Jurnal Serambi Engineering JSE
Volume XI, No.3, Juli 2026 Hal 20990 - 21001
p-ISSN : 2528-3561
e-ISSN : 2541-1934

Minimizing Paper Machine Downtime at PT DAP Using the Reliability-Centered Maintenance (RCM) Approach

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Received: August 2, 2026 Approved: August 8, 2026

Abstract
PT. DAP is a manufacturing company in the pulp and paper industry that faces frequent machine breakdowns and downtime, which adversely affect the achievement of production targets. This study aims to develop a maintenance strategy to minimize downtime on the PM1 paper machine using the Reliability-Centered Maintenance (RCM) approach. The results indicate that the critical components of the Palm Guide Roll system are the Air Bellow, Pneumatic Air Cylinder, and Paddle Blade. The recommended optimal replacement intervals are 24 days for the Air Bellow, 53 days for the Pneumatic Air Cylinder, and 54 days for the Paddle Blade. The proposed maintenance strategy applies a Time-Directed (TD) maintenance policy to the Air Bellow and Pneumatic Air Cylinder, and a Condition-Directed (CD) maintenance policy to the Paddle Blade. The proposed maintenance strategy is expected to reduce the Total Minimum Downtime (TMD) of the critical components by 4.74% and decrease component replacement costs by IDR 20,444,146.34 (4%) on the paper machine.
Keywords: *reliability-centered maintenance, paper machine, preventive maintenance, downtime, total minimum downtime*

Abstrak
PT. DAP merupakan perusahaan manufaktur di industri pulp dan kertas yang menghadapi permasalahan tingginya frekuensi *breakdown* dan *downtime* pada mesin produksi sehingga berdampak pada pencapaian target produksi. Penelitian ini bertujuan merumuskan strategi perawatan untuk meminimalkan *downtime* pada mesin kertas PM1 menggunakan pendekatan *Reliability Centered Maintenance* (RCM). Hasil penelitian menunjukkan bahwa komponen kritis pada sistem *Palm Guide Roll* adalah *Air Bellow*, *Pneumatic Air Cylinder*, dan *Paddle Blade*. Interval penggantian optimal yang direkomendasikan yaitu 24 hari untuk Air Bellow, 53 hari untuk *Pneumatic Air Cylinder*, dan 54 hari untuk *Paddle Blade*, dengan strategi *Time-Directed* (TD) pada *Air Bellow* dan *Pneumatic Air Cylinder* serta *Condition-Directed* (CD) pada Paddle Blade. Usulan strategi perawatan tersebut mampu menurunkan *Total Minimum Downtime* (TMD) pada komponen kritis sebesar 4,74 % serta usulan perawatan menghasilkan penurunan biaya penggantian komponen sebesar Rp20.444.146,34 atau 4% pada mesin kertas.
Kata kunci: *reliability-centered maintenance, mesin kertas, pemeliharaan preventif, downtime, total minimum downtime*

1. Introduction

In the modern industrial era, the manufacturing sector plays a vital role in supporting economic growth by improving productivity and production efficiency. One of the key factors in ensuring sustainable production is machine reliability and the implementation of an effective maintenance system. A well-planned maintenance program can minimize machine downtime, maintain product quality, and reduce operational costs [1].

PT DAP is a manufacturing company operating in the pulp and paper industry. Its primary production facility is the Fourdrinier PM1 paper machine, which is used to produce corrugating medium (CME) paper. As the main machine in the production line, the Fourdrinier PM1 continuously forms paper sheets, making its reliability essential to maintaining production capacity and ensuring product quality [2].

In its daily operations, PT DAP experiences several challenges in maintaining the reliability of the Fourdrinier PM1 paper machine. Frequent production disturbances, reduced machine operating speed, unexpected machine breakdowns, and increasing downtime have negatively affected the achievement of production targets. These conditions indicate that several machine components have deteriorated and have not received adequate maintenance. Furthermore, preventive maintenance scheduling has not been implemented consistently, and machine condition data have not been fully utilized to support effective maintenance planning. Similar conditions are commonly found in manufacturing industries in Indonesia, where maintenance activities are often performed without considering equipment reliability, resulting in reduced machine effectiveness and increased maintenance costs [3].

To address these problems, a more systematic and reliability-based maintenance system is required. One of the most widely adopted approaches is Reliability-Centered Maintenance (RCM). RCM focuses on identifying critical components, analyzing potential failure modes, and determining the most appropriate maintenance strategies to improve equipment reliability while reducing the likelihood of unexpected failures [4]. Previous studies have demonstrated that the implementation of RCM can effectively reduce machine downtime, improve maintenance efficiency, and enhance equipment reliability across various industrial sectors [5], [6].

The proposed solution in this study begins by identifying the critical components of the Fourdrinier PM1 paper machine based on historical failure data and downtime records. Subsequently, the Reliability-Centered Maintenance (RCM) approach is applied to determine the most appropriate maintenance strategies, including Time-Directed (TD) and Condition-Directed (CD) maintenance tasks, to minimize production downtime and improve maintenance effectiveness.

Based on these considerations, this study aims to identify the critical components of the Fourdrinier PM1 paper machine and develop an optimal maintenance strategy using the Reliability-Centered Maintenance (RCM) approach at PT DAP. The proposed maintenance strategy is expected to reduce machine downtime, improve maintenance effectiveness, and support the long-term sustainability of production operations.

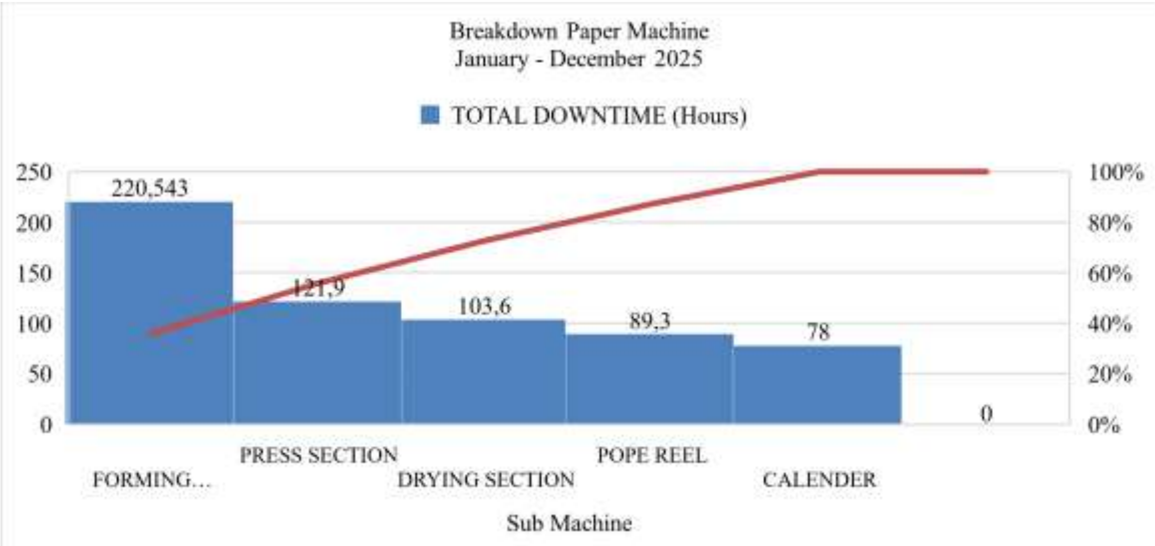

Fig. 1: Paper Machine Downtime Data
Source: PT. DAP

2. Methodology

Research Flow

This study employs the Reliability-Centered Maintenance (RCM) approach, a systematic maintenance management method used to develop maintenance schedules that meet operational requirements, improve equipment design through failure analysis, maintain system reliability and safety by implementing preventive maintenance, and reduce maintenance time and costs [7]. The research methodology is illustrated in **Figure 1**.

Figure 1 illustrates the research methodology employed in this study. This research was conducted at PT DAP, with the Fourdrinier PM1 paper machine serving as the object of the study. The Reliability-Centered Maintenance (RCM) approach was applied to identify critical machine components and develop an optimal maintenance strategy for minimizing production downtime.

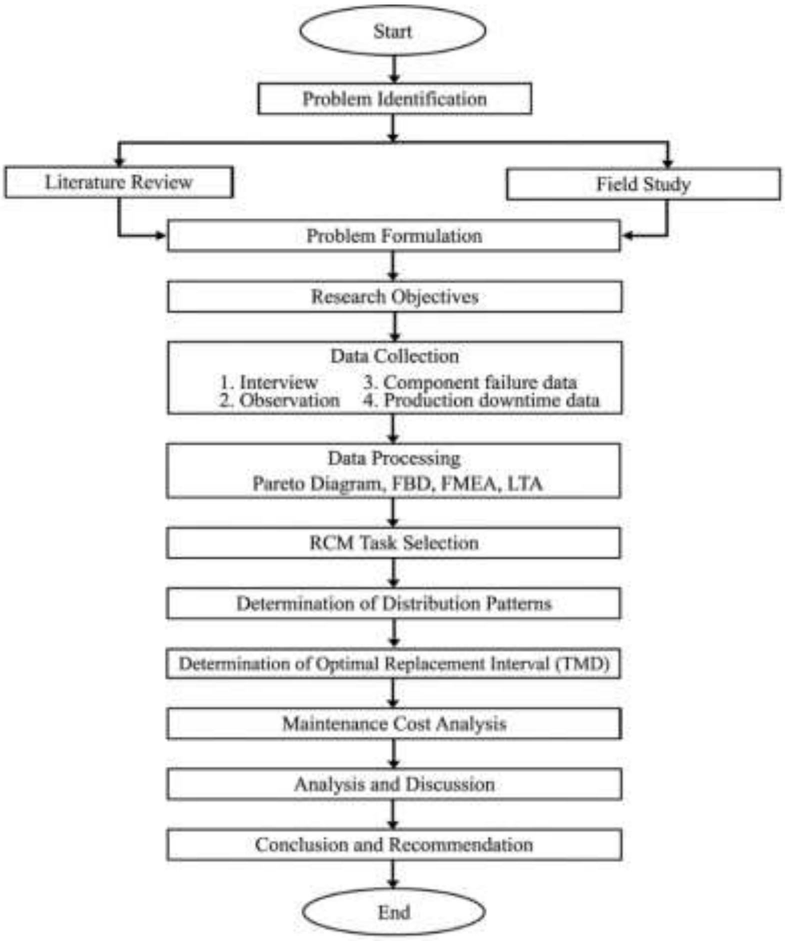

Fig. 2: Research Flow Diagram

Research Focus

This study focuses on identifying the critical components of the Fourdrinier PM1 paper machine at PT DAP that frequently experience failures and determining an optimal maintenance strategy using the Reliability-Centered Maintenance (RCM) approach. The primary objective is to minimize machine downtime and improve equipment reliability through Failure Mode and Effects Analysis (FMEA), Logic Tree Analysis (LTA), maintenance task selection, and the determination of optimal component replacement intervals using the Total Minimum Downtime (TMD) method.

Research Scope

The scope of this study is limited to the Fourdrinier PM1 paper machine at PT DAP. The analysis is based on machine failure, downtime, and maintenance history data collected from January to December 2025. The research includes identifying critical components using a Pareto chart, developing a Function Block Diagram (FBD), conducting Failure Mode and Effects Analysis (FMEA) and Logic Tree Analysis (LTA), calculating the Mean Time Between Failures (MTBF) and Mean Time to Repair (MTTR), performing statistical distribution analysis of failure data, determining optimal replacement intervals using the Total Minimum Downtime (TMD) method, and evaluating maintenance costs.

Data collection Method

Data collection in this study was conducted to obtain the information required for reliability analysis and maintenance planning. The data used in this research consist of primary and secondary data, as described below:

a. Primary data were collected through interviews with machine operators, maintenance technicians, and maintenance supervisors, as well as direct observations of machine conditions and maintenance activities in the production area. These data were used to identify failure types, determine the causes of downtime, and understand the maintenance procedures currently implemented.

b. Secondary data were obtained from company records and maintenance documents, including machine breakdown history, downtime records, failure types, maintenance activities, and information on failed components during the period from January to December 2025. These data served as the basis for reliability analysis, maintenance strategy development, and maintenance cost evaluation.

Reliability Centered Maintenance

Reliability-Centered Maintenance (RCM) is a systematic maintenance management approach designed to develop maintenance schedules that satisfy operational requirements, improve equipment design through failure analysis, maintain system reliability and safety, and optimize maintenance time and costs [7]. This approach focuses on maintaining equipment reliability and availability by identifying the most appropriate maintenance strategy whether preventive, predictive, or corrective, based on the level of risk and the operational impact of potential failures. The implementation of RCM can reduce machine downtime and improve production efficiency by applying maintenance strategies that are tailored to the operating conditions of the equipment [8].

Diagram Pareto

Critical machine components are identified using a Pareto chart, which ranks failure frequencies from the highest to the lowest. The Pareto chart is one of the fundamental quality control tools based on the 80/20 principle, which states that approximately 80% of problems are typically caused by 20% of the underlying factors. This technique helps identify the most significant failure causes that should be prioritized for corrective and preventive maintenance actions [9].

Functional Block Diagram (FBD)

A Functional Block Diagram (FBD) is used to describe the functional relationships among subsystems within a machine or system. It illustrates the flow of inputs and outputs between system components and provides a clear representation of the interactions among subsystems, facilitating reliability and maintenance analyses [10].

Failure Mode and Effect Analysis (FMEA)

Failure Mode and Effects Analysis (FMEA) is a systematic method used to identify potential failure modes in equipment, systems, or processes, evaluate their effects on system performance, determine their causes, and prioritize risks for corrective action. The primary objective of FMEA is to prevent failures, improve equipment reliability, and enhance maintenance effectiveness. The implementation of FMEA consists of the following steps [1], [3]:

a. Identify the functions and components of the system.
b. Identify potential failure modes.
c. Determine the effects of each failure mode.
d. Identify the causes of each failure mode.
e. Evaluate the risk of each failure mode based on three parameters:

$$\text{RPN} = \text{Severity} \times \text{Occurrence} \times \text{Detection}$$

The calculated RPN values are used to prioritize maintenance actions. Components with higher RPN values require greater attention because they present a higher risk of failure. Therefore, FMEA provides a systematic basis for identifying critical components and supporting maintenance decision-making [11].

Logic Tree Analysis (LTA)

Logic Tree Analysis (LTA) is a qualitative analysis method used to classify failure modes according to their consequences for system operation, safety, and maintenance requirements. The purpose of LTA is to determine the maintenance priority and appropriate maintenance strategy for each failure mode identified through the FMEA process [7]. The LTA evaluation is conducted based on the following four decision criteria [12]:

a. Evident: Can the operator detect the system failure while the machine is operating under normal conditions?
b. Safety: Does the failure have the potential to pose a risk to personnel safety?

c. Outage: Does the failure cause a complete or partial shutdown of the machine or production process?
d. Category: Based on the answers to the above questions, each failure mode is classified into one of the following categories: Category A: Safety-related failures, Category B: Failures that cause operational disruptions, Category C: Failures that primarily result in economic losses, Category D: Hidden failures that cannot be detected during normal machine operation.

Task Selection

This stage involves selecting the most appropriate maintenance task based on the results of the Reliability-Centered Maintenance (RCM) analysis. The selection of maintenance tasks should consider cost-effectiveness, risk level, and their impact on equipment reliability, availability, and operational safety [1]. According to the RCM methodology, maintenance tasks are classified into four categories [7]:

a. Time-Direct (TD)
Time-Directed (TD) maintenance is a preventive maintenance strategy performed at predetermined time intervals or operating ages. It is applied to components that are susceptible to age-related deterioration or wear and are replaced or overhauled before failure occurs.
b. Condition Direct (CD)
Condition-Directed (CD) maintenance is performed by monitoring and evaluating the actual condition of machine components through inspections, testing, or condition-monitoring techniques. Maintenance actions, such as repair or replacement, are carried out only when signs of deterioration or potential failure are detected.
c. Finding Failure (FF)
Failure-Finding (FF) maintenance is intended to detect hidden failures that cannot be identified during normal machine operation. This maintenance activity is performed through scheduled inspections or functional tests to ensure that protective or standby components remain operational.
d. Run to Failure (RTF)
Run-to-Failure (RTF) is a maintenance strategy in which equipment is allowed to operate until failure occurs. This strategy is appropriate for non-critical components when preventive maintenance is not technically necessary or economically justified.

Determination of Failure Distribution Patterns

Failure distribution analysis is conducted to identify the statistical distribution that best represents the failure characteristics and service life of machine components. This analysis provides essential information for estimating component reliability and determining optimal maintenance intervals [11]. Several probability distributions are commonly used in reliability analysis, including the Exponential, Normal, Lognormal, and Weibull distributions. According to Ebeling, the selection of an appropriate failure distribution depends on the characteristics of the failure data and the objectives of the reliability analysis. When the number of failure observations is relatively limited, the distribution parameters can be estimated using the Least Squares Method, also known as Least Squares Fitting. The mathematical equations for each probability distribution are presented as follows:

a. Lognormal Distribution

$$PDF \rightarrow f(t) = \frac{1}{t.s\sqrt{2n}} exp\,\{-\frac{1}{2^S}[In\,t - t_{med}]^2\}$$

$$\text{Reliability Function} \rightarrow R(t) = 1 - \emptyset[\mu\frac{1}{s}In\left(\frac{t}{t_{med}}\right)] \quad (1)$$

$$\text{Failure Rate } \lambda\,(t) = \frac{f(t)}{R(t)}$$

$$MTTF \rightarrow exp\,(t_0 + 0{,}5\,s^t$$

b. Normal Distribution

$$PDF \rightarrow f(t) = \frac{1}{(\sigma)\sqrt{2\pi}}\int_{-\infty}^{1} exp\,[-\frac{(x-\mu)^2}{2\sigma^2}]dx$$

$$\text{Reliability Function} \rightarrow R(t) = 1 - (\emptyset\left(\frac{t-\mu}{\sigma}\right)) \quad (2)$$

$$F(t) \rightarrow \emptyset(\frac{t-\mu}{\sigma})$$

$$\text{Failure Rate } (t) = \frac{f(t)}{1 - \emptyset\left(\frac{t-\mu}{\sigma}\right)}$$
$$MTTF = \mu$$

c. Exponential Distribution

$$PDF \rightarrow f(t) = \lambda e^{\lambda t}$$
$$\text{Reliability Function} \rightarrow R(t) = \lambda e^{-\lambda t}$$
$$F(t) \rightarrow 1 - e^{-\lambda t} \quad (3)$$
$$Failure\ Rate \rightarrow h(t) = \lambda$$
$$MTTF = \frac{1}{\lambda} atau 1/\lambda$$

d. Weibull Distribution

$$PDF \rightarrow f(t) = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1} \cdot e - \left(\frac{t}{\theta}\right)\beta$$
$$\text{Reliability Function} \rightarrow R(t) = e^{-\left(\frac{t}{\theta}\right)\beta}$$
$$F(t) \rightarrow 1 - e^{-\left(\frac{t}{\theta}\right)\beta} \quad (4)$$
$$Failure\ rate \rightarrow h(t) = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)\beta - 1$$
$$MTTF \rightarrow \theta T\left(1 + \frac{1}{\beta}\right)$$

Determining the Optimal Replacement Interval (Total Minimum Downtime)

The primary objective of maintenance management is to minimize equipment downtime in order to maintain equipment availability and ensure uninterrupted production operations [13]. Total Minimum Downtime (TMD) is a maintenance optimization method used to determine the optimal replacement interval for machine components by minimizing the total expected downtime of the system. This method balances the downtime resulting from scheduled preventive replacements with the downtime caused by unexpected component failures, thereby identifying the replacement interval that minimizes total downtime. The TMD value is calculated based on the preventive replacement time, the corrective replacement time following component failure, and the expected number of failures occurring within the replacement interval [7].

$$D(t) = \frac{(H(t)Tf + Tp)}{(tp + Tp)} \quad (5)$$

with:

$H(t)$	= expected number of failures during the interval(0.tp),
Tf	= replacement time after damage occurs (failure replacement time),
Tp	= preventive replacement time,
$tp + Tp$	= preventive replacement interval.

The Total Minimum Downtime (TMD) method is based on determining the optimal replacement interval (tp) for machine components. If a component follows a specific failure distribution, its probability density function is represented by $f(t)$. Accordingly, the expected number of failures occurring within the replacement interval $(0, tp)$ can be calculated using the following equation:

$$H(tp) + \sum_{t=0}^{tp-1} [1 = H(tp) - 1 - i] \int_{i}^{i+1} f(t)dt \quad (6)$$

$H(0)$ is set equal to zero, so for tp =0, then $H(tp)$= $H(0)$.

Maintenance Cost Analysis

Maintenance costs are estimated based on component replacement costs, labor costs, and production losses resulting from machine downtime [7]. For scheduled restoration or preventive replacement tasks, maintenance costs are calculated by considering the costs associated with component repair or replacement. The maintenance cost is determined using the following equation:

$$Cf = Cr + MTTR + (Co + Cw) \quad 7$$

Where:
Cf = Repair cost for each damage or replacement per maintenance cycle
Cr = Cost of replacing damaged components
Co = Cost of lost production
Cw = Labor cost Cf (repair cost), then the calculation for the costs incurred is performed.

The maintenance cost analysis is based on the proposed maintenance strategy developed in the previous stage. The maintenance costs are calculated using the following equation:

$$Tc = (C_m + C_r + f_m) \quad 8$$

Where:
C_m = Cost incurred for maintenance
C_r = Component cost
f_m = Frequency of preventive maintenance implementation

3. Results and Discussion

Functional Block Diagram

The Functional Block Diagram (FBD) of the paper machine is shown in **Figure 3**.

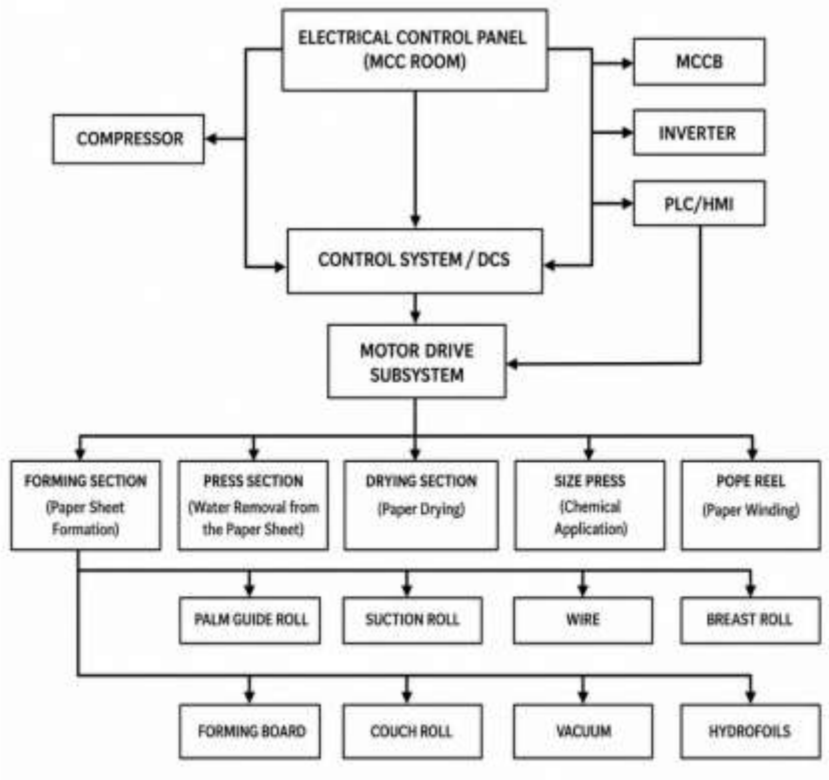

Fig. 3: Functional Block Diagram Paper Machine

Critical Component Selection

The identification of critical components using the Pareto chart begins by calculating the weighted value of each component based on its failure frequency and unit replacement cost. The calculation results are presented in **Figure 4**.

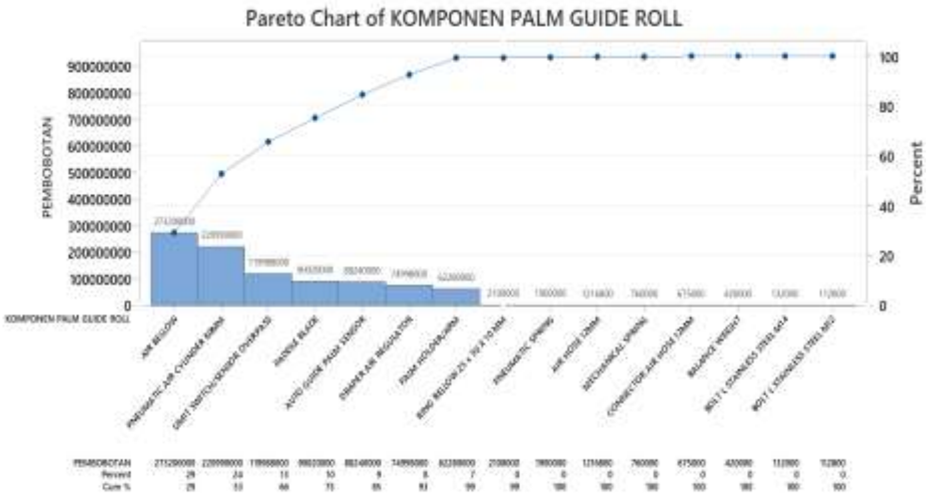

Fig. 4: Paper machine palm guide roll component damage data
Source: Damage data on PT. DAP paper machines

Based on **Figure 4**, the Pareto chart of the Palm Guide Roll components indicates that the majority of the weighted contribution is concentrated in a few key components. The Air Bellow contributes the largest proportion (29%), followed by the Pneumatic Air Cylinder (24%) and the Limit Switch/Overpass Sensor (13%). Together, these three components account for approximately 66% of the total weighted value. When the Paddle Blade (10%) and the Auto Guide Palm Sensor (9%) are included, the cumulative contribution reaches approximately 85%. According to the Pareto principle, these five components are identified as the critical components and should therefore be prioritized for inspection, maintenance, and preventive maintenance activities.

Failure Mode and Effect Analysis (FMEA)

The Risk Priority Number (RPN) values were classified into four risk categories: low, medium, high, and very high. Failure modes with an RPN value greater than 100 were classified as high-risk failures, indicating that corrective actions and further analysis were required [14].

Table 1. FMEA Analysis of Critical Components

Component	Function	Failure Mode	Cause of Failure	Failure Effect	SEV	OCC	DET	RPN	RANK
Pneumatic Air Cylinder	Automatically actuates the guide roll mechanism to maintain proper wire alignment.	The cylinder fails to move or exhibits weak stroke	Seal leakage, low air pressure, or piston seizure	The guide roll fails to correct the wire position, causing wire misalignment	8	4	4	128	2
Air Bellow	Regulates the pressure and motion response of the guide roll system	The air bellow leaks or loses pressure	Rubber material wear, tearing, or excessive air pressure	The auto guide system becomes unstable and exhibits a slow correction response	7	5	5	175	1
Auto Guide Palm Sensor	Detects the wire position and provides correction signals to the guide system	The sensor fails to detect the wire position	Sensor contamination , damage, or misalignment	The auto guide system fails to operate, causing the wire to deviate from its intended path	9	3	3	81	4
Paddle Blade	Detects the mechanical movement of the wire in the palm guide system	Paddle wear or fracture	Continuous contact with the wire or material fatigue	Wire position detection becomes inaccurate.	6	4	5	120	3
Limit Switch/Sensor Overpass	Provides a safety limit when the guide position exceeds the preset limit	Limit switch fails to actuate	Mechanical damage, broken wiring, or contamination	The system fails to stop during overtravel, potentially damaging the wire	8	3	4	96	5

A summary of the FMEA results is presented in **Table 2**.

Table 2. Summary of FMEA Analysis Results

Component	RPN	Rank	Category
Air Bellow	175	1	High
Pneumatic Air Cylinder	128	2	High
Paddle Blade	120	3	High
Limit Switch/Sensor Overpass	96	4	Low
Auto Guide Palm Sensor	81	5	Low

Based on the FMEA results, the Air Bellow was identified as the most critical component, with the highest Risk Priority Number (RPN) of 175, ranking first among all evaluated components. This result indicates that the Air Bellow has the greatest potential risk of failure, as it plays a crucial role in regulating the pressure and motion response of the guide roll system. The Pneumatic Air Cylinder ranked second with an RPN of 128, indicating that its failure could disrupt the guide roll mechanism responsible for automatically correcting the wire position. The Paddle Blade ranked third with an RPN of 120 and functions as the mechanical sensing component that detects wire movement within the Palm Guide Roll system. Meanwhile, the Limit Switch/Overpass Sensor and the Auto Guide Palm Sensor recorded RPN values of 96 and 81, respectively. Based on the established RPN criterion (RPN > 100), the Air Bellow, Pneumatic Air Cylinder, and Paddle Blade were identified as critical components and selected for further analysis.

Logic Tree Analysis

The results of the Logic Tree Analysis (LTA) for each critical component are described as follows:

a. Air Bellow
The LTA results indicate that the Air Bellow is classified as a Category A component, indicating that it is highly critical because its failure directly affects both operational safety and machine reliability. The primary failure modes of this component include air leakage and unstable air pressure caused by worn, torn, or ruptured rubber material. These failures may pose a safety risk to operators working near the component and can also damage the wire clothing (forming fabric), potentially disrupting the production process..

b. *Pneumatic Air Cylinder*
Based on the LTA results, the Pneumatic Air Cylinder is classified as a Category B component. Although failure of this component does not directly threaten operator safety, it can cause significant operational disruptions because the guide roll mechanism is unable to automatically correct the wire position, resulting in wire misalignment during production.

c. *Paddle Blade*
The Paddle Blade is also classified as a Category B component because its failure primarily affects machine performance rather than operational safety. The most common failure mode is paddle wear caused by continuous friction between the paddle and the moving wire, which reduces the accuracy of wire movement detection.

Task Selection

Based on the RCM analysis, the maintenance task selected for each critical component is as follows:

a. Air Bellow: A Time Directed (TD) maintenance strategy was selected for the Air Bellow because its failure is primarily age-related and follows a predictable deterioration pattern. Therefore, scheduled replacement at predetermined intervals is considered the most effective approach to preventing unexpected failures and minimizing production downtime.
b. Pneumatic Air Cylinder: A Time-Directed (TD) maintenance strategy was also selected for the Pneumatic Air Cylinder because its failure pattern is associated with component aging. Preventive replacement at predetermined intervals is considered appropriate to prevent failures caused by seal leakage, pressure loss, and piston seizure, thereby improving machine reliability.
c. Paddle Blade: A Condition-Directed (CD) maintenance strategy was selected for the Paddle Blade because its physical condition can be directly assessed through routine inspections. Maintenance actions, including component replacement, are performed only when signs of

wear or deterioration are detected, allowing maintenance decisions to be based on the actual condition of the component.

Determination of Distribution Patterns

The failure distribution of each critical component was determined using Minitab 22. The analysis results are presented as follows:

Table 3. distribution test results using Minitab 22 software

Component	Pattern of Distribution	Parameter
Air Bellow	Weibull	β =6,46818, θ=26,9514
Pneumatic Air Cylinder	Weibull	β =61,8696, θ=57,3077
Paddle Blade	Weibull	β =154,117, θ=56,5481

The Weibull distribution analysis of the Air Bellow produced a shape parameter (β) of 6.46818 and a scale parameter (θ) of 26.9514. Since β>1, the Air Bellow exhibits a wear-out failure pattern, indicating that the probability of failure increases as the component ages.

The Weibull distribution analysis of the Pneumatic Air Cylinder yielded a shape parameter (β) of 61.8696 and a scale parameter (θ) of 57.3077. The exceptionally high β value indicates that component failure is strongly influenced by aging and service life, suggesting that failures predominantly occur during the wear-out phase.

Similarly, the Weibull distribution analysis of the Paddle Blade produced a shape parameter (β) of 154.117 and a scale parameter (θ) of 56.5481. These results indicate that the Paddle Blade also exhibits a wear-out failure pattern, with failures primarily caused by progressive mechanical wear during operation.

Recommended Intervals for Component Replacement

The optimal replacement interval (tpt_ptp) was determined based on the calculation of the downtime function, $D(t)$. The optimal replacement time corresponds to the point at which $D(t)$ reaches its minimum value before increasing again. This minimum point represents the condition in which the expected total downtime is minimized, making it the most appropriate time to perform preventive component replacement before the probability of failure begins to increase.

Table 4. recommended component replacement intervals

Component	D(t)	Day Interval (tp)
Air Bellow	0,001456287	The recommended replacement interval for the component is 24 days
Pneumatic Air Cylinder	0,001196168	The recommended replacement interval for the component is 53 days
Paddle Blade	0,000297837	The recommended replacement interval for the component is 54 days

Table 5. Comparison of TMD before and after the proposal

Component	TMD Before Proposal	TMD After Proposal	TMD decline	TMD Decrease Percentage
Air Bellow	0,522227379	0,518438099	0,00378928	0,73%
Pneumatic Air Cylinder	0,429454896	0,425835671	0,003619226	0,84%
Paddle Blade	0,10950663	0,106030062	0,003476568	3,17%

Based on **Table 5**, all critical components exhibited lower Total Minimum Downtime (TMD) values following the implementation of the proposed maintenance strategy, indicating improvements in equipment reliability and maintenance effectiveness. The Air Bellow showed a reduction in TMD from 0.522227379 to 0.518438099, representing a decrease of 0.00378928 (0.73%). Similarly, the Pneumatic Air Cylinder exhibited a reduction in TMD from 0.429454896 to 0.425835671, corresponding to a decrease of 0.003619226 (0.84%). The Paddle Blade demonstrated the greatest improvement, with its TMD decreasing from 0.10950663 to 0.106030062, representing a reduction of 0.003476568 (3.17%). Overall, these results indicate that the proposed maintenance strategy effectively reduced downtime for all three critical components. Among them, the Paddle Blade achieved the greatest improvement, as reflected by the highest percentage reduction in TMD.

Cost Analysis

The existing maintenance practice is based on a predetermined replacement schedule that considers labor costs, spare part replacement costs, and production losses resulting from machine downtime. In contrast, the proposed maintenance strategy determines the optimal replacement interval based on the Total Minimum Downtime (TMD) criterion to minimize overall downtime. The results of the maintenance cost analysis are presented below.

Table 6. Comparison of component costs before and after the proposal

Component	Pre-proposal Costs	Post-Proposal Costs	Cost Savings	Percentage Decrease
Air Bellow	Rp270.956.153,61	Rp260.702.655,73	Rp10.253.497,88	4%
Pneumatic Air Cylinder	Rp222.635.052,22	Rp216.307.188,56	Rp6.327.863,66	3%
Paddle Blade	Rp90.170.714,06	Rp86.307.929,26	Rp3.862.784,80	4%
TOTAL	Rp583.761.919,89	Rp563.317.773,55	Rp20.444.146,34	4%

Based on **Table 6**, the implementation of the proposed replacement intervals resulted in annual maintenance cost savings of IDR 20,444,146.34, representing a 4% reduction compared with the existing maintenance costs.

4. Conclusion

Based on the results of this study, the Pareto chart and Failure Mode and Effects Analysis (FMEA) identified the Air Bellow, Pneumatic Air Cylinder, and Paddle Blade as the critical components of the Palm Guide Roll system. The application of the Reliability-Centered Maintenance (RCM) approach determined the optimal replacement intervals to be 24 days for the Air Bellow, 53 days for the Pneumatic Air Cylinder, and 54 days for the Paddle Blade. The recommended maintenance strategies consisted of Time-Directed (TD) maintenance for the Air Bellow and Pneumatic Air Cylinder, and Condition-Directed (CD) maintenance for the Paddle Blade. The implementation of these strategies reduced the Total Minimum Downtime (TMD) of the critical components by 4.74%, with the Paddle Blade showing the greatest reduction of 12 minutes (3.17%), followed by the Pneumatic Air Cylinder with 8.89 minutes (0.84%), and the Air Bellow with 7.68 minutes (0.73%). In addition, the proposed maintenance strategy reduced the annual component replacement cost by IDR 20,444,146.34, representing a 4% reduction compared with the existing maintenance practice.

These findings demonstrate that the Reliability-Centered Maintenance (RCM) approach is effective in identifying critical components, optimizing maintenance intervals, and improving maintenance performance. Therefore, the proposed maintenance strategy can serve as a practical reference for reducing downtime, improving equipment reliability, and enhancing maintenance cost efficiency at PT DAP.

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