = t_{med} \cdot e^{\frac{s^2}{2}} \quad (18)$$

where t_{med} is median (a scale parameter) and s is the shape parameter.

4. Normal Distribution

$$\text{MTTR} = \mu \quad (19)$$

where μ is mean value.

Once the MTTF and MTTR have been calculated, the next step is determining the replacement time interval using the age replacement method. Age replacement is a method of preventive replacement that is based on the age of a component. Its purpose is to determine the optimal time for preventive replacement based on the age of the component. The calculation for the replacement time interval is based on the lowest downtime value of $D(t_p)$ [27].

Data Collection

For this study, we analyzed engine damage data from January 1, 2022, until December 31, 2022, that was tracked on SAP, a CMMS. Our focus was on Sabiz 1, a plant with around 200 pieces of equipment that are crucial to the production process. Using various parameters, we identified the critical machine for our research. One key factor was the equipment that caused the most extended downtime due to damage. This mattered because it affected the plant's operations and ultimately hindered the achievement of production targets. As a result, this equipment needed extra attention.

The equipment with the highest damage frequency is an important parameter to consider. This indicates a need for analysis to determine frequent damage causes and give the equipment special attention. Using historical data on equipment damage from SAP, we found ten equipment requiring the above parameter. Three units of equipment were selected that contributed to the top downtime duration as the main objects of research and were referred to as critical machines, namely the high-pressure pump, which contributed 188 hours of duration and 117 times failures occurred; conveyor base powder, with a duration of 52 hours and 11 failures occurred; and extraction air tower, with a duration of 93 hours and times failures occurred. Furthermore, failure time data for critical machines from SAP can be obtained. Table 1 displays a sample of high-pressure pump data.

Table 1. Failure Time Data of High-Pressure Pump

No	Date	Start Time	Finish Time	Dur (Min)
1	04/01/2022	14:30	15:30	60
2	12/01/2022	06:30	08:00	90
3	15/01/2022	10:30	11:35	65
:	:	:	:	:
115	21/11/2022	10:00	16:00	360
116	29/11/2022	11:00	12:00	60
117	29/12/2022	22:30	23:48	78

RESULTS AND DISCUSSION

Potential Failures Identification

At this step, an analysis is carried out to find out what potential failures occur most frequently in each of the critical machines that have been previously selected. FMEA considers severity, occurrence, and detection in determining the potential failure by calculating the RPN (SxOxD). The following is an explanation of the failure modes of the components, referring to the highest RPN value for each piece of equipment. The high-pressure pump has v packing set and plunger as the components with the highest RPN (75), which means they are considered the most frequent reasons for failure. Conveyor base powder has a conveyor belt as the component with the highest RPN (20), which is considered the most frequent reason for failure. Extraction tower fans have blowers as the component with the highest RPN (40), which is considered the most frequent reason for failure.

Root Cause Analysis

The root cause analysis stage is carried out to determine the failure causes in each of these critical machines. A fishbone diagram is used to determine the cause of failure. The following is a fishbone showing the causes of failure in each piece of equipment, shown in Figures 2, Figure 3, and Figure 4.

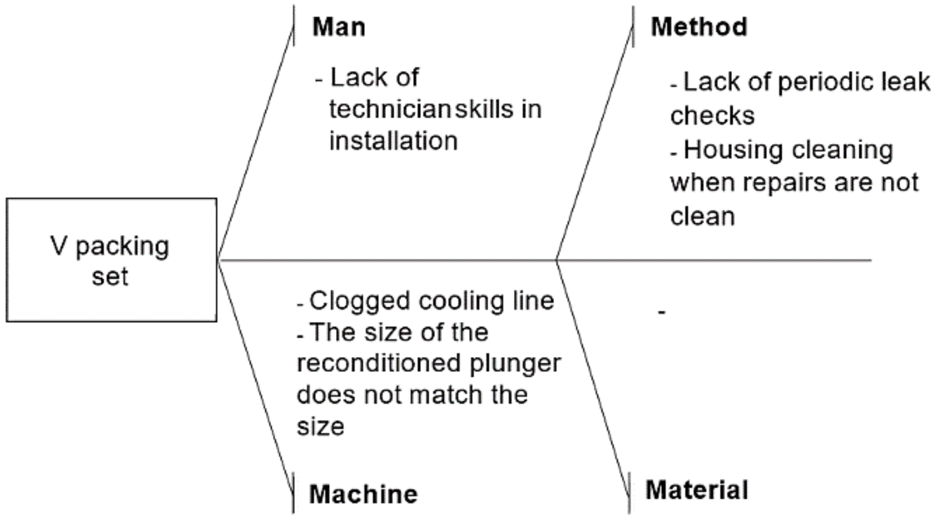

Figure 2. Fishbone for High-Pressure Pump

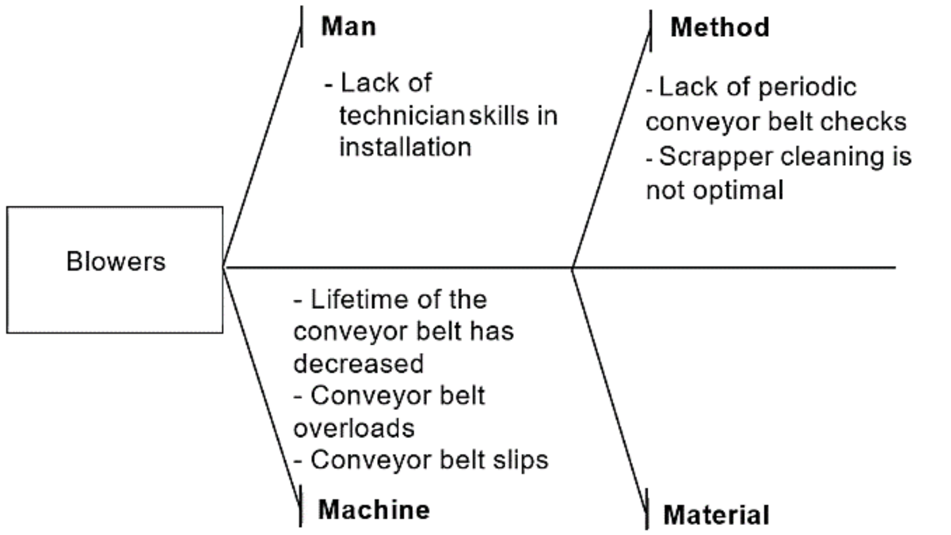

Figure 3. Fishbone for Conveyor Base Powder

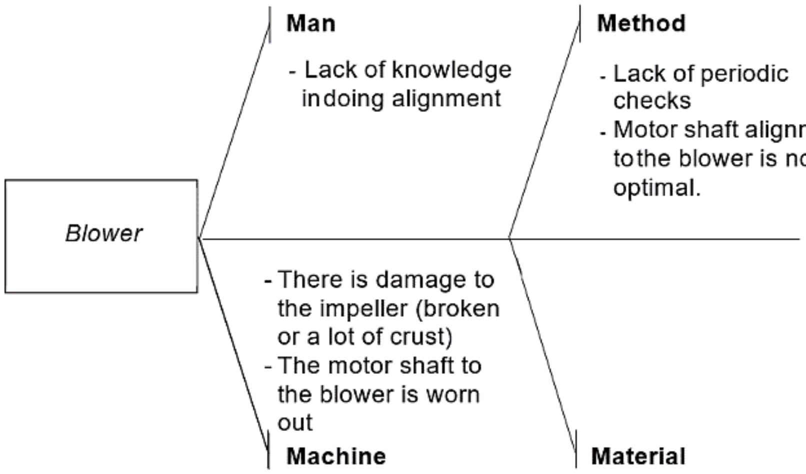

Figure 4. Fishbone for Extraction Tower Fan

RCM Worksheet

Based on the previous analysis, it is necessary to determine what actions will be taken to reduce the possibility of damage. In looking for actions that can be decided for the causes of component damage to each equipment, the RCM Decision Worksheet is used, described previously. From the RCM Decision Worksheet, the proposed task for the high-pressure pump is cleaning the cooling line and frequently replacing the v-packing set based on the reliability calculation. The proposed task for conveyor base powder is checking the thickness of the conveyor belt and pressing the connection of the conveyor belt frequently based on the reliability calculation. The proposed extraction tower fan task is checking the blowers' vibration, shaft alignment, and mounting condition.

Failure Duration Calculation

The RCM Worksheet has identified the task for preventive maintenance, and the next step is calculating the failure time for each component to get a suitable interval for preventive maintenance. The first step is calculating failure duration by calculating the difference between the end time and the start time of the failure. For example, the calculation for failure on January 4, 2022, is 14:30 – 15:30 = 60 minutes. After calculating the duration, the next step is the calculation of time to failure and time to repair concerning these points:

1. As a sample, high-pressure pump failure time data is used on January 12, 2022, and January 15, 2022. TTF will be calculated on January 15, referring to the damage that occurred on January 12, 2022. The TTF on January 4, 2022, cannot be searched because that date is the first day of equipment damage in 2022.
2. Sabiz plant operates from Monday to Saturday. Meanwhile Sunday, the plant stops, so in this calculation, Sunday (for 24 hours) is not included.
3. Notice the failure that occurred on January 12, 2022. Things that we need to look for are the duration interval, which is calculated from the hour when the failure occurs, which is 08:00 on January 12, 2022, until the end of the day on January 12, 2022, which is 00:00. Then, between 08:00 on January 12, 2022, and 00:00 on January 12, there are 960 minutes.
4. Pay attention to the damage that occurred on January 15, 2022. Things that we need to look for are the duration interval, which is calculated from the end of the day on January 14, 2022, which is 00:00, until the start of the damage, which is 10:30. Then, between 00:00 on January 15, 2022, and 10:30 on January 12, there are 630 minutes.
5. The total number of days the equipment operates is calculated. Calculates days from the start of the damage until the damage occurs again without counting Sundays. Between January 12 and January 15, 2022, there are four days. Because in steps 3 and 4, the duration has been searched for on January 12 and January 15, each day's calculation will be reduced by 2. Then an interval of days is found, which is two days or 2880 minutes.
6. The last thing is the sum of the durations found in stages 3, 4, and 5. TTF results on January 15 are based on calculations, namely 960 minutes + 630 minutes + 2880 minutes = 4470 minutes.
7. The steps above are applied to each TTF calculation for each date referring to previous damaged data. The following are the results of

calculations for the high-pressure pump which is shown in Appendix 1.

Distribution Identification

In the next step, we will process the TTF and TTR data from each high-pressure pump, conveyor base powder, and extraction tower fan data to determine the appropriate distribution using Minitab software. We will use four distributions: Weibull, exponential, lognormal, and normal. Table 2 and Table 3 will display the Anderson Darling values and correlation coefficient on the TTF and TTR data.

Based on Table 2 and Table 3, it was found that the lognormal distribution had the highest correlation coefficient value compared to other distributions for TTF data on all three equipment. Additionally, the lognormal distribution also had the lowest Anderson-Darling value. Based on these findings, the lognormal distribution was selected as optimal for the TTF data on all three equipment.

The next stage of identification of the distribution is the goodness of fit test to prove that the determination of the distribution in the index of fit is suitable for use in the analysis. The following is the goodness of fit test hypothesis:

H_0: The data follows a lognormal distribution.
H_1: The data does not follow a lognormal distribution.

The goodness of fit results in Figure 5 shows that the most significant p-value and the smallest AD value are in the lognormal distribution. In addition, the p-value (0.053) > α (0.05); therefore, there is insufficient evidence at the 5% level to reject H_0.

Table 2. Index of Fit of TTF Data

Equipment	Selected Distribution	Anderson-Darling	Correlation Coefficient
High-Pressure Pump	Lognormal	0.089	0.983
Conveyor Base Powder	Lognormal	1.584	1.345
Extraction Tower Fan	Lognormal	0.640	0.993

Table 3. Index of Fit of TTR Data

Equipment	Selected Distribution	Anderson-Darling	Correlation Coefficient
High-Pressure Pump	Lognormal	10.687	0.871
Conveyor Base Powder	Lognormal	1.345	0.975
Extraction Tower Fan	Lognormal	1.412	0.965

Hence, the data follows a lognormal distribution. Figure 5 displays the goodness of fit results for TTF high-pressure pump data as a sample. Table 4 contains the complete goodness of fit results for all TTF data, which indicates the selection of a lognormal distribution.

Furthermore, as a sample, the TTR conveyor base powder data shows that the lognormal distribution has the largest p-value with the smallest AD value (see Figure 6). In addition, the calculated p-value (0.576) is higher than α (0.05), so there is insufficient evidence to reject H_0. Hence, the data follows a lognormal distribution.

Based on the goodness of fit results shown in Table 5, the lognormal distribution is the most suitable fit distribution. Therefore, the MTTF and MTTR calculations will be conducted according to the lognormal distribution rule.

In order to calculate the MTTF and MTTR, certain parameters must be determined by processing the data. Table 6 provides an example of how to determine the necessary parameters for calculating MTTF for high-pressure pump data. The same calculation process applies to other equipment.

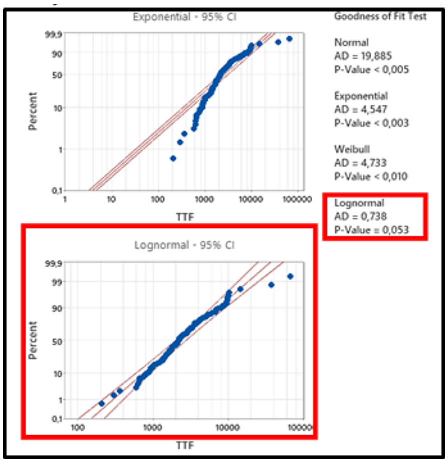

Figure 5. Goodness of Fit Test for High-Pressure Pump TTF Data

Table 4. Distribution Selected for Each TTF Equipment

Equipment	Fit Distribution	P Value	AD
High-Pressure Pump	Lognormal	0.053	0.738
Conveyor Base Powder	Lognormal	0.313	0.389
Extraction Tower Fan	Lognormal	0.899	0.184

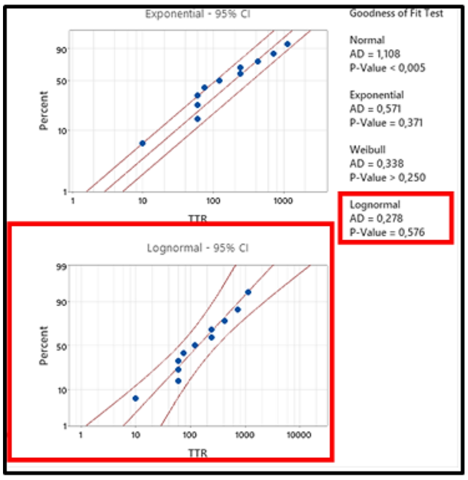

Figure 6. Goodness of Fit Test for Conveyor Base Powder TTR

Table 5. Distribution Selected for Each TTR Equipment.

Equipment	Fit Distribution	P Value	AD
High-Pressure Pump	Lognormal	0.062	10.448
Conveyor Base Powder	Lognormal	0.576	0.278
Extraction Tower Fan	Lognormal	0.052	0.950

Table 6. Calculation of High-Pressure Pump MTTF Parameter

i	ti	xi=ln(ti)	ln(ti)-t	$(\ln(ti)-t)^2$
1	9540	9.163	1.385	1.917
2	4470	8.405	0.627	0.393
3	3025	8.015	0.236	0.056
:	:	:	:	:
115	9780	9.188	1.409	1.987
116	38070	10.547	2.769	7.665
∑	**457275**	**902.319**	**0.000**	**91.693**

Based on the table, the following calculation can be obtained:

$$\mu = \bar{t}$$

$$\bar{t} = \sum_{i=l}^{n} \frac{ln\ ti}{n}$$

$$= 7.779$$

$$t_{med} = e^{\mu}$$

$$= 2388.959$$

$$s = \sqrt{\frac{\sum_{i=l}^{n}\left(\frac{ln\ ti}{n}\right)^2}{n}}$$

$$= 0.889$$

$$MTTF = t_{med}\, e^{\frac{s^2}{2}}$$

$$= 3546.944$$

The following is the result of all MTTF and MTTR for each piece of equipment, as shown in Table 7.

Determination of Preventive Maintenance Interval

The determination of preventive maintenance is divided into two categories: check activity and replacement activity. The following is a sample calculation of preventive maintenance interval with check activity for high pressure pump.

1. Working Hours average in a month
   - Working hours in a month = 20 days
   - Working hours in a day = 24 hours
   - Working hours average in a month = 480 hours.
2. Failure Frequency
   Failure frequency in a period (12 months in 2022) = 117 times.
3. Average repair time
   $$\frac{1}{\mu} = \frac{MTTR}{\text{Working hr average in a month}}$$
   $$\mu = 310.314$$
4. Average Check Time
   Duration for check activity (ti) = 30 minutes = 0,5 hours.
   $$\frac{1}{i} = \frac{ti}{t} = \frac{\text{average 1 time of checking}}{\text{working hours average in a month}}$$
   $$i = 960$$
5. Average of Failure
   $$k = \frac{\text{average 1 time of checking}}{\text{working hours average in a month}}$$
   $$= 9.75$$
6. Optimum Check Frequency
   $$n = \sqrt{\frac{k.i}{\mu}} = 5.492$$
7. Check activity interval.
   $$\frac{t}{n} = \frac{\text{average working hours}}{n} = 87.3 \text{ hours}$$

Hence, the preventive maintenance interval for check activity is 87.3 hours or four days. The same step was also carried out to find interval for check activity of conveyor base powder and extraction tower fan.

Table 7. MTTF and MTTR for Each Equipment

Equipment	MTTF (hr)	MTTR (hr)
High-Pressure Pump	59.116	1.547
Conveyor Base Powder	508.452	7.196
Extraction Air Tower	344.050	3.529

The following is the sample calculation of preventive maintenance interval with replacement activity for high-pressure pump. Before the calculation is carried out, it is necessary to know some of the parameters that have been previously obtained, as follows.

t_p = preventive time interval in the calculation, 45 hours will be chosen as the interval, so the sample calculation will use 45 hours).
s = 0.899
t_{med} = 2388.959 min = 39.816 hours
MTTF = 3546.944 min = 59.116 hours
MTTR = Tp = Tf = 92.809 min= 1.547 hours
Φ = cumulative distribution function of the normal distribution

Based on those parameters, the calculation of $D(t_p)$ (total downtime per unit time for replacement activity) can be started in the following step.

$$F(t_p) = F(45)$$
$$= \Phi\left(\frac{1}{s} ln \frac{tp}{\text{tmed}}\right)$$
$$= \Phi\left(\frac{1}{0.899} ln \frac{45}{39.816}\right) = 0.5547469$$

$$R(t_p) = R(45) = 1 - \Phi\left(\frac{1}{s} ln \frac{t_p}{t_{med}}\right) = 0.445$$

$$M(t_p) = M(45) = \frac{MTTF}{F(t_p)} = 106.564$$

$$D(t_p) = \frac{Tp.R(t_p)+Tf.(1-R(t_p))}{(t_p+Tp).R(t_p)+\{((M(t_p))+Tf.(1-R(t_p))\}}$$
$$= \frac{1.547.\ 0.455+1.547.(1-0.455)}{(45+1.547).0.455+\{(106.564)+1.547.(1-0.455)}$$
$$= 0.0191699$$

As shown in the Table 8, the calculations were carried out using t_p 1-59 hours because it is referred to the MTTF value until the smallest $D(t_p)$ is found. Based on all the calculations found that the smallest value of $D(t_p)$ is 0,0191669, so it can be said that the preventive maintenance interval for replacement activity is 45 hours, or 2 days.

Table 8. Age Replacement for High-Pressure Pump

t_p	$F(t_p)$	$R(t_p)$	$M(t_p)$	$D(t_p)$
40	0.50206	0.497931	117.744	0.019172304
41	0.51314	0.486854	115.203	0.019171604
42	0.52394	0.476053	112.828	0.019171304
43	0.53447	0.465523	110.605	0.019171204
44	0.54474	0.455258	108.521	0.019171104
45	0.55474	0.445253	106.563	0.01916991
46	0.56449	0.435501	104.723	0.019171104
47	0.57400	0.425997	102.989	0.019198253
48	0.58326	0.416735	101.353	0.019293936
49	0.59229	0.407708	99.808	0.019393358

These calculations can be visualized in Figure 7 which forms a bathtub curve. Based on bathtub curve theory, it can show the relationship between component failure rates and time. A good curved bathtub model must have a relatively wide flat portion. This implies that the bath failure rate curve can increase so rapidly during the wear phase that it has two relatively clear change points [28]. Hence, we can conclude that the longer usage time of plunger & v packing set of high-pressure pump so the downtime may be accurate in that part also high and the lowest downtime is in 45 hours. The same step was also carried out for finding interval for the replacement of the conveyor base powder and extraction tower fan.

Based on the calculation of intervals for checking and replacing activities using the same method as before, the results of the analysis of preventive activities submitted through the RCM Worksheet can be summarized in Table 9. The interval for replacing activity of extraction tower fan was not included because by checking the vibration of blowers is enough to monitor the condition of it and we can easily find the abnormality because of the intense of checking.

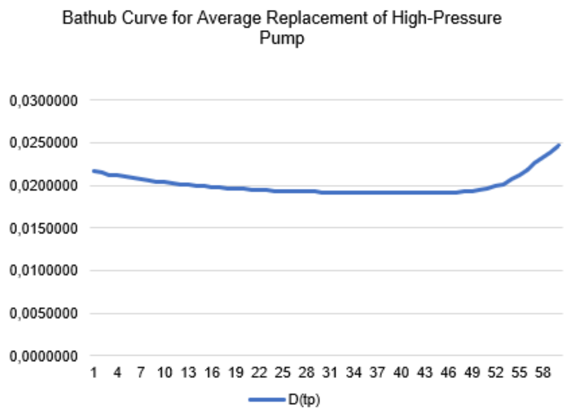

Figure 7. Bathtub Curve for Average Replacement of High-Pressure Pump

Table 9. Proposed Preventive Activities and Time Intervals

Equipment	Proposed Preventive Maintenance	Time Interval
High-Pressure Pump	Cooling line cleaning	4 Days
	Replacement of plunger and v packing set	2 Days
Conveyor Base Powder	Checking the thickness of conveyor belt	7 Days
	Pressing the connection of conveyor belt	17 Days
Extraction Air Tower	Checking the vibration of blowers and checking the shaft alignment and mounting condition	7 Days

Reliability Before and After Preventive Maintenance

In order to know how good the impact of preventive maintenance implementation, we can compare the reliability value before the equipment get preventive maintenance and after the preventive maintenance is implemented. The following is a sample calculation of reliability before and after preventive maintenance for high pressure pump:

1. Reliability before preventive maintenance

   Tmed = 2388.959

   Φ = Lognormal distribution value

   μ = 2388.959

   t = MTTF = 3546.944

   R(t) = 1 - Φ $\left(\frac{1}{2} ln \frac{t}{\mu}\right)$

   R(t) = 1 - Φ $\left(0.5\ ln \frac{3546.944}{2388.959}\right)$

   R(t) = 0.422 = 42%

2. Reliability after preventive maintenance

   Tmed = 2388.959

   Φ = Lognormal distribution value

   μ = 2388.959

   t = Check activity interval = 87.3

   N = 0

   $R(T)^{n}$ = 1 - Φ $\left(\frac{1}{2} ln \frac{t}{\mu}\right)^{n}$

   $R(T)^{n}$ = 1 - Φ $\left(0.5\ ln \frac{87.3}{2388.959}\right)^{0}$

   $R(T)^{n}$ = 1

   R(t – nT) = 1 - Φ $\left(\frac{1}{2} ln \frac{t-nT}{\mu}\right)$

   R(t – nT) = 1 - Φ $\left(\frac{1}{2} ln \frac{8.73-0\times 87.3}{2388.959}\right)$

   R(t – nT) = 0.744 = 74%

   Rm(T) = $R(T)^{n}$ x R(t – nT) = 1 x 74%

   Rm(T) = 74%

So, we can conclude that the reliability increases from 42% to 74% after preventive maintenance is implemented. Based on the calculation above, we can calculate the reliability comparation from other equipment after the implementation of preventive maintenance that can be summarized in Table 10.

Table 10. Reliability Before and After Preventive Maintenance

Equipment	Before	After
High-Pressure Pump	42%	74%
Conveyor Base Powder	40%	89%
Extraction Air Tower	68%	85%

The results of these calculations are in line with the statement by [29] that the reliability function indicates the repairs that occur on the machine after and before preventive maintenance operations. This measurement indicates the reliability of the machine after preventative maintenance is completed. It becomes clear that the reliability of the machine increases due to the improvements made during the maintenance operation. Therefore, preventative maintenance operations work to improve the machine's reliability and increase the time between faults.

Cost Comparison

They provided data that indicates Sabiz 1 has an estimated breakdown rate of Rp. 20,000 per minute. This value is calculated based on various factors, including the depreciation of Sabiz 1's assets, energy consumption (such as electricity and air), and labor costs. This information is used to determine the cost of downtime losses in minutes.

Conversely, to implement the preventive maintenance, the company needs IDR 109.000.000 for high pressure pump and IDR 42.000.000 for conveyor base powder. Before optimizing the preventive maintenance of the high-pressure pump, the costs that had to be incurred in one year were IDR 694,648,958, with details that the machine was damaged 117 times with the replacement of the v packing set and plunger for each damage and causing 188 hours of downtime in 2022. With the replacement of the v packing sets regularly every 2 days will reduce the frequency of sudden replacement of v packing sets and replaced with regular and planned replacements with 182 v packing set replacements in one year with a total downtime of 91 hours. The estimated costs incurred after optimization are IDR 219,000,000, a decrease of 68% from before.

Furthermore, if the preventive maintenance is implemented, the percentage of savings is expected to decrease by around 75% for conveyor base powder from IDR 273.448.958 in 2022 to IDR 67.200.000 in 2024, with a savings rate of IDR 206.248.958. The details show that the equipment was damaged 11 times by re-pressing torn conveyor belts and causing 52 hours of downtime in 2022. The hope is that checking the thickness of the conveyor belt every four days will prevent sudden tearing of the conveyor belt so that it can reduce the duration of downtime that occurs. To be more optimal, conveyor belt joint pressing is also applied routinely once every 17 days which requires a total downtime of 21 hours in one year. According to [30][31], the implementation of preventive maintenance can help to reduce maintenance costs and increase the efficiency of equipment. Quality control is also an important aspect that affects costs, including quality loss threshold and maintenance expenses. By using this model, businesses can minimize the overall costs and ensure the production of high-quality products.

CONCLUSION

Three critical machines have been found: a high-pressure pump, a base powder conveyor, and an extraction tower fan. Failure modes were found for each critical machine: the high-pressure pump with leakage failure of the v packing set, base powder conveyor with tear conveyor belt failure, and extraction tower fan with high blower vibration failure. The analysis shows that the processed data has the highest correlation value and the lowest Anderson Darling value in the lognormal distribution, so the distribution chosen to continue data processing is the lognormal distribution. Based on the data processing, it was found that appropriate preventive maintenance activities for each critical machine were: high-pressure pumps with cooling line cleaning activities (4 days) and v packing set replacement (2 days); conveyor base powder with the activities of checking the thickness of the conveyor belt (7 days) and pressing the conveyor belt joints (17 days); extraction tower fan by checking the vibration of the blower, mounting, shaft, and impeller (7 days). By implementing preventive maintenance, it can be simulated that it can reduce costs incurred compared to before optimization was carried out. The percentage of savings is expected to decrease by around 68% for high-pressure pumps and around 75% for conveyor base powder.

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APPENDIX

Appendix 1. TTF Calculation for High-Pressure Pump

No	Date	TTR	End of The Day - Malfuction Start Time	Malfunction End Date - End of the Day	Duration of Equipment Operation Days	TTF
1	04 January 2022	60	870	510		-
2	12 January 2022	90	390	960	8640	9540
3	15 January 2022	65	630	745	2880	4470
4	18 January 2022	120	840	480	1440	3025
5	20 January 2022	90	90	1260	1440	2010
6	21 January 2022	70	1210	160	0	2470
7	22 January 2022	90	870	480	0	1030
8	25 January 2022	125	775	540	1440	2695
9	29 January 2022	85	50	1305	4320	4910
10	01 February 2022	70	1190	180	1440	3935
:	:	:	:	:	:	:
113	19 September 2022	60	600	780	1440	2805
114	27 September 2022	480	540	420	8640	9960
115	21 November 2022	360	600	480	66240	67260
116	29 November 2022	60	660	720	8640	9780
117	29 December 2022	78	1350	12	36000	38070