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Determination of Maintenance Intervals Using Multi-Criteria Approach to Increase Machine Availability at a Cement Company

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Abstract. A downtime will decrease machine availability that will affect reliability and maintainability. If interval time between two consecutive machine failures is approach to zero, it shows that the machine reliability is low, and so the availability. In the other hand, if interval time between is high, the machine availability and reliability are high. However, the procuring cost of the machine components is expensive. The problem is what is the maintenance interval time in order to optimize machine availability and reliability. In this study, the downtime is minimized by determining maintenance intervals using a multicriteria, i.e. reliability, availability, and maintainability (RAM). The model used in this research is the Age Replacement Model. A case study of a cement company is taken to show the determination of the maintenance interval. The observation shows that the Kiln Division has the longest total downtime of 1,846 hours/year although the Kiln Division has implemented overhaul during 15 days and maintenance one times. The total downtime of the Kiln Division was caused by failure to the Grate Cooler machine by 56.582%. A maintenance interval is proposed, and the result shows that the proposed maintenance intervals reduce total downtime by 86.6% and improve machine availability by 1,8%.

Keywords: Reliability, Maintainability, Availability, Maintenance Interval.

INTRODUCTION

Demand of cement in Indonesia is always increasing from year to year due to Indonesian Government is implementing a Masterplan for the Acceleration and Expansion of Indonesia's Economic Development (MP3EI). One of the main concerns in the program is constructing transportation line infrastructure such as roads and ports. Meanwhile, the cement industry is one of the main pillars in the development of transportation line infrastructure, therefore supply of cement must be guaranteed. PT X is a cement company in Indonesia. The cement production process consists of three divisions, i.e. Raw Mill, Kiln, and Finish Mill Divisions.

PT X has implemented overhaul during 15 days and maintenance one times. However, downtime is still occurred. Observation results that the Kiln Division has longest total downtime of 1.845,6 hours. The processes at the Kiln Division are using Suspension Preheater, Rotary Kiln and Grate Cooler. The Grate Cooler has the largest percentage of downtime at 56.582% of the total Kiln Division downtime. The downtime causes the production process stop and the production target cannot be met. Finally, the company will lose the opportunity to get the targeted profit.

The downtime will decrease machine availability. Stapelberg (2009) states that machine availability is affected by the level of reliability and maintainability. Availability is related with reliability and maintainability in term of time by Mean Time to Failure (MTTF) and Mean Time to Repair (MTTR). According to Picknell and Sifonte (2017) MTTF is defined as the average time between damage of a component, while MTTR is the average time needed to repair. MTTF and MTTR can be used to determine machine reliability and maintainability. MTTF indicates maintenance needs. If MTTF is approach to zero, it indicates high maintenance needs so that the machine availability is low.

Likewise, a low MTTF will reduce machine reliability so that the possibility of machine damage is high. This will reduce availability due to repair activities. Meanwhile, if MTTF is high, it indicates that the machine reliability is high because it does not be easily failure. It means that the machine has a high availability. However, the procuring cost of the machine components is expensive.

Low machine availability will decrease the output of production due to obstruction of the production process so that it will lose an opportunity to get the targeted profit. Thus, what the problem will be answered by this research is, what is the maintenance interval time in order to optimize machine availability. The maintenance intervals will be determined by using multicriteria i.e. reliability, availability, and maintainability (RAM).

METHOD

The International Electrotechnical Commission (IEC) explains that maintenance is a combination of all technical, administrative and managerial actions during the life cycle of a machine or equipment intended to maintain or restore the expected operating functions (Mehairjan, 2013) The main objectives of maintenance according to is to maintain the availability of equipment or production facilities to meet the needs in accordance with the targets and production plans (O'Connor, 2001). According to the purpose of maintenance, there are two policy of the maintenance program i.e. preventive maintenance and corrective maintenance.

Preventive maintenance is carried out to extend the life of the equipment or increase the reliability of the equipment. These maintenance actions vary from minor maintenance, maintenance or replacement of components in a planned manner. Meanwhile, Corective Maintenance is an act of returning the condition of equipment or components when failure in the form of repair or replacement of failure components (Dhillon, 2002). Failure rate of machine or component will change throughout the operating time. The pattern of the failure rate of a component or machine is shown by a Bathtub (see Figure 1).

According to Ebeling (2019) the pattern of component failure rate is divided into three periods, that is early failure, random failure, and wear out failure which is illustrated in Figure 1. According to O'conor (2001) the failure rate in each period has certain characteristics. Period of early failure is referred to as early damage which is marked by a decrease in the failure rate. Random failure period is characterized by a constant failure rate. Wear out period is characterized by an increased failure rate due to deteriorating component conditions and use that has exceeded component life.

Distribution of failure rate and repair time used in this research are Weibull, normal, lognormal, and exponential distribution. If the failure rate is constant then it is used an exponential distribution and if the failure rate is not constant then the distribution used is Weibull, normal, and lognormal distribution. Age Replacement Model (ARM) is adopted to determine preventive maintenance time intervals (see Figure 2). In this model, the preventive maintenance will take place when the machines or equipments have been operated during specified age, t. If there are no machine failures during t, then the replacement is still done as a preventive replacement.

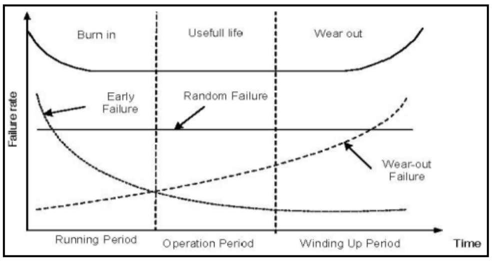

Figure 1. Bathub Curve
Source: Ebeling (2019)

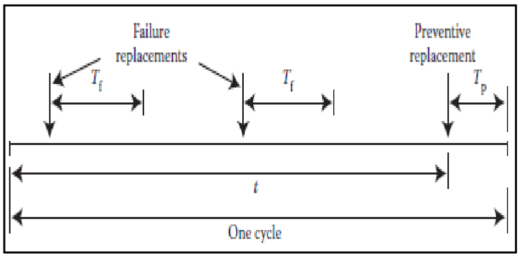

Figure 2. Age Replacement
Model: minimized downtime
Source: Jardine dan Tsang (2013)

Increased frequency of preventive maintenance causes downtime due to maintenance will increase, but downtime due to failure of the machine will decrease. The age replacement model purpose to determine the optimal age (t) that minimize total downtime. Total expected downtime is influenced by two conditions, i.e. downtime due to maintenance and downtime due to failure. The probability of downtime per unit time for maintenance is determined by comparing total expected downtime and expected one cycle time. Age replacement model integrates multicriteria i.e. reliability, maintainability, and availability.

The availability is related with reliability and maintainability by MTTF and MTTR. MTTF is used to calculate the interval of average failure time when maintenance is carried out at t, while MTTR is used to determine the time needed to repair (T_f). Reliability, Maintainability and Avalaibility are determined from the value of MTTF, MTTR and the probability of downtime in interval t.

The calculation steps are described as follows:

Determination of time to failure (TTF) and time to repair (TTR).

TTF is measured from the starting time of the operating machine until the next failure occurs, while TTR is determined from the time needed for maintenance.

Determination of TTF and TTR distribution (Eksponential, Normal, Lognormal, or Weibull) using least square method, and then select the distribution with the biggest index of fit. The index of fit is calculated using Equation (1).

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

where:

i : i^{th} failure

n : sum of data

$F_{(ti)}$: median rank approach during interval t

r : Index of fit

1. Test the selected distribution using the Goodness of fit test.
   - If Exponential Distribution is selected, then use Bartlett's Test.
   - If Normal or Lognormal Distribution is selected, then the C test with the Kolmogorov-Smirnov Test.
   - If Weibull Distribution is selected, then use Mann’s Test.
   - If the selected distribution does not meet the hypothetical of each test, then select distribution with the next smallest index of fit. Fit test again the selected distribution.

2. Calculation MTTF and MTTR

- If the selected distribution is Exponential, then failure rate parameter is calculated using Equation (2), while MTTR is calculated using Equation (3).

$$\lambda = \frac{\sum_{i=1}^{n} x_i y_i}{\sum_{i=1}^{n} x_i^2} \quad \text{.........} (2)$$

$$\text{MTTF/MTTR} = \frac{1}{\lambda} \quad \text{.........} (3)$$

where:

λ : failure rate

- If the selected distribution is Normal or Lognormal Distribution, then Standard Deviation and medium of distribution is calculated using Equation (4) and (5) respectively. MTTF or MTTR is then calculated using Equation (6).

$$s = \sqrt{\frac{\sum_{i=1}^{n}(\ln t_i - \bar{t})^2}{n-1}} \quad \text{.........} (4)$$

$$t_{med} = e^{\bar{t}} \quad \text{.........} (5)$$

$$\text{MTTF/MTTR} = t_{med}\, e^{\frac{s^2}{2}} \quad \text{.........} (6)$$

where:

s : Standard Deviation

$\bar{t}$: average time

t_{med} : medium of distribution

- If the selected distribution is Weibull Distribution, shape parameter and scale parameter is calculated using Equation (7) to (10), then MTTR and MTTF is calculated using Equation (11).

$$b = \frac{n\sum_{i=1}^{n} x_i y_i - (\sum_{i=1}^{n} x_i)(\sum_{i=1}^{n} y_i)}{n\sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2} \quad \text{.........} (7)$$

$$a = \bar{\mathbf{y}} - b\bar{\mathbf{x}} \quad \text{.........} (8)$$

$$\beta = b \quad \text{.........} (9)$$

$$\theta = \mathbf{e}^{-(\frac{\alpha}{\beta})} \quad \text{.........} (10)$$

$$\text{MTTF/MTTR} = \theta\Gamma\,(1 + \frac{1}{\beta}) \quad \text{.........} (11)$$

where:

θ : scale parameter

β : shape parameter

Γ : Gamma function

3. Calculation of Reliability and Maintainability

- If the selected distribution is Exponential, then reliability is calculated using Equation (12) while maintainability is calculated using Equation (13).

$R_{(t)} = \mathbf{e}^{-(\lambda t)}$ ....(12)

$M_{(t)} = 1 - \mathbf{e}^{-\frac{t}{MTTR}}$ .... (13)

where:

$R_{(t)}$: reliability

$M_{(t)}$: maintainability

- If the selected distribution is Normal Distribution, then reliability is calculated using Equation (14) while maintainability is calculated using Equation (15).

$R_{(t)} = 1 - \Phi\,[\frac{t - \bar{t}}{s}]$ .... (14)

$M_{(t)} = \frac{1}{s\sqrt{2\pi}}\,\mathbf{e}^{-\frac{1}{2}(\frac{t - t_{med}}{s})^2}$ ....(15)

where:

Φ : z probability

t : interval time to repair

- If the selected distribution is Lognormal Distribution, then reliability is calculated using Equation (16) while maintainability is calculated using Equation (17).

$R_{(t)} = 1 - \Phi\,[\frac{1}{s}\,\text{In}\,\frac{t}{tmed}]$ .... (16)

$M_{(t)} = \frac{1}{ts\sqrt{2\pi}^{2}}\,\mathbf{e}^{(\frac{(\ln_t - \bar{t})^2}{2s^2})}$ .... (17)

- If the selected distribution is Weibull Distribution, then reliability is calculated using Equation (18) while maintainability is calculated using Equation (19).

$R_{(t)} = \mathbf{e}^{-(\frac{t}{\theta})^{\beta}}$ .... (18)

$M_{(t)} = 1 - \mathbf{e}^{-(\frac{t}{\theta})^{\beta}}$ .... (19)

4. Calculation of Availability

- Expected failure cycle to maintain and replacement is calculated using Equation (20), the downtime of each machine or component cycle is calculated using Equation (21), component availability is calculated using Equation (22), and serial system avalability is calculated using Equation (23).

$N_{(t)} = \frac{MTTF}{1 - R_{(t)}}$ .... (20)

$D_{(t)} = \frac{Tp\,R_{(t)} + Tf\,(1 - R_{(t)})}{(t + Tp)R_{(t)} + ((N_{(t)} + Tf)\,(1 - R_{(t)})}$ .... (21)

$A_{(t)} = 1 - D_{(t)}$ .... (22)

$A_{s(t)} = \prod_{i=1}^{n} A_{i(t)}$ .... (23)

where:

$N_{(t)}$: average of failure time if a maintenance is done at t

$D_{(t)}$: downtime probability at t

T_f : time to repair failure

T_p : time to maintain a machine

$A_{i(t)}$: Availability of component i during interval maintenance t

$A_{s(t)}$: serial system avalability

5. Determination of maintenance interval by calculating some serial system avalability at different t, and then choose t with minimum downtime.

   Calculation production rate at the proposed maintenance interval.

DISCUSSION

Downtime

In the cement company that is taken as a case study, the Grate Cooler is a machine with longest downtime. The Grate Cooler machine consists of several components. Some components that make Grate Cooler breakdown and causes downtime are Grate Plate, Crankshaft, Motor Bearing, Rotor and V-belt.

According to Picknell and Sifonte (2017), Time to Failure (TTF) is an interval time between two consecutive failures, while Time To Repair (TTR) is a time needed to repair the machine or component. The scheme of determining TTF and TTR is shown in Figure 3. In this study, the downtime involves time to repair or to replace components, while the downtime caused by non-technical activities are not involved. The downtime is shown in Table 1, while the time to repair is shown in Table 2.

TTF and TTR Distribution

The distribution of TTF and TTR of each component is determinated from the index of fit that is calculated using Equation (1). The result can be seen at Table 3.

Distribution Selection

TTF data of Grate Plate has the largest index of fit on the Exponential Distribution. However, the normality test using Barlett's test does not show that TTF data of Grate Plate do not suitable for Exponential Distribution. Therefore, it must be tested for distributions with the second-largest index of fit, i.e. Lognormal Distribution. TTF data are then tested using the Kolmogorov-Smirnov test. The result shows that the TTF Grate Plate data suitable for the Lognormal Distribution.

Meanwhile, the TTR data have the largest index of fit for Weibull Distribution so that the TTR data is tested using Mann's test. The results show that the Grate Plate TTR data suitable for

Weibull distribution.

Distribution fit tests for all components were carried out in the same way, and the results are shown in Table 4.

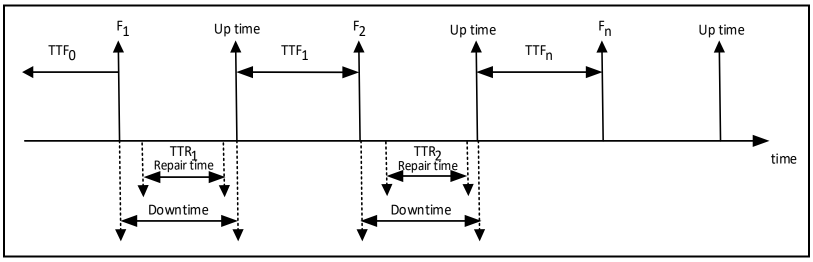

Figure 3. TTF calculation scheme and TTR determination

Table 1. Downtime Grate Cooler

Component	Frequency	Total Downtime (hours)
Grate Plate	30	587.210
Crankshaft	17	388.313
Bearing Motor	4	29.428
Rotor	6	24.643
V-belt	4	14.701
Total	61	1,044.285

Table 2. Time of maintenance activity

No	Component	Average Maintenance Time (hours)
1	Grate Plate	24.84
2	Crankshaft	20.84
3	Bearing Motor	5.54
4	Rotor	2.02
5	V-belt	1.91

Table 3. Index of fit

Component	Variabel	Distribution			
		Exponential	Normal	Lognormal	Weibull
Grate Plate	TTF	0.990	0.903	0.984	0.968
	TTR	0.750	0.580	0.641	0.550
Crankshaft	TTF	0.971	0.977	0.976	0.991
	TTR	0.908	0.989	0.985	0.987
Bearing Motor	TTF	0.991	0.951	0.985	0.967
	TTR	0.969	0.909	0.913	0.876
Rotor	TTF	0.931	0.941	0.961	0.955
	TTR	0.779	0.911	0.896	0.943
V-belt	TTF	0.849	0.930	0.900	0.933
	TTR	0.999	0.976	0.989	0.973

Table 4. Distribution fit test

Component	TTF		TTR	
	Distribution	r	Distribution	R
Grate Plate	Exponential	0.984	Weibull	0.550
Crankshaft	Weibull	0.991	Normal	0.989
Bearing Motor	Exponential	0.991	Weibull	0.876
Rotor	Lognormal	0.961	Weibull	0.943
V-belt	Weibull	0.933	Lognormal	0.989

MTTF and MTTR

MTTF and MTTR are calculated by determining the parameters in the selected distribution, and the results are shown by Table 5.

Table 5. MTTF and MTTR

Component	Parameter of MTTF	MTTF (hour)	Parameter of MTTR	MTTR (hour)
Grate Plate	$s = 0.796$ $t_{med} = 643.8$	884.0	$\beta = 2.184$ $\theta = 30.1$	26.7
Crankshaft	$\beta = 1.426$ $\theta = 1,334.0$	1,212.4	$s = 0.145$ $t_{med} = 20.7$	20.9
Bearing Motor	$s = 0.635$ $t_{med} = 2,838.6$	3,473.7	$\beta = 7.747$ $\theta = 5.9$	5.5
Rotor	$s = 0.521$ $t_{med} = 4,007.2$	4,590.9	$\beta = 7.009$ $\theta = 2.2$	2.0
V-belt	$\beta = 0.951$ $\theta = 6,550.5$	6,700.4	$s = 0.288$ $t_{med} = 1.9$	1.9

Reliability, Maintainability and Availability

Reliability, Maintainability, and Availability of the existing conditions are shown in Table 6. The serial system availability is then calculated as a product over the availability of each component, and the existing serial system availability is 96.52.

Table 6. Reliability, Maintainability, and Availability of existing condition

Component	Reliability (%)	Maintainability (%)	Availability (%)
Grate Plate	34.5	53.6	97.86
Crankshaft	41.8	87	98.80
Bearing Motor	37.5	46.2	99.88
Rotor	39.7	46.6	99.97
V-belt	36	72.2	99.98

The proposed maintenance interval

The maintenance interval of each component is determined by trial and error to calculate downtime using the Age Replacement model at several t, and then maintenance interval is chosen for t at the lowest downtime. Table 7 shows the downtime at some t for the Grate Plate component. As can be seen in Table 7, the minimum downtime occurs at t = 564 hours, while the existing mean time to failure is 884 hours. This means that maintenance interval is proposed after the Grate Cooler is operated for 564 hours. In addition, it is also calculated R(t), N(t), and A(t) at various t to determine changes in production levels.

Maintenance intervals for other components are calculated in the same way, and Table 8 shows the calculation results. Table 8 also shows a comparison between the existing and proposed conditions.

Components Condition in the Bathtub Curve

Table 5 shows that the standard deviation of Grate Plate, Motor Bearing, and Rotor Components are less than one, which indicates a decreasing failure rate. According to the bathtub curve criteria (O'Connor, 2001), the decreasing show that Grate Plate, Motor Bearing, and Rotor Components are in early failure condition (see Figure 1). The failures are generally occurred by usage error, or component material is not suitable with the standard needed. If these components are failures, they should be replaced.

At can be seen in Table 5, the Crankshaft component has a shape parameter greater than one, which indicates an increasing failure rate. In the bathtub curve, this component is in wear-out failure position. The wear-out failure period indicates that the component has exceeded the component's life. Preventive maintenance actions that can be carried out for this component are checking the lubricant condition and tightening the bolt to prevent it from loosing.

In Table 5 it is shown that the V-belt component has a shape parameter less than one, which indicates a decreasing failure rate. It fits with early failure period characteristics. When the component damage during this period, it is better to replace it.

Table 7. Downtime of Grate Plate at several t

t (hour)	$R_{(t)}$	$N_{(t)}$	$D_{(t)}$	$A_{(t)}$
300	0.831	5,236.012	0.021711	0.978289
350	0.778	3,980.748	0.021370	0.978630
400	0.725	3,213.710	0.021134	0.978866
450	0.674	2,707.635	0.020981	0.979019
500	0.625	2,354.234	0.020895	0.979105
550	0.578	2,096.485	0.020863	0.979137
**564	0.566	2,036.663	0.020862	0.979138
600	0.535	1,901.961	0.020874	0.979126
650	0.495	1,751.062	0.020920	0.979080
700	0.458	1,631.342	0.020993	0.979007
750	0.424	1,534.565	0.021089	0.978911
800	0.392	1,455.092	0.021204	0.978796
850	0.364	1,388.946	0.021333	0.978667
*883,980	0.345	1,350.101	0.021427	0.978573
900	0.337	1,333.254	0.021473	0.978527
950	0.313	1,285.889	0.021622	0.978378

* average of failure interval at existing condition
** proposed mantenance interval

Table 8. Comparison of existing and proposed component performance

Component	Existing				Proposed			
	MTTF (jam)	$R_{(t)}$	$M_{t)}$	$A_{(t)}$	t (jam)	$R_{(t)}$	$M_{(t)}$	$A_{(t)}$
Grate Plate	883.980	0.345	0.536	0.9786	564	0.566	0.536	0.9791
Crankshaft	1,212.396	0.418	0.870	0.9880	1,035	0.498	0.870	0.9881
Bearing Motor	3,473.706	0.375	0.462	0.9988	2,500	0.579	0.462	0.9989
Rotor	4,590.867	0.397	0.466	0.9997	3,400	0.624	0.466	0.9997
V-belt	6,700.369	0.360	0.722	0.9998	6,700.369	0.360	0.722	0.9998

Existing Performance Using Multi Criteria

Table 6 shows that the Grate Plate component has the smallest level of reliability, which means that Grate plate is a critical component and is often have failures. Bearing Motor component have the lowest level maintainability which indicates that this component is the most difficult to repair when failure occurs.

Proposed Maintenance Intervals Using Multi Criteria

Availability is influenced by reliability and maintainability. In Table 8 it is shown that the maintainability of each component does not change because the machine design is not changed. Therefore, availability is increased by increasing reliability. As can be seen in Table 8, the reliability at the proposed conditions are increased, except for the V-belt component. This shows that the proposed maintenance intervals can increase reliability so that the availability increases.

Meanwhile, the reliability of the V-belt component at the proposed condition does not change because the proposed maintenance interval is the same as MTTF (see Table 8). Based on trial and error using Age Replacement Model, it is found that minimum downtime is exceeding MTTF. Therefore, maintenance intervals are set at MTTF in order to prevent the V-belt damage before maintenance time.

According to the proposed maintenance intervals, a preventive maintenance schedule of the Grate Cooler machine is then arranged for one year. The schedule is shown in Figure 4. As can be seen in Figure 4, the proposed preventive maintenance is carried out 27 times a year with a total expected downtime of 286.74 hours. This reduces 72.3% of the existing total downtime, which is 1,044.285.

In Figure 4 it is also shown that several preventive maintenances activities are close together so that they can be combined at one time. The revised preventive maintenance is shown in Figure 5. This makes the frequency of preventive maintenance is being 17 times with the total expected downtime of 140.34 hours per year. When it is compared to the existing conditions, the revised preventive maintenance can reduce total downtime by 86.6% and increase the availability of the Grate Cooler machine by 1.73%.

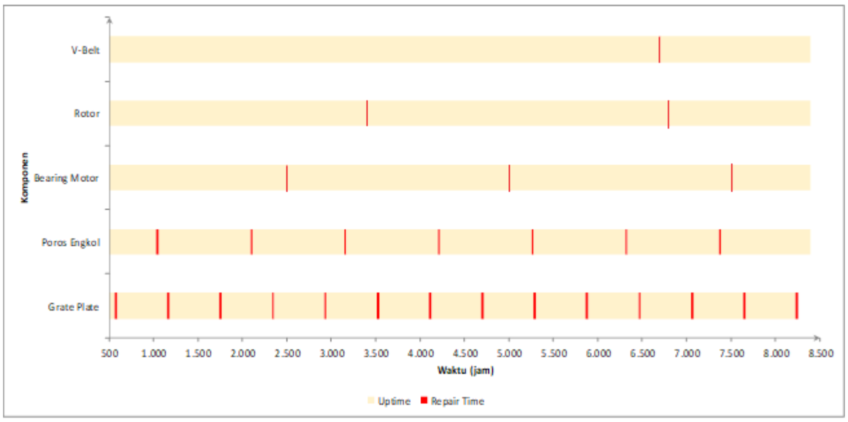

Figure 4. Scheme of preventive maintenance implementation

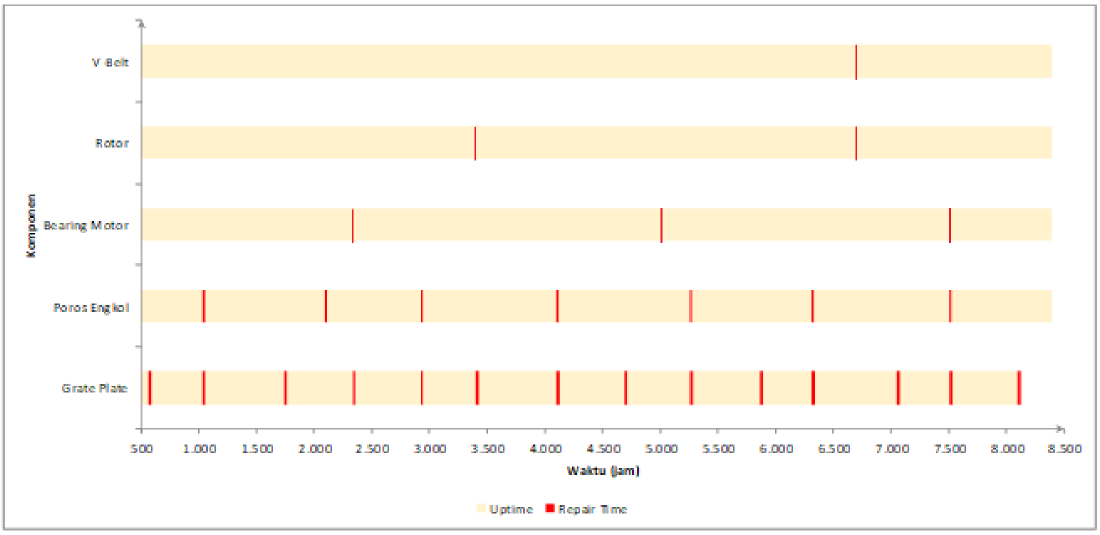

Figure 5. Scheme of combined preventive maintenance implementation

CONCLUSION

Based on discussion, it can be concluded that the proposed maintenance intervals increase reliability and availability, but maintainability is constant due to unchanged machine design. The maintenance intervals are arranged at minimum downtime. However, when the maintenance time at minimum downtime exceeds MTTF, then maintenance intervals are set at the MTTF to avoid machine damage before maintenance time. Preventive maintenance should be scheduled by maintaining several components simultaneously to reduce total downtime.

This study involves reliability, availability, and maintainability criteria. For further research, cost can be considered as another criterion.

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