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Research article

Reliability-Based Preventive Maintenance Scheduling for Raw Mill Equipment to Minimize Downtime at PT X

Alfadhlani, Ahmad Zuhair, Prima Fithri

Departemen Teknik Industri, Fakultas Teknik, Universitas Andalas, Kampus Unand Limau Manis, Padang, Indonesia 25163

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CORRESPONDENCE

E-mail: alfadhlani@eng.unand.ac.id

A B S T R A C T

PT X is one of Indonesia's cement companies operating three active plants: Plant IV, V, and VI. Production data from 2022 and 2023 indicated that Plant V achieve only 79% and 86% of its production targets, with high downtime resulting from a reliance on corrective maintenance. This study proposes a preventive maintenance schedule to reduce downtime using the Reliability-Centered Maintenance (RCM) method for controlling critical components and an age-based replacement model for minimizing downtime. The analysis identified eight critical components in Raw Mill Machines 1 and 2, with reliability improvements ranging from 14% to 58%. Implementation of the proposed schedule resulted in increased machine availability by 5.1% and 4.65%, and system reliability improved by 33.71%. These findings demonstrate that RCM-based preventive maintenance effectively enhances operational performance.

1. INTRODUCTION

The Indonesian cement industry has experienced rapid growth, driven by infrastructure development and increasing demand. Strategic national projects; such as the construction of the new capital city (IKN), have further increased cement demand and intensified competition to achieve production efficiency and cost minimization. This situation compels companies to continually enhance customer value and production costeffectiveness to achieve performance excellence [1].

Smooth production processes are crucial for delivering high-value products and maintaining a competitive advantage. The optimal availability of production facilities, particularly machinery, is a key factor in ensuring uninterrupted operations. Equipment failure or performance degradation can significantly disrupt production activities [2].

As market competition intensifies, the ability to maintain smooth production and deliver value-added products becomes a crucial factor in sustaining a competitive advantage. Industrial development increasingly emphasizes rapid response and damage prevention. One of the key enablers of production continuity is the optimal availability of company facilities. For medium- and large-scale enterprises, production machinery must remain efficient and effective at all times. Any malfunction or decline in machine performance can directly impact production continuity.

PT X is one of the largest and oldest cement manufacturers in Indonesia, with an annual production capacity of 8,900,000 tons. The company faces on-

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going challenges in remaining productive and meeting market demand. Therefore, optimizing machinery maintenance is essential to sustain and enhance productivity.

2. PROBLEM DESCRIPTION

PT X faces ongoing challenges in meeting the growing market demand. To maintain and enhance productivity, machinery maintenance has become essential. The company currently operates three plants (IV, V, and VI) with a total annual cement production capacity of 42 million tons. In addition to cement, PT X also produces clinker, which serves as the primary raw material for cement. The cement production process involves four main types of machinery: the Raw Mill, the Kiln, the Roller Press, and the Cement Mill, while clinker production concludes at the Kiln stage. A comparison between the target and actual clinker production for each plant is presented in Figure 1.

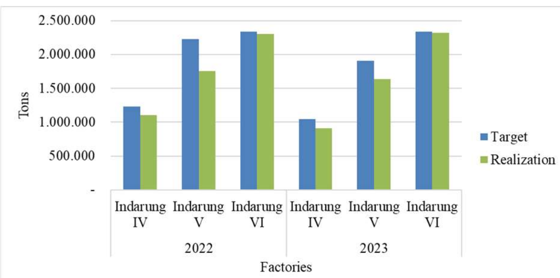

Figure 1. Clinker Production

Clinker production data from 2022 and 2023 indicate that Plant V failed to meet its production targets for those years. The plant achieved only 79% and 86% of the target, with clinker outputs of 1,752,337 tons and 1,635,851 tons, respectively. This shortfall was primarily due to excessive machine downtime, which exceeded the planned limits. Downtime—defined as the period during which machinery is non-operational due to scheduled maintenance or unexpected failures—can halt production processes and negatively impact productivity, efficiency, and cost [3]. Machine downtime data for Plant V in 2023 is presented in Table 1.

Maintenance is essential to ensure machine reliability and optimal performance [4]. Downtime data from Plant V in 2023 shows that Raw Mill 1 and Raw Mill 2 experienced the highest levels of unplanned downtime. Totaling 449.97 and 577.85 hours, respectively. This excessive downtime was caused by the application of corrective maintenance, which involves performing maintenance only after a failure occurs, resulting in significant and unpredictable production interruptions [5].

Table 1. Plant Machinery Downtime

Machine	Planned (Hours)	Unplanned (Hours)
Raw Mill 1	2887.17	449.97
Raw Mill 2	2892.42	577.85
Kiln	2742.9	371.32
Roller Press 1	34.37	285.67
Roller Press 2	34.37	164.45
Cement Mill 1	353.32	349.42
Cement Mill 2	210.02	327.37

The Raw Mill plays a vital role in the cement production process by mixing and grinding raw materials into Raw Mix, which is subsequently processed into clinker and cement. Any interruption in Raw Mill operations can disrupt the entire production flow. Therefore, addressing downtime issues in the Raw Mill should be a primary focus.

To minimize downtime, a preventive maintenance strategy is necessary—one that replaces components before they fail [4]. It is also necessary to evaluate the existing maintenance schedule. This study employs the Reliability-Centered Maintenance (RCM) approach, which focuses on critical system elements, resource optimization, failure risk analysis, and flexible application to industrial machinery [6].

RCM has been applied in various previous studies, including maintenance management for paper production machinery [7], sugar mills [6], and medical equipment [8]. This research proposes a maintenance schedule that focuses on the timely replacement of critical components to reduce downtime and improve achievement of production targets at PT X. Accordingly, the study aims to determine the optimal maintenance schedule for critical components, estimate Raw Mix reserve requirements during downtime, and maximize machine availability and reliability.

3. RESEARCH METHODOLOGY

3.1. Experimental Design

This study was conducted to evaluate the maintenance policy and types of failures in the Raw Mill machinery at Plant V of PT X. Raw data were processed from the determination of maintenance policies for Raw Mill components to the calculation of their availability and reliability. The research stages are as follows:

1. Reliability Centered Maintenance (RCM)

RCM is a maintenance management method that utilizes asset reliability information to determine effective and efficient maintenance policies. The RCM stages include:

   a. System description and Functional Block Diagram (FBD)
   b. Root Cause Failure Analysis (RCFA)
   c. Failure Mode and Effect Analysis (FMEA)
   d. Logic Tree Analysis (LTA)

2. Calculating Time To Failure (TTF) and Time To Repair (TTR)

TTF and TTR are calculated for each critical component of the Raw Mill. The calculations are based on machine downtime data resulting from the failure of each critical component. The TTF and TTR data are then evaluated for goodness of fit against Weibull, normal, lognormal, and exponential distributions.

3. Calculating the Goodness-of-Fit Index for TTF and TTR

The goodness-of-fit index is calculated for the TTF and TTR data of each critical component. Distribution parameters for Weibull, normal, lognormal, and exponential models are also determined. The distribution with the highest goodness-of-fit index is selected for hypothesis testing.

4. Testing the Distribution Hypothesis for TTF and TTR

The distribution with the highest goodness-of-fit index is tested to validate its suitability. Mann's Test is used for Weibull distribution, the Kolmogorov–Smirnov Test for normal and lognormal distributions, and Bartlett's Test for exponential distribution. The hypotheses are:

- Null hypothesis: the data follow the selected distribution
- Alternative hypothesis: the data do not follow the selected distribution

If the null hypothesis is rejected, the following highest goodness-of-fit index is selected for further testing.

5. Calculating MTTF and MTTR

MTTF (Mean Time To Failure) represents the average operational time of a component, calculated based on historical data distribution. MTTR (Mean Time To Repair) is the average repair time, also derived from the selected distribution formula. These values are used to determine the optimal replacement interval for critical components.

6. Calculating the Replacement Interval for Critical Components

The preventive replacement interval for critical components is calculated to determine the timing that yields the lowest expected downtime. The expected downtime is derived from the MTTR distribution and evaluated against the replacement interval to identify the minimum downtime scenario.

7. Calculating the Inspection Interval for Critical Components

Inspection intervals are calculated for critical components using a model that minimizes downtime. Inspections are conducted to perform maintenance and prevent potential failures before they occur, thereby extending the equipment's lifespan.

8. Calculating Raw Mix Reserve Requirements

The plant maintains a minimum Raw Mix reserve of 18,000 tons to support preventive maintenance (PMc). The reserve calculation is based on the required volume during machine downtime. This analysis also assesses the alignment of proposed replacement and inspection schedules with the plant's reserve policy.

9. Calculating Availability and Reliability of Critical Components

Availability and reliability calculations are performed to determine whether improvements have occurred. If improvements are observed, the proposed preventive maintenance strategy is considered adequate and preferable to the current condition. If no improvement is found, the proposal is deemed unsuitable for implementation.

3.2. Data Collection

One of the machines used in the cement production process, experiencing the most extended downtime at PT X, is the Raw Mill Machines 1 and 2, which operate in parallel and have recorded downtime durations of 449.97 and 577.85 hours, respectively. Unexpected component failures caused the downtime. Therefore, this study focuses on the component failures that led to downtime in these two machines.

3.2.1. Raw Mill System Description

Raw materials such as limestone, clay, silica sand, and iron sand are mixed and ground using the Raw Mill machine, producing an output known as Raw Mix. If there is a disruption in raw material transportation, it will also affect the Raw Mill operation, causing it to stop. Therefore, raw material transport is considered an integral part of the Raw Mill system. The system description of the Raw Mill is illustrated in Figure 2.

A similar study in [6] states that system descriptions provide an overview of the interrelationships among system components. In line with this, the Raw Mill system operates using electrical power. Once the raw materials enter the system, they are processed by a Grinding Table that rotates horizontally, while the Tyre Mill moves vertically. If the raw materials are not finely ground and cannot pass through the classifier, they are redirected to the Elevator Mill and reintroduced through the Feed Inlet. Meanwhile, the Raw Mix exits through the classifier and is transferred to the silo.

3.2.2. Root Cause Failure Analysis (RCFA)

The RCFA was conducted through interviews with the maintenance management team responsible for the Raw Mill machinery. The interviews employed the Five Whys technique, which involves asking successive "why" questions up to five levels to identify the root cause of component failure. The RCFA results, obtained using the Five Whys method, are presented in Table 2. The identified failure causes reached levels 2, 3, and 4, with level 5 not always attained, as the root cause was sufficiently identified at earlier stages. An example of the RCFA interview for the Tyre Mill component is as follows:

a. Why did the Raw Mill stop operating? Because the maximum vibration alarm was triggered.
b. Why was the maximum vibration alarm triggered? Because of the raw material buildup inside the Raw Mill.
c. Why did raw material buildup occur inside the Raw Mill? Because the Tyre Mill broke.

3.2.3. Failure Mode and Effect Analysis (FMEA)

The determination of Severity (S), Occurrence (O), and Detection (D) values was carried out through interviews and discussions with the Raw Mill maintenance management team. Subsequently, the Risk Priority Number (RPN) was calculated to indicate the failure risk level of each component. The RPN results for Raw Mills 1 and 2 are presented in Table 3. The highest RPN was found in the Tyre Mill component for both machines, as it is directly related to the machine's primary function and contributes significantly to extended downtime durations. Therefore, its severity and occurrence values are high, reflecting the critical impact of failure on core machine operations.

Additionally, the main drive component also showed a high severity score, as it supplies power to the machine—any failure in this component results in immediate downtime. Meanwhile, the detection values for all components were relatively low, ranging from 2 to 4, due to the presence of alarm systems that activate when failures occur during operation.

Based on the RPN values of components contributing to machine downtime, critical components were identified using the Pareto principle [9]. The results of this classification are shown in Table 4. Group A, which contains the critical components, accounts for 80% of the machine failure risk. These critical components include: Tyre Mill, Mill Auxiliaries, Transport Feeding, Bridge Scrapper, Clay Transport, Inner Part, Feeder Clay, and Bucket Excavator.

3.2.4. Logic Tree Analysis (LTA)

LTA was conducted on the critical components of Raw Mill Machines 1 and 2. The results of the analysis, which identify more effective maintenance strategies for these components, are presented in Table 5. Several critical components pose safety risks to operators, including the Bridge Scrapper, Clay Transport, and Bucket Excavator, all of which are part of the raw material transport system. These components carry the risk of raw materials coming into contact with operators during operation.

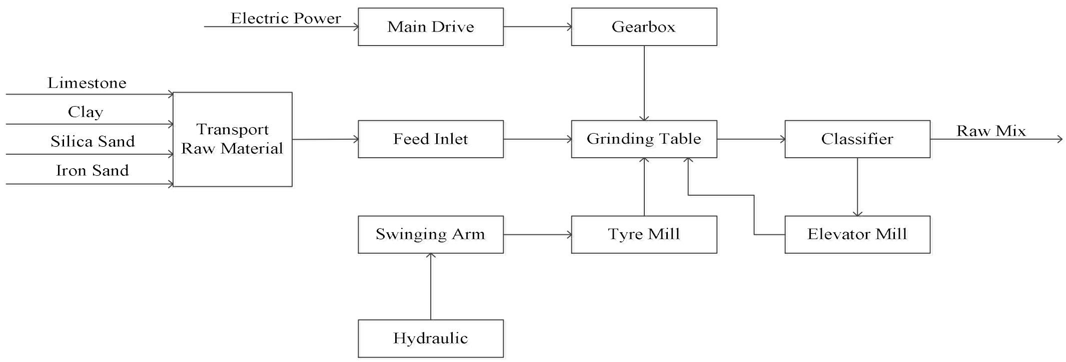

Figure 2. Raw Mill System

Table 2. Root Cause Failure Analysis Results

Component	Failure Cause	Description
Tyre Mill	Tyre broken	Level 3
Main Drive	Fuse blown	Level 3
Feeder Clay	The Dosimat shaft pin is broken	Level 2
Feeder Limestone	Dosimat chain broken	Level 2
Elevator Mill	Bucket elevator damaged	Level 3
Bridge Scrapper	The blade hanger of the Bridge Scrapper fractured	Level 2
Bucket Excavator	BCE chain broken	Level 2
Clay Transport	Belt torn	Level 2
Inner Part	Scattering plate detached	Level 2
Mill Auxiliaries	Seal needs replacement	Level 3
Classifier	Classifier bearing damaged	Level 2
Transport Feeding	Belt torn	Level 4

Table 3. Failure Mode and Effect Analysis

Component Type	Failure Impact	Raw Mill 1					Raw Mill 2				
		Downtime (Hours)	S	O	D	RPN	*Downtime* (Hours)	S	O	D	RPN
Tyre Mill	Primary function lost (warning)	32.88	9	8	4	288	103.93	9	10	4	360
Mill Auxiliaries	Primary function degraded	41.72	7	9	4	252	93.05	8	10	3	240
Transport Feeding	Primary function lost	30.88	8	8	3	192	25.58	7	7	4	196
Bridge Scrapper	Primary function lost	101.07	8	10	2	160	135.40	8	10	2	160
Clay Transport	Primary function lost	62.22	8	10	2	160	71.45	5	10	3	150
Inner Part	Functional comfort degraded	48.55	5	9	3	135	35.90	8	9	2	144
Feeder Clay	Primary function degraded	39.18	7	9	2	126	32.22	8	8	2	128
Bucket Excavator	Primary function lost	27.92	8	7	2	112	37.82	7	9	2	126
Elevator Mill	Functional comfort lost	11.78	6	4	4	96	15.48	6	5	4	120
Classifier	Primary function lost	29.68	8	7	1	56	14.75	7	4	2	56
Main Drive	Non-functional	16.12	10	5	1	50	12.27	10	4	1	40
Feeder Limestone	Primary function degraded	7.97	7	3	2	42	0.00	8	1	1	8

Table 4. Critical Component Identification

Raw Mill 1			Raw Mill 2		
Component Type	Cumulative	Group	Component Type	Cumulative	Group
Tyre Mill	17%	A	Tyre Mill	21%	A
Mill Auxiliaries	32%	A	Transport Feeding	35%	A
Transport Feeding	44%	A	Mill Auxiliaries	46%	A
Bridge Scrapper	53%	A	Bridge Scrapper	55%	A
Clay Transport	63%	A	Inner Part	64%	A
Inner Part	71%	A	Clay Transport	72%	A
Feeder Clay	79%	A	Bucket Excavator	80%	A
Bucket Excavator	85%	B	Feeder Limestone	87%	B
Elevator Mill	91%	B	Elevator Mill	94%	B
Classifier	94%	B	Feeder Clay	97%	C

Main Drive	97%	C	Main Drive	100%	C
Feeder Limestone	100%	C	Classifier	100%	C

Table 5. Logic Tree Analysis

Component Type	LTA						Maintenance Strategy	Maintenance Interval
	1	2	3	4	5	6		
Tyre Mill	*Yes*	*No*	*Yes*	*No*	*Yes*	-	PM	Hours
Mill Auxiliaries	*Yes*	*No*	*Yes*	*No*	*Yes*	-	PM	Hours
Transport Feeding	*Yes*	*No*	*Yes*	*No*	*Yes*	-	PM	Hours
Bridge Scrapper	*Yes*	*Yes*	-	*No*	*Yes*	-	PM	Hours
Clay Transport	*Yes*	*Yes*	-	*No*	*Yes*	-	PM	Hours
Inner Part	*Yes*	*No*	*Yes*	*No*	*Yes*	-	PM	Hours
Feeder Clay	*Yes*	*No*	*Yes*	*No*	*Yes*	-	PM	Hours
Bucket Excavator	*Yes*	*Yes*	-	*No*	*Yes*	-	PM	Hours

Table 6. Goodness of Fit Tyre Mill 1

Distribution	AD	ρ
Normal	0,622	0,067
Exponential	0,259	0,858
Weibull	0,281	>0,250
Lognormal	0,176	0,885

Table 7. Distribution of TTF and TTR Data for Critical Components

Raw Mill 1						
Component Type	**TTF Distribution**	**AD**	**ρ-*value***	**TTR Distribution**	**AD**	**ρ-*value***
Tyre Mill	Lognormal	0.176	0.885	Lognormal	0.420	0.252
Mill Auxiliaries	Weibull	0.491	0.208	Lognormal	0.556	0.120
Transport Feeding	Weibull	0.368	0.250	Lognormal	0.259	0.640
Bridge Scrapper	Weibull	0.250	0.250	Lognormal	0.446	0.260
Clay Transport	Normal	0.199	0.699	Lognormal	0.235	0.607
Inner Part	Lognormal	0.151	0.926	Lognormal	0.348	0.377
Feeder Clay	Weibull	0.402	0.194	Lognormal	0.270	0.570
Raw Mill 2						
Component Type	**TTF Distribution**	**AD**	**ρ-*value***	**TTR Distribution**	**AD**	**ρ-*value***
Tyre Mill	Normal	0.445	0.206	Lognormal	0.520	0.128
Transport Feeding	Weibull	0.254	0.250	Lognormal	0.507	0.175
Mill Auxiliaries	Weibull	0.219	0.250	Normal	0.228	0.751
Bridge Scrapper	Weibull	0.415	0.250	Lognormal	0.329	0.505
Inner Part	Lognormal	0.204	0.791	Weibull	0.198	0.250
Clay Transport	Lognormal	0.262	0.642	Lognormal	0.389	0.335
Bucket Excavator	Normal	0.181	0.774	Lognormal	0.312	0.389

All critical components are assigned a Preventive Maintenance (PM) strategy, as it has proven effective in reducing machine downtime [10] and minimizing safety risks associated with unexpected failures. Scheduled maintenance allows for proactive intervention, thereby enhancing both operational reliability and workplace safety.

3.3. Confirmation Experiment

Distribution testing was conducted on the Time To Failure (TTF) and Time To Repair (TTR) data of critical components in Raw Mill Machines 1 and 2. The best-fitting distribution pattern was determined using the Anderson-Darling (AD) statistic in Minitab software. An example of the TTF data for the Tyre

Mill component in Raw Mill Machine 1 is shown in Table 6.

The Anderson-Darling (AD) value indicates the degree of deviation between the data pattern and a given distribution; the smallest AD value is selected, signifying the closest fit to the distribution. In Table 6, the lognormal distribution yields the lowest AD value, leading to the following hypothesis test:

H_0: The TTF data for Tyre Mill 1 follow a lognormal distribution.
H_1: The TTF data for Tyre Mill 1 does not follow a lognormal distribution.

Table 6 also shows that the ρ-value for the lognormal distribution is 0.885, which is greater than 0.05; therefore, H_0 is accepted. The results of distribution testing for TTF and TTR data of other critical components are presented in Table 7.

3.4. Statistical Analysis

3.4.1. MTTF and MTTR

The calculation of Mean Time To Failure (MTTF) and Mean Time To Repair (MTTR) for critical components of Raw Mill Machines 1 and 2 was performed using ©Minitab software. The MTTF and MTTR values for each critical component of both machines are presented in Table 8. The MTTF values vary across components due to differences in the distribution patterns of TTF and TTR data, as well as the frequency of component failures. The higher the failure frequency, the shorter the TTF, which consequently results in a lower MTTF. Differences in MTTR values are attributed to the varying parameters of the TTR distribution.

3.4.2. Replacement Interval

The replacement interval for components was calculated using the age replacement model, aimed at minimizing downtime, which aligns with the study's objective—to reduce downtime and improve the availability of components and machinery. The preventive replacement interval is adjusted to the factory's maintenance schedule, which is once per week or every 298 operating hours, alternating between Raw Mill Machines 1 and 2. An example of the preventive replacement interval calculation for the Tyre Mill 1 component is shown in Table 9.

The results indicate that the lowest expected downtime occurs at an interval (tp) of 596 hours. An example of the calculation is as follows:

$$D(596) = \frac{4{,}1\times 0{,}29 + 4{,}1\times 0{,}71}{(596+4{,}1)\times 0{,}29 + (859+4{,}1)\times 0{,}71} = 0{,}005\,\frac{hours}{hours}$$

Subsequently, the calculation of preventive replacement intervals was carried out for all critical components of Raw Mill Machines 1 and 2. The results of these calculations are presented in Table 9. The value of $D(tp)$ represents the expected downtime allocated per unit of the preventive cycle time, such that $D(tp)$ reaches its minimum point. The determination of preventive replacement intervals is based on the smallest expected downtime value $D(tp)$ for each critical component.

3.4.3. Inspection Interval

The calculation of inspection intervals utilizes the inspection frequency minimization model to minimize downtime. The results of the inspection interval calculations for critical components are presented in Table 10. An example of the calculation for the Tyre Mill 1 component is shown as follows:

$$n = \sqrt{\frac{1 \times 0{,}0134}{0{,}0068}} \approx 2\ times\ a\ month$$

$$Inspection\ Interval = \frac{596}{2} = 298\ hours$$

The inspection frequency is influenced by inspection time and failure rate, and is inversely proportional to repair time. The calculation results indicate that the higher the inspection frequency, the shorter the inspection interval. However, none of the inspection frequencies exceed twice per month, allowing inspection intervals to be scheduled precisely during planned machine maintenance periods.

4. DISCUSSIONS

4.1. Replacement and Inspection Schedule

The scheduling process is based on the calculated preventive replacement and inspection intervals for each critical component. The proposed preventive maintenance schedule for Raw Mill Machines 1 and 2 is presented in Table 11. The letter "G" indicates component replacement, the letter "I" indicates component inspection, and the shaded columns represent the weeks during which the machines are scheduled for maintenance.

Table 8. MTTF and MTTR of Critical Components

Component Type	TTF Distribution Parameters					MTTF	TTR Distribution Parameters					MTTR
Raw Mill 1												
	α	β	μ	σ	θ	(Hours)	α	β	μ	σ	θ	(Hours)
Tyre Mill	-5.3	0.92	-	-	330	597.7	-0.92	1	-	-	2.5	4.1
Mill Auxiliaries	-2.4	0.41	-	-	309	959.0	-0.06	0.58	-	-	1.1	4.9
Transport Feeding	2.1	0.34	-	-	482	2553.0	-0.23	0.77	-	-	1.3	3.1
Bridge Scrapper	-3.9	0.71	-	-	242	299.9	-0.91	0.96	-	-	2.6	2.6
Clay Transport	-0.9	0.0008	1116	1231	-	1345.1	-0.51	0.7	-	-	2.1	5.7
Inner Part	-12.6	1.85	-	-	936	1084.3	-0.92	0.73	-	-	3.5	8.9
Feeder Clay	-1.9	0.34	-	-	325	1903.8	-0.78	0.77	-	-	2.8	6.4
Raw Mill 2												
Component Type	**TTF Distribution Parameters**					**MTTF**	**TTR Distribution Parameters**					**MTTR**
	α	β	μ	σ	θ	(Hours)	α	β	μ	σ	θ	(Hours)
Tyre Mill	-1.2	0.002	586	481	-	586.0	-0.64	0.5	-	-	3.6	18.2
Transport Feeding	-3.2	0.53	-	-	409	734.2	-0.38	0.58	-	-	1.9	8.7
Mill Auxiliaries	-3.5	0.55	-	-	598	1025.3	-1.59	0.69	2.3	1.5	-	2.3
Bridge Scrapper	-2.8	0.55	-	-	154	262.4	-0.79	0.96	-	-	2.3	3.9
Inner Part	-8.7	1.29	-	-	841	1133.8	-2	0.88	-	-	9.8	10.4
Clay Transport	-5.3	0.9	-	-	536	659.6	-0.15	0.73	-	-	1.2	3.2
Bucket Excavator	-0.9	0.0009	1114	1154	-	1113.9	-0.91	0.7	-	-	3.7	10.1

Table 9. Preventive Replacement Interval Calculation for Tyre Mill 1

t_p (Hours)	$(ln\ (t/t_{med})\ /\ s)$	$F(t_p)$	$R(t_p)$	$T_f * F(t_p)$	$T_p * R(t_p)$	$M(t_p)$	$D(t_p)$
298	-0.09	0.46	0.54	1.89	2.19	1291.06	0.00535
596	0.54	0.71	0.29	2.88	1.20	846.21	**0.00525**
894	0.91	0.82	0.18	3.34	0.74	729.09	0.00535
1192	1.18	0.88	0.12	3.59	0.49	678.68	0.00548

Table 10. Preventive Replacement and Inspection Intervals for Critical Components

Component Type	$D(tp)$ (Hours/hour)	Replacement Interval (Hours)	k	i (*month*)	μ (*month*)	n	Inspection Interval (Hours)
Raw Mill 1							
Tyre Mill	0,0053	596	1	0,0134	0,0068	2	298
Mill Auxiliaries	0,0041	2682	2	0,0017	0,0083	1	596
Transport Feeding	0,0010	10430	2	0,0017	0,0052	1	596
Bridge Scrapper	0,0065	298	3	0,0017	0,0043	2	298
Clay Transport	0,0034	1192	1	0,0017	0,0080	1	596
Inner Part	0,0057	894	1	0,0017	0,0123	1	596
Feeder Clay	0,0028	8344	1	0,0017	0,0108	1	596
Raw Mill 2							
Component Type	**$D(tp)$ (Hours/hour)**	**Replacement Interval (Hours)**	**k**	**i (*month*)**	**μ (*month*)**	**n**	**Inspection Interval (Hours)**
Tyre Mill	0,020277618	596	1	0,0134	0,0114	2	298
Transport Feeding	0,0091	1.490	2	0,0017	0,0145	1	596
Mill Auxiliaries	0,0018	1.788	2	0,0017	0,0039	1	596
Bridge Scrapper	0,0116	596	4	0,0017	0,0066	2	298
Inner Part	0,0067	894	1	0,0017	0,0167	1	596
Clay Transport	0,0037	596	2	0,0017	0,0053	1	596
Bucket Excavator	0,0060	1.192	1	0,0017	0,0170	1	596

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Table 11. Proposed Preventive Maintenance Schedule

Machines	Month/ Week To-	January				February				March				April				May				Juny				July				August				September				October				November				December			
	Components	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Raw Mill 1	*Tyre Mill*	G		I		G		I		G		I		G		I		G		I		G		I		G		I		G		I		G		I		G		I		G		I		G		I	
	Mill Auxiliaries	G				I				I				I				I		G				I				I				I				I		G				I				I			
	Transport Feeding	G				I				I				I				I				I				I				I				I				I				I				I			
	Bridge Scrapper	G		G		G		G		G		G		G		G		G		G		G		G		G		G		G		G		G		G		G		G		G		G		G		G	
	Clay Transport	G				I				G				I				G				I				G				I				G				I				G				I			
	Inner Part	G				I		G				I		G				I		G				I		G				I		G				I		G				I		G				I	
	Feeder Clay	G				I				I				I				I				I				I				I				I				I				I				I			
Raw Mill 2	*Tyre Mill*		G		I		G		I		G		I		G		I		G		I		G		I		G		I		G		I		G		I		G		I		G		I		G		I
	Transport Feeding		G				I				I		G				I				I		G				I				I		G				I				I		G				I		
	Mill Auxiliaries		G				I				I				G				I				I				G				I				I				G				I				I		
	Bridge Scrapper		G		I		G		I		G		I		G		I		G		I		G		I		G		I		G		I		G		I		G		I		G		I		G		I
	Inner Part		G				I		G				I		G				I		G				I		G				I		G				I		G				I		G				I
	Clay Transport		G				G				G				G				G				G				G				G				G				G				G				G		
	Bucket Excavator		G				I				G				I				G				I				G				I				G				I				G				I		

Table 12. Maximum Availability of Critical Components

Raw Mill 1				Raw Mill 2			
Component Type	A_P	A_I	A_M	**Component Type**	A_P	A_I	A_M
Tyre Mill	99.5%	96.6%	96.1%	Tyre Mill	98.0%	96.2%	94.2%
Mill Auxiliaries	99.6%	98.2%	97.8%	Transport Feeding	99.1%	96.9%	96.0%
Transport Feeding	99.9%	98.8%	98.7%	Mill Auxiliaries	99.8%	99.1%	98.9%
Bridge Scrapper	99.4%	98.4%	97.7%	Bridge Scrapper	98.8%	97.0%	95.9%
Clay Transport	99.7%	99.0%	98.7%	Inner Part	99.3%	98.2%	97.5%
Inner Part	99.4%	98.6%	98.0%	Clay Transport	99.6%	98.8%	98.4%
Feeder Clay	99.7%	98.8%	98.5%	Bucket Excavator	99.4%	98.1%	97.5%

Table 13. Expected Improvement in Machine Availability

Machine	D_1 (Hours)	D_2 (Hours)	Target Availability	A_1	A_2	Availability Improvement
Raw Mill 1	356.50	162.43	64.66%	61.90%	67.00%	5.10%
Raw Mill 2	497.53	335.04		60.39%	65.03%	4.64%

Table 14. Expected Average Reliability Improvement of Critical Components

Raw Mill 1			
Component Type	**Average $R(t)$**	**Average $R(t-nT)$**	**Average Improvement**
Tyre Mill	21%	65%	44%
Mill Auxiliaries	6%	29%	22%
Transport Feeding	4%	21%	17%
Bridge Scrapper	23%	60%	37%
Clay Transport	30%	72%	42%
Inner Part	32%	90%	58%
Feeder Clay	4%	18%	14%
Raw Mill 2			
Component Type	**Average $R(t)$**	**Average $R(t-nT)$**	**Average Improvement**
Tyre Mill	29%	78%	49%
Transport Feeding	10%	39%	30%
Mill Auxiliaries	12%	43%	31%
Bridge Scrapper	8%	38%	30%
Inner Part	32%	82%	51%
Clay Transport	23%	67%	44%
Bucket Excavator	27%	71%	44%

Table 15. Expected Improvement in Machine Reliability

Machine	Distribution	α	β	$MTTF_1$	R_1	R_{P1}	Distribution	λ	$MTTF_2$	R_2	R_{P2}
Raw Mill 1	Weibull	0.7	θ	55.8	50.0%	66.1%	Exponential	0.0032	298	99.4%	99.8%
Raw Mill 2	Weibull	0.7	46	55.7	32.2%		Exponential	0.0009	596	76.2%	

4.2. Availability of Critical Components and Machines

The maximum availability of components is derived from the calculated preventive replacement and inspection intervals. The maximum availability values for each critical component are shown in Table 12, while machine availability is presented in Table 13. For large-scale enterprises, ideal component availability is above 90% [11]. The results in Table 11 indicate that the availability of each critical component exceeds 90%, suggesting that the proposed preventive maintenance schedule is applicable for improving component availability. Additionally, calculations were performed for Raw Mill Machines 1 and 2 to compare availability before and after the implementation of the proposed preventive maintenance schedule. The results in Table 13 show that machine availability has surpassed the target threshold within one year of operation. This improvement is attributed to the reduction in expected machine downtime. As machine downtime decreases, availability increases-demonstrating an inverse relationship.

Where D_1 = downtime of critical components, D_2 = expected downtime of critical components, A_1 = machine availability, and A_2 = expected machine availability.

4.3. Reliability of Critical Components and Machines

Reliability is calculated for each critical component and machine, both before and after the implementation of the proposed preventive maintenance schedule, as expected. The expected reliability improvement for each critical component is presented in Table 14. An example of the reliability calculation

for the Tyre Mill 1 component, which follows a lognormal distribution, is shown as follows:

$$R(600) = 1 - \Phi\left[\frac{1}{2} \times ln\left(\frac{600}{329,82}\right)\right] = 0,2629$$

$$R(t - Tn) = 1 - \Phi\left[\frac{1}{2} \times ln\left(\frac{600-5 \quad \times 1}{329,82}\right)\right] = 1$$

The calculation results indicate that the expected reliability of all critical components improves on average when the proposed preventive maintenance schedule is implemented. The most significant improvement is observed in the Inner Part component, while the smallest occurs in the Feeder Clay component. The variation in the average expected reliability improvement is due to differences in replacement intervals. The longer the replacement interval, the lower the reliability at the next replacement time, which in turn results in a lower average reliability over time.

The expected reliability improvement of Raw Mill Machines 1 and 2, which are configured in parallel, is also calculated based on historical machine failure data and the proposed preventive maintenance schedule. Historical reliability is determined by identifying the failure distribution and Mean Time to Failure (MTTF) using ©Minitab software. Reliability is calculated at time (t) = 5,664 hours and is presented in Table 15. Based on the results in Table 15, the expected reliability improvement of the machines can be calculated as follows:

$$\text{Improvement in R}(5664) = 99{,}8\% - 66{,}1\% = 33{,}7\%$$

Based on the calculations, it can be observed that the expected reliability of the machine increases by 33.7% when the proposed preventive maintenance (PM) schedule is implemented. This improvement in expected reliability indicates that the proposed PM schedule is superior to the historical condition and, therefore, can be utilized in the planning and implementation of critical component maintenance for the machine.

4.4. Raw Mix Spare Requirements

Raw Mix is the output of the Raw Mill process, which serves as the input for the Kiln Machine. During Raw Mill downtime, the Kiln requires a reserve of Raw Mix. The planned maintenance (downtime) duration for the Raw Mill is 12 hours per maintenance cycle. Therefore, the required Raw Mix reserve during the downtime of one Raw Mill is calculated as follows:

Production rate (2 machines) = 500 tons/hour
Kiln feeding rate = 442 tons/hour

Therefore *Minimum Raw Mix reserve* would be;
= 12 hours × 442 tons/hour - (250 tons/hours × 12 hours)
= 5,304 tons – 3,000 tons = 2,304 tons

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Where R_1 = historical reliability; R_{P1} = historical reliability of parallel machines; R_2 = expected reliability; R_{P2} = expected reliability of parallel machines.

5. CONCLUSION

This study proposes a preventive maintenance schedule that includes replacement and inspection intervals for critical components, aiming to improve machine availability and reliability, as well as ensure sufficient Raw Mix reserves during machine downtime. The replacement schedule for critical components of Raw Mill Machines 1 and 2 is as follows: Tyre Mill every 596 hours; Mill Auxiliaries every 2,682 and 1,788 hours; Transport Feeding every 10,430 and 1,490 hours; Bridge Scrapper every 298 and 596 hours; Clay Transport every 1,192 and 596 hours; and Inner Part every 894 hours. Additionally, there are distinct critical components between Raw Mill 1 and 2: the Feeder Clay is changed every 8,344 hours for Raw Mill 1, and the Bucket Excavator is changed every 1,210 hours for Raw Mill 2.

The inspection schedule for critical components of Raw Mill Machines 1 and 2 includes Tyre Mill and Bridge Scrapper every 298 hours. In contrast, other components—Mill Auxiliaries, Transport Feeding, Inner Part, Clay Transport, Feeder Clay, and Bucket Excavator—are inspected every 596 hours. The maximum availability of each critical component exceeds 90%. Furthermore, the availability of Raw Mill 1 increased by 5.1% to reach 67% annually, and Raw Mill 2 rose by 4.64% to reach 65.03%, both surpassing the target availability of 64.66% per year.

In addition, the reliability of critical components and the Raw Mill system improved by 33.71%. The expected increase in machine availability and reliability indicates that the proposed preventive maintenance schedule for Raw Mill critical components is suitable for implementation. The required Raw Mix reserve to perform one maintenance cycle, if this schedule is adopted, amounts to 2,304 tons.

REFERENCES

[1] A. Kaleka and N. A. Morgan, "How marketing capabilities and current performance drive strategic intentions in international markets," *Industrial Marketing Management*, vol. 78, pp. 108–121, 2019, doi: 10.1016/j.indmarman.2017.02.001.

[2] T. Ahdiyat and Y. A. Nugroho, "Performance Analysis of Bandsaw Machine Using Overall Equipment Effectiveness (OEE) Method and Six Big Losses at PT Quartindo Sejati Furnitama (in Indonesian)," *Jurnal Cakrawala Ilmiah*, vol. 2, no. 1, 2022, doi: 10.53625/jcijurnalcakrawalailmiah.v2i1.3509.

[3] D. Ariansyah, F. Rosa, and G. Colombo, "Smart maintenance: A wearable augmented reality application integrated with CMMS to minimize unscheduled downtime," *Comput Aided Des Appl*, vol. 17, no. 4, 2020, doi: 10.14733/cadaps. 2020.740-751.

[4] P. Gackowiec, "General overview of maintenance strategies – concepts and approaches," *Multidisciplinary Aspects of Production Engineering*, vol. 2, no. 1, pp. 126–139, 2019, doi: 10.2478/mape-2019-0013.

[5] S. Gan, Z. Song, and L. Zhang, "A maintenance strategy based on system reliability considering imperfect corrective maintenance and shocks," *Comput Ind Eng*, vol. 164, 2022, doi: 10.1016/j.cie.2021.107886.

[6] I. H. Afefy, A. Mohib, A. M. El-kamash, and M. A. Mahmoud, "A new framework of reliability-centered maintenance," *Jordan Journal of Mechanical and Industrial Engineering*, vol. 13, no. 3, pp. 175–190, 2019.

[7] H. H. Azwir, A. I. Wicaksono, and H. Oemar, "Manajemen Perawatan Menggunakan Metode RCM Pada Mesin Produksi Kertas," *Jurnal Optimasi Sistem Industri*, vol. 19, no. 1, 2020, doi: 10.25077/josi.v19.n1.p12-21.2020.

[8] A. Shamayleh, M. Awad, and A. O. Abdulla, "Criticality-based reliability-centered maintenance for healthcare," *J Qual Maint Eng*, vol. 26, no. 2, pp. 311–334, 2020, doi: 10.1108/JQME-10-2018-0084.

[9] B. Mohamed, E. Abbes, B. Bachir, and B. M. El Haddaoui, "Maintenance of drilling machines using Pareto ABC method," *Глобальная энергия*, vol. 28, no. 1, 2022.

[10] L. Martins, F. J. G. Silva, C. Pimentel, R. B. Casais, and R. D. S. G. Campilho, "Improving preventive maintenance management in an

energy solutions company," in *Procedia Manufacturing*, 2020, pp. 1551–1558, doi: 10.1016/j.promfg.2020.10.216.

[11] M. M. Hutabarat and A. Muhsin, "Work Effectiveness Analysis of the Auto Hanger Machine Using the Overall Equipment Effectiveness (OEE) Method (in Indonesian)," *OPSI*, vol. 13, no. 1, p. 56, 2020, doi: 10.31315/opsi.v13i1.3468.