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Optimization of Preventive Replacement of Critical Components in the Komatsu PC2000-8 Excavator to Minimize Downtime at PT XYZ

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ABSTRACT
The availability of primary loading equipment, particularly the Komatsu PC2000-8 excavator, is a key determinant of operational efficiency in open-pit mining. Failures of critical components directly affect downtime, maintenance costs, and key performance indicators, including physical availability (PA), mean time between failures (MTBF), and mean time to repair (MTTR). Current preventive maintenance practices, which largely follow generic original equipment manufacturer (OEM) replacement intervals, often fail to prevent actual breakdowns, highlighting the need to optimize preventive replacement intervals based on cost and downtime minimization. This study aims to determine the optimal preventive replacement intervals for the critical components of the Komatsu PC2000-8 excavator to minimize downtime and maintenance costs while improving equipment availability. The study employed a quantitative comparative optimization approach. Critical components were identified using a Pareto diagram based on failure frequency and cumulative downtime. Reliability analysis was performed by selecting the most appropriate time-between-failures distribution using Relyence Weibull software to estimate the distribution parameters. Reliability, hazard rate, MTBF, and cost analyses comparing preventive and corrective replacement—including spare parts, labor, supporting equipment, and lost production or contractual implications—were subsequently performed. An Age Replacement policy was then optimized to determine replacement intervals that minimized the long-run average cost per unit time while satisfying equipment availability constraints. The results indicated that the optimal preventive replacement intervals based on cost minimization were 11,545 hours for the Boom Cylinder, 16,820 hours for the Turbocharger, 7,366 hours for the Water Pump, 20,026 hours for the Final Drive, and 19,624 hours for the Radiator.

INTRODUCTION

The efficiency of open-pit coal mining operations depends heavily on the availability and reliability of primary loading equipment, such as large-capacity excavators (Karikari, 2026; Lin, 2026; S. Q. Liu et al., 2025; Tasoglu et al., 2026). As the primary equipment in the excavation and loading cycle, excavator downtime directly interrupts the entire production chain, including hauling and supporting equipment operations, resulting in substantial productivity losses and potential contractual penalties. In the Indonesian coal mining industry, which possesses one of the largest coal reserves in the Asia-Pacific region, maintaining high operational efficiency has become increasingly important amid fluctuating coal prices and intensifying competition among mining contractors.

PT XYZ, a major mining contractor operating more than 15 mining sites across Kalimantan, Sulawesi, and Sumatra, faces persistent challenges in maintaining excavator availability. The company operates seven Komatsu PC2000-8 excavators as its primary loading equipment, supported by 40 dump trucks, four bulldozers, and two motor graders. Among these, excavators play the most critical role in the production system because they perform the excavation and loading processes (Kim et al., 2025; W. Liu et al., 2022; Molaei et al., 2023). When an excavator experiences a breakdown, excavation activities cease, preventing both overburden and coal from being loaded. Consequently, dump trucks cannot transport material, and the entire production chain is disrupted. Therefore, equipment availability has been established as one of the key performance indicators (KPIs) by the mine owner to ensure contractual production targets are achieved (Levious, 2024).

To monitor equipment performance, PT XYZ applies several KPIs, including physical availability (PA), mean time to repair (MTTR), and mean time between failures (MTBF) (Karikari, 2026; Kononis et al., 2026; Moemenishahraki, 2025; Prabowo & Baskoro, 2026; Tasoglu et al., 2026). These indicators are intended to minimize excavator downtime, maintain production targets, and improve operational efficiency. The company's target PA decreased from 96.06% in the first year to 92.85% in the third year, while the MTTR target increased from 2 to 6 hours, and the MTBF target decreased from 100 to 72 hours. This trend reflects management's recognition that, as equipment ages, failures become more frequent and repairs require more time, ultimately reducing equipment availability. Accordingly, these KPI targets anticipate the gradual decline in equipment reliability throughout its operational life (Alade et al., 2024; Marinagi et al., 2023; Rediske et al., 2022; Souifi et al., 2022).

Throughout the contract period, PT XYZ encountered ongoing challenges in maintaining equipment availability. Equipment availability affects not only production performance but also compliance with contractual obligations between the contractor and the mine owner. Failure to achieve production targets may result in contractual penalties. Therefore, an effective maintenance strategy is essential for minimizing downtime and sustaining operational performance. Beyond its technical implications, equipment downtime also has significant financial consequences. PT XYZ estimates downtime costs using the hourly rental value of each type of heavy equipment. Excavators have the highest hourly operating value (IDR 288xxxx/hour), followed by dump trucks (IDR 144xxxx/hour), indicating that downtime involving excavators results in the greatest financial losses. Operationally, excavators function as the primary loading equipment; consequently, when an excavator is unavailable, dump trucks, bulldozers, and motor graders cannot operate efficiently. Thus, the financial impact of downtime is determined not only by the hourly operating value of each unit but also by the equipment's role within the production system.

PT XYZ currently implements preventive, predictive, and corrective maintenance strategies to improve equipment reliability, maximize availability, and extend the service life of its heavy equipment fleet. Preventive maintenance is conducted on a scheduled basis and includes routine inspections, lubrication, and replacement of consumable components. However, in practice, preventive maintenance is still largely based on original equipment manufacturer (OEM) recommendations, which primarily specify the replacement of basic components, such as filters and lubricants, at 250-hour service intervals. This approach may result in both over-maintenance, through premature component replacement, and under-maintenance, by delaying the replacement of other critical components until failure occurs. Consequently, equipment availability declines because many critical components are replaced only after failure through corrective maintenance.

Predictive maintenance at PT XYZ is intended to improve maintenance effectiveness by monitoring component conditions using onboard sensors and the Vehicle Health Monitoring System (VHMS). However, its implementation remains suboptimal because operational data can only be downloaded during scheduled preventive maintenance, which occurs every 250 operating hours. Moreover, VHMS data require specialized interpretation, and inaccurate analysis may lead to inappropriate maintenance decisions, unnecessary work, incorrect spare-parts procurement, and prolonged downtime. As a result, predictive maintenance has not achieved its intended effectiveness, and the company continues to rely heavily on corrective maintenance following component failure.

Corrective maintenance at PT XYZ involves replacing components only after failure has occurred. Because this strategy is reactive, it frequently results in unplanned downtime and substantially higher repair costs than scheduled maintenance. Its implementation also presents significant logistical challenges, particularly regarding spare-parts procurement. Since many mining sites are located far from authorized distributors, obtaining replacement components often requires considerable lead time. This situation is further complicated by the need to mobilize supporting equipment and maintenance personnel on short notice after a failure occurs. In addition, the high cost of major heavy-equipment components places considerable pressure on maintenance budgets when emergency procurement is required. Unexpected demand for replacement parts also increases the risk of delivery delays or stock shortages, particularly for infrequently used or imported components. Consequently, corrective maintenance not only extends equipment downtime but also introduces uncertainty into operational planning.

Failure frequency and repair duration vary considerably among excavator components. A preliminary analysis of failure records identified five critical components of the Komatsu PC2000-8 excavator that contributed most significantly to downtime: the boom cylinder, turbocharger, water pump, final drive, and radiator. These components exhibited both high failure frequencies and extended repair durations, while also requiring costly replacement parts, making them the primary targets for maintenance optimization.

The Age Replacement method provides a systematic approach for determining optimal preventive replacement intervals by balancing the costs of scheduled replacement against the costs associated with unexpected failures. Under this policy, a component is replaced either at a predetermined replacement age (t_p) or upon failure, whichever occurs first (Jardine & Tsang, 2013). This method is particularly suitable for critical components exhibiting increasing failure rates because it identifies replacement intervals that minimize the long-run average cost per unit time or total downtime. Previous studies have successfully applied the Age Replacement method to various industrial applications, including filling machines (Mustofa et al., 2018), water pumps (Answary & Waluyo, 2024), and projection spot-welding machines (Ulugbek et al., 2018). Within the mining sector, reliability-centered maintenance approaches have been investigated for heavy equipment (Burhannudin & Anshori, 2022; Sembiring et al., 2021; Silva et al., 2023); however, the application of Age Replacement optimization to large-capacity Komatsu PC2000-8 excavators operating in Indonesian coal mines has received limited attention.

Despite the growing body of literature on maintenance optimization, several important research gaps remain. First, although OEM recommendations provide general replacement intervals for excavator components, they do not account for site-specific operating conditions, actual failure characteristics, or the cost structure of Indonesian coal mining operations. Consequently, these recommendations may not minimize either downtime or maintenance costs. Second, most previous studies have optimized either maintenance cost or equipment availability independently, without simultaneously addressing both objectives, despite their equal importance for mining contractors operating under contractual availability requirements. Third, although the Age Replacement method has been widely applied in other industries, its systematic application to the critical components of the Komatsu PC2000-8 excavator in Indonesian coal mining has not been adequately reported in the peer-reviewed literature. Finally, no previous study has comprehensively compared optimal preventive replacement intervals derived from reliability-based optimization with existing OEM-recommended intervals and mean time to failure (MTTF)-based intervals to evaluate their relative effects on equipment reliability, availability, downtime, and maintenance cost.

Given these identified research gaps, this study applies a reliability-based quantitative approach using the Age Replacement method to optimize preventive replacement intervals for the critical components of the Komatsu PC2000-8 excavator. The study employs two optimization criteria: (1) cost minimization, which seeks to minimize the long-run average maintenance cost per unit time, and (2) downtime minimization, which seeks to minimize total downtime per unit time while maintaining the required equipment availability. This dual-objective approach is particularly relevant to PT XYZ because it enables the company to select maintenance strategies that align with either economic or operational priorities, depending on contractual requirements and operational objectives. The analysis utilizes operational and reliability data for the Komatsu PC2000-8 excavator collected from January 2021 to December 2025, including downtime records, failure-time distribution parameters, maintenance durations, and comprehensive maintenance cost data.

Specifically, this study aims to: (1) identify the critical components of the Komatsu PC2000-8 excavator based on failure frequency and cumulative downtime; (2) determine the optimal preventive replacement intervals using the Age Replacement method under the cost-minimization criterion; (3) determine the optimal preventive replacement intervals using the Age Replacement method under the downtime-minimization criterion; (4) compare the reliability and availability achieved using the optimized replacement intervals with those obtained under the existing mean time to failure (MTTF)-based practice and the original equipment manufacturer (OEM) recommendations; (5) evaluate the potential reductions in maintenance costs and downtime resulting from the implementation of the optimized replacement intervals over the excavator's 72,000-hour operational life; and (6) conduct a sensitivity analysis to identify the variables with the greatest influence on maintenance costs and downtime.

This study is expected to make three main contributions. From a theoretical perspective, it extends the application of the Age Replacement method to large-capacity excavators operating in Indonesian coal mining and provides empirical evidence regarding optimal replacement intervals for five critical components. From a practical perspective, it offers PT XYZ a data-driven maintenance strategy capable of reducing downtime and maintenance costs while improving equipment availability, thereby supporting the achievement of contractual production targets and reducing the risk of contractual penalties. From a policy perspective, the findings may support the development of more accurate, site-specific maintenance protocols that move beyond generic OEM recommendations, thereby contributing to improved operational efficiency and competitiveness in the Indonesian mining industry. Accordingly, this study is expected to bridge the gap between theoretical maintenance optimization models and their practical implementation in the mining sector.

METHOD

This study employed a structured quantitative approach using a reliability-based preventive replacement optimization model based on the Age Replacement policy. The primary objective was to determine the optimal preventive replacement interval (t_p) using two optimization criteria: (1) minimization of the long-run average maintenance cost and (2) minimization of average downtime while maintaining the required equipment availability. The analysis utilized operational and reliability data from the Komatsu PC2000-8 excavator at PT XYZ collected between January 2021 and December 2025. The dataset included downtime records, failure-time distribution parameters, maintenance durations, and maintenance cost components, including replacement costs, labor costs, and production loss costs. Data were collected through direct observation of preventive maintenance activities, structured interviews with relevant personnel, and analysis of the company's historical maintenance records.

Data analysis was performed using Relyence Weibull software. Operational records were first converted into time-between-failures (TBF) data, and a Pareto analysis was conducted to identify the critical components based on failure frequency and cumulative downtime. A goodness-of-fit test was then performed to determine the most appropriate probability distribution and estimate the reliability parameters, including the failure rate, mean time between failures (MTBF), and mean time to repair (MTTR). Numerical optimization was subsequently conducted to determine the optimal preventive replacement intervals by evaluating candidate intervals around the existing mean time to failure (MTTF)-based practice and the original equipment manufacturer

(OEM) recommendations. Finally, a sensitivity analysis was performed to assess the robustness of the optimized replacement intervals under varying maintenance costs and maintenance durations.

RESULT AND DISCUSSION

Optimal Preventive Replacement Intervals of Critical Components Using The Age-Replacement Method.

After the optimal preventive replacement interval is obtained, a comparison is made with the MTTF value as a representation of existing conditions and the replacement interval recommended by the Dealer/OEM for each critical component, either based on the criteria of cost minimization and downtime minimization.

Component Replacement Intervals Using the Age-Replacement Method to Minimize Total Costs

The optimal preventive replacement interval based on the cost minimization criteria obtained, is further compared to the Dealer/OEM recommendation replacement interval as the value based on existing conditions (MTTF. The calculation results show that the optimal preventive replacement interval (tp) for all critical components is smaller than the OEM recommendation interval and MTTF value. At shorter intervals, the cost of failure is still relatively low, while at longer intervals, the risk of failure increases so that the cost of replacing the damage becomes greater. Therefore, the total cost of maintenance reaches the minimum value at the optimal preventive replacement interval (tp) based on the cost minimization criterion, which is set as the optimal preventive replacement interval. The expected rate of total cost for critical components of the PC2000-8 Excavator can be seen in Figures 1 to 5.

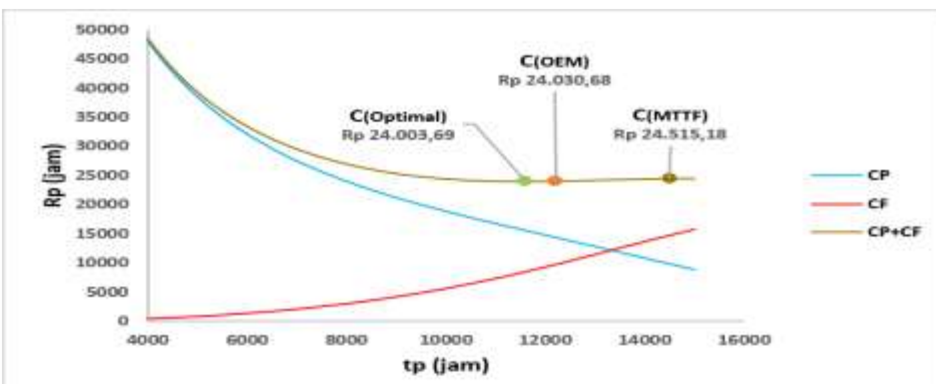

Figure 1 Total Cost Expectation Rate Curve Cylinder Boom

Source: Data processing results using Relyence Weibull software (PT XYZ operational data, 2021-2025)

Based on Figure 1, the curve shows the relationship between the preventive replacement interval (tp) and the expected total cost of maintenance of the Cylinder Boom components. In shorter (tp), the cost of prevention is relatively high because replacements are done more frequently. Conversely, in longer (tp), the cost of damage increases as the risk of component failure increases. The optimal preventive replacement interval was obtained at (tp) 11,545 hours with an expected total cost of Rp 24,003.69 per hour. This cost value is lower than the OEM recommendation at (tp) 12,000 hours with an expected total cost of IDR 24,030,667 per hour, as well as the existing condition or MTTF at (tp) 14,579,756 hours with an expected total cost of IDR 24,515,181 per hour. Thus, (tp) 11,545 hours was chosen as the optimal preventive reimbursement interval as it resulted in the lowest expected total cost of care. Next, Figure 2 presents the expected rate curve of the total cost for the Turbocharge component.

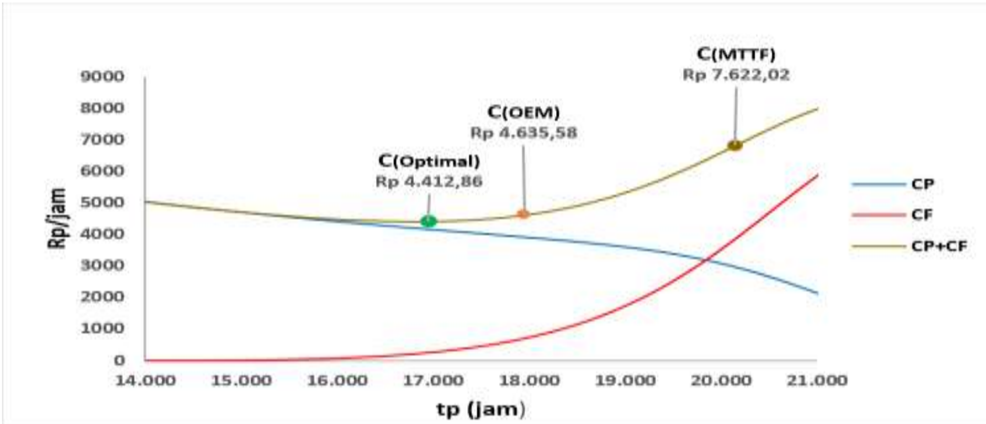

Figure 2 Total Cost Expectation Rate Curve Turbocharge

Source: Data processing results using Relyence Weibull software (PT XYZ operational data, 2021-2025)

Based on Figure 2, the curve shows the expected change in the total maintenance cost of the Turbocharge component with the variation in the preventive replacement interval (tp). At too short intervals (tp), prevention costs tend to be higher because component replacements are done more frequently. Conversely, as the TP gets longer, the cost of damage increases because the chance of component failure becomes greater. The calculation results show that the optimal preventive replacement interval for Turbocharge components is obtained at (tp) 16,820 hours with an expected total cost of Rp 4,412,855 per hour. This cost value is lower than the OEM recommendation at (tp) 18,000 hours with an expected total cost of IDR 4,635,577 per hour, as well as the existing condition or MTTF at (tp) 20,710 hours with an expected total cost of IDR 7,622,019 per hour. Thus, the replacement of Turbocharge components at (tp) 16,820 hours is considered the most economical because it results in the lowest expected total maintenance cost compared to OEM methods and existing conditions. Figure 3 presents the expected rate curve of the total cost for Water Pump components.

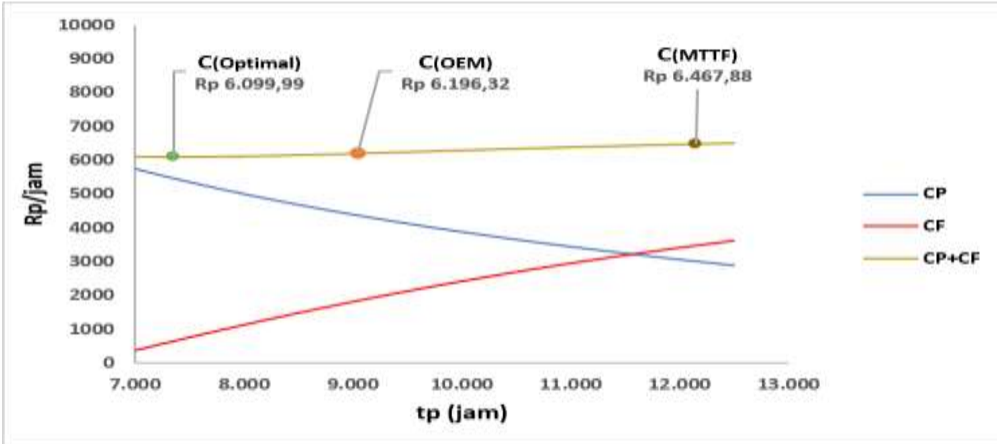

Figure 3 Total Cost Expectation Rate Curve Water Pump

Source: Data processing results using Relyence Weibull software (PT XYZ operational data, 2021-2025)

Based on Figure 3, the curve shows the change in the expected total cost of replacing Water Pump components with the variation in the preventive replacement interval (tp). At (tp) that is too short, the cost of preventive replacement tends to be higher because components are replaced more frequently. Conversely, the longer it is (tp), the cost due to damage increases as the chance of component failure increases. The calculation results show that the optimal preventive replacement interval for Water Pump components is obtained at (tp) 7,366 hours with an expected total cost of Rp 6,099.99 per hour. This cost value is lower than the OEM recommendation at (tp) 9,000 hours with an expected total cost of IDR 6,196.32 per hour, as well as the existing condition or MTTF at (tp) 12,052 hours with an expected total cost of IDR 6,467.88 per hour. Thus, the replacement of the Water Pump at (tp) 7,366 hours is considered the most economical because it results in the lowest expected total maintenance cost compared to OEM methods and existing conditions. Figure 5.4 presents the total cost expected rate curve for Final Drive components.

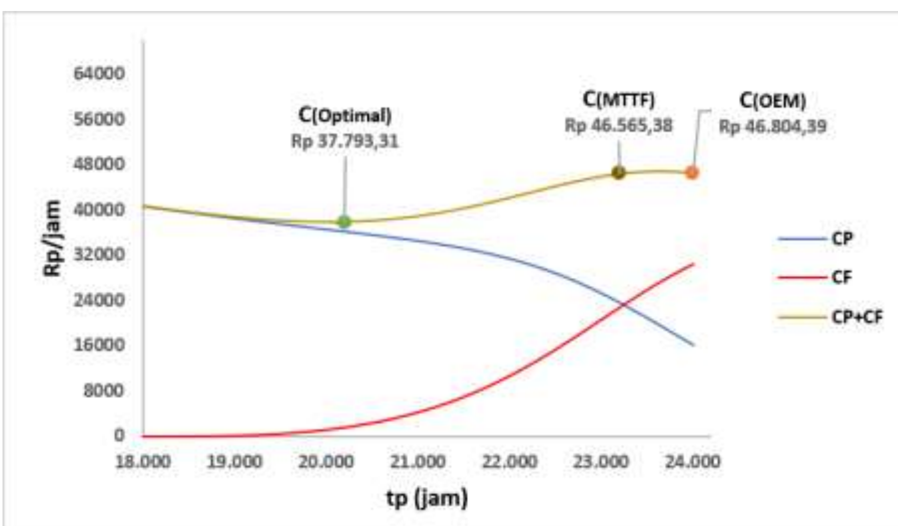

Figure 4 Total Cost Expectation Rate Curve Final Drive

Source: Data processing results using Relyence Weibull software (PT XYZ operational data, 2021-2025)

Based on Figure 4, the curve shows the expected change in the total maintenance cost of Final Drive components to the variation in the preventive replacement interval (tp). The cost of preventive replacement tends to decrease when (tp) is extended as the frequency of replacement becomes lower. However, at longer intervals, the cost of damage increases as the risk of component failure increases. The calculation results show that the optimal preventive replacement interval for the Final Drive component is obtained at (tp) 20,026 hours with an expected total cost of Rp 37,793,312 per hour. This cost value is lower than the existing condition or MTTF at (tp) 23,467 hours with an expected total cost of IDR 46,565,378 per hour, and the OEM recommendation at (tp) 24,000 hours with an expected total cost of IDR 46,804,393 per hour. Thus, the replacement of the Final Drive at (tp) 20,026 hours is considered the most economical because it results in the lowest expected total maintenance cost. Figure 5.5 presents the expected rate curve of the total cost for the Radiator components.

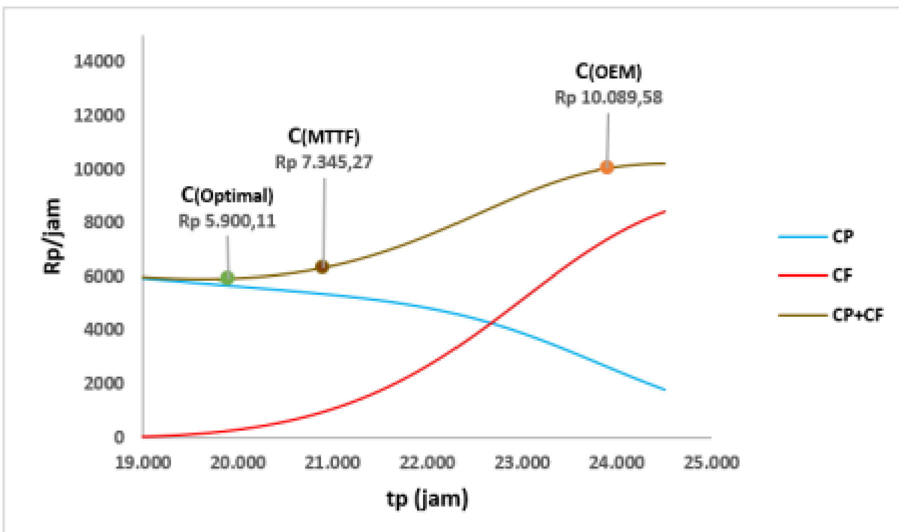

Figure 5 Total Cost Expectation Rate Curve Radiator

Source: Data processing results using Relyence Weibull software (PT XYZ operational data, 2021-2025)

Based on Figure 5, the curve shows the expected change in the total maintenance cost of the Radiator component with the variation in the preventive replacement interval (tp). The cost of preventive replacement decreases when (tp) gets longer because the frequency of replacement becomes lower. In contrast, the cost due to damage increases as the (tp) increases, as the risk of component failure becomes greater. The calculation results show that the optimal preventive replacement interval for radiator components is obtained at (tp) 19,624 hours with an expected total cost of Rp 5,900,112 per hour. This cost value is lower than the existing condition or MTTF at (tp) 21,879 hours with an expected total cost of IDR 7,345,273 per hour, as well as the OEM recommendation at (tp) 24,000 hours with an expected total cost of IDR 10,089,579 per hour. Thus, the replacement of the radiator at (tp) 19,624 hours is considered the most economical because it results in the lowest expected total maintenance cost.

Component Replacement Intervals Using the Age Replacement Method to Minimize Downtime

The optimal preventive replacement interval based on the minimized downtime approach obtained, is then compared to the dealer recommendation (OEM) interval and the MTTF value-based interval for each critical component. The calculation results show that the optimal preventive replacement interval (tp) for all critical components has a smaller value than the OEM recommendation interval and the MTTF value. The expected rate of total downtime can be seen in Figures 6 to 10

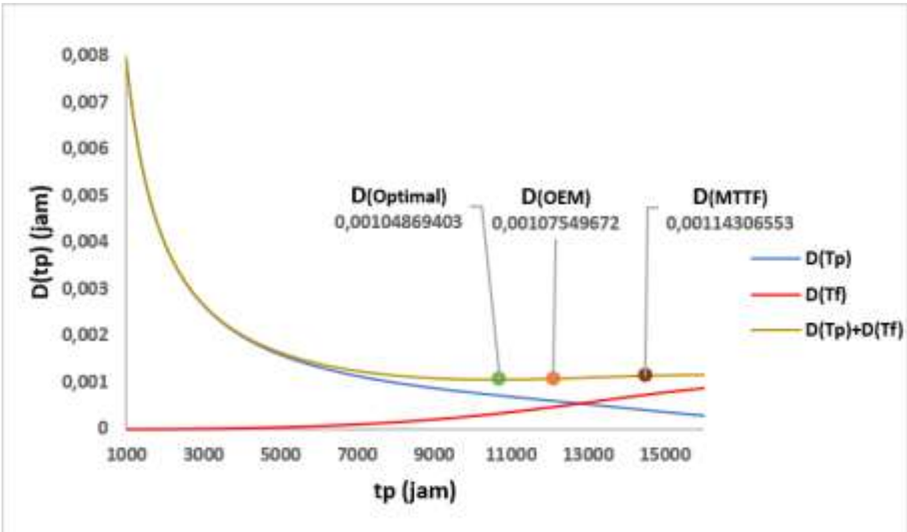

Figure 6 Expectations of the Curve Lays Downtime Cylinder Boom

Source: Data processing results using Relyence Weibull software (PT XYZ operational data, 2021-2025)

Based on Figure 6, the curve shows the relationship between the preventive replacement interval (tp) and the expected downtime average per hour of operation for the Cylinder Boom. Downtime. The result of preventive replacement is relatively high in the short term (TP) because the frequency of replacement is higher, resulting in downtime. As a result of the damage increases in the length (TP). The optimal preventive replacement interval was obtained at (tp) 10,690 hours, with expectations downtime of 0.00104869403 hours per operating hour, lower than the OEM recommendation of (tp) 12,000 hours with expectations downtime of 0.00106281737 hours per operating hour, and the existing condition of MTTF at (TP) 14,579,756 hours with an expected downtime of 0.00112278253 hours per operating hour of operation. Figure 7 presents the total expected rate curve for downtime for the Turbocharge components.

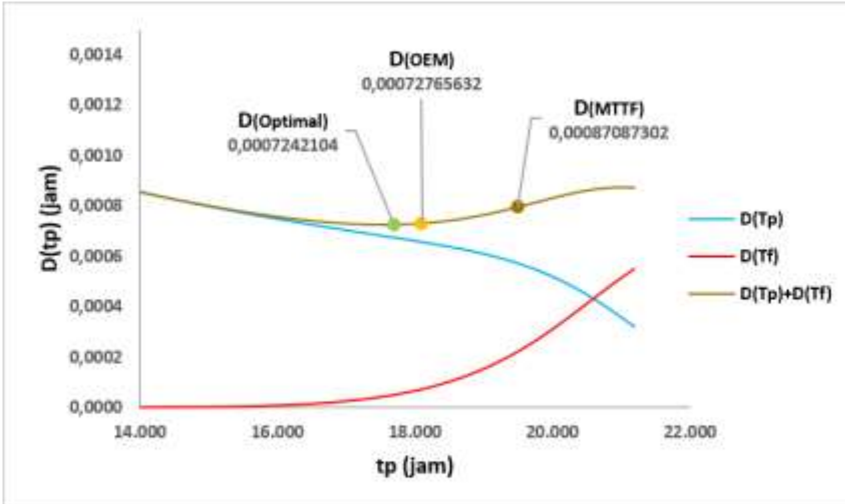

Figure 7 Expectations of the Curve Lays Downtime Turbocharge

Source: Data processing results using Relyence Weibull software (PT XYZ operational data, 2021-2025)

In Figure 7, show Expectations downtime average per hour of operation for the Turbocharge components. Downtime due to preventive replacement is high in short (tp) due to the frequency of replacements, whereas downtime as a result of the damage increases in the length (TP). The optimal interval is set at (tp) 17,555 hours, with expected downtime 0.0007242104 hours per operating hour, lower than the OEM recommendation of (tp) 18,000 hours with expectations of downtime amounting to 0.00072765632 hours per hour of operation, and the existing condition of MTTF at (tp) 20,710 hours with expectations of downtime 0.00087087302 hours per operating hour. Next, Figure 8 presents the total expected rate curve for the downtime for the Water Pump.

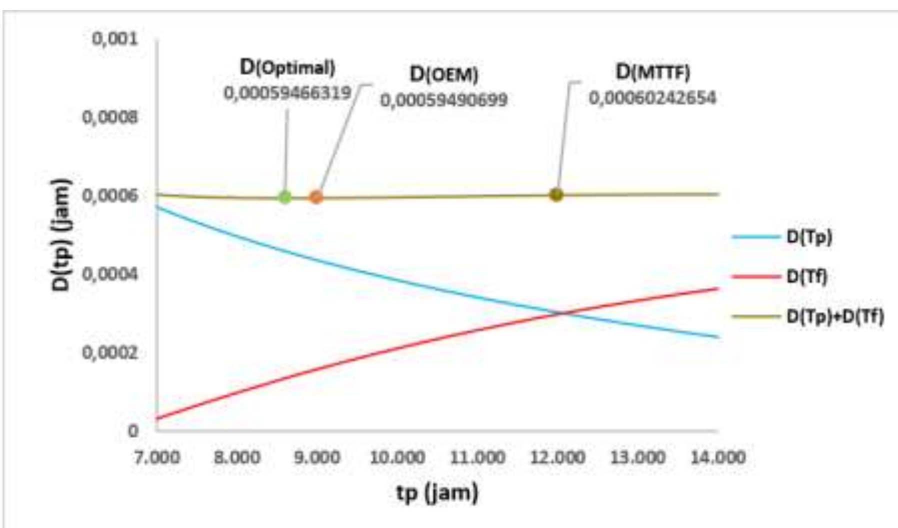

Figure 8 Expectations of the Curve Lays Downtime Water Pump

Source: Data processing results using Relyence Weibull software (PT XYZ operational data, 2021-2025)

Based on Figure 8, the curve shows the expected average downtime per hour of operation for the Water Pump. Downtime due to replacement prevention is high at short (tp), while downtime due to damage increases at long tp. The optimal interval was obtained at (tp) 8,618 hours with an expected downtime of 0.00059466319 hours per operating hour, lower than the OEM recommendation at (tp) 9,000 hours with an expected downtime of 0.00059490699 hours per operating hour, and the existing condition of MTTF at (tp) 12,052 hours with an expected downtime of 0.00060242654 hours per operating hour. Figure 9 presents the expected rate curve of total downtime for Final Drive components.

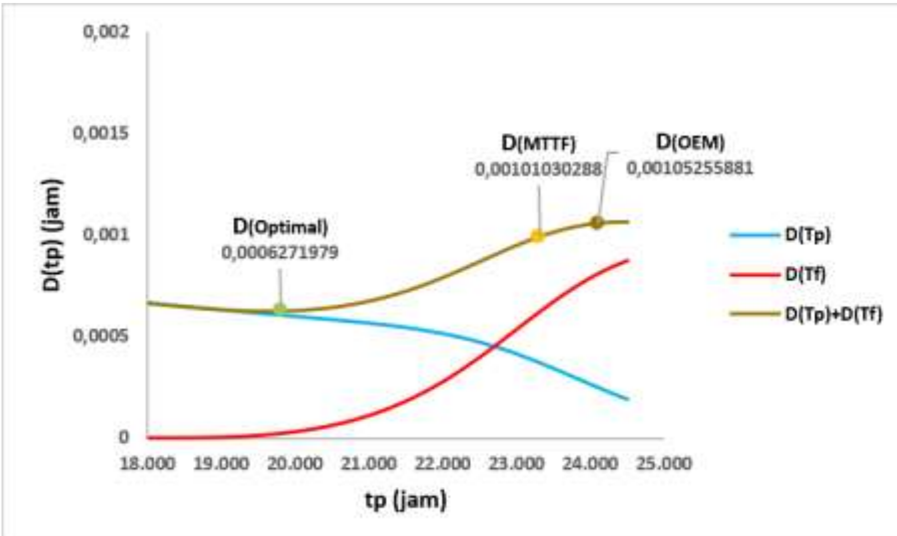

Figure 9 Expectations of the Curve Lays Downtime Final Drive

Source: Data processing results using Relyence Weibull software (PT XYZ operational data, 2021-2025)

Based on Figure 9, the curve shows the expected downtime average per hour of operation for the Final Drive. Downtime due to high preventive replacement in short (TP), while downtime As a result of the damage increases in the length (TP). The optimal interval was obtained at (tp) 19.643 hours with expected downtime by 0.0006271979 hours per hour of operation, lower than the OEM recommendation of (tp) 24,000 hours with expected downtime 0.00105255881 hours per hour of operation, and the existing condition of MTTF at (tp) 23,467 hours with expected downtime 0.00101030288 hours per hour of operation. Figure 10 presents the total expected rate curve for the downtime for components Radiator.

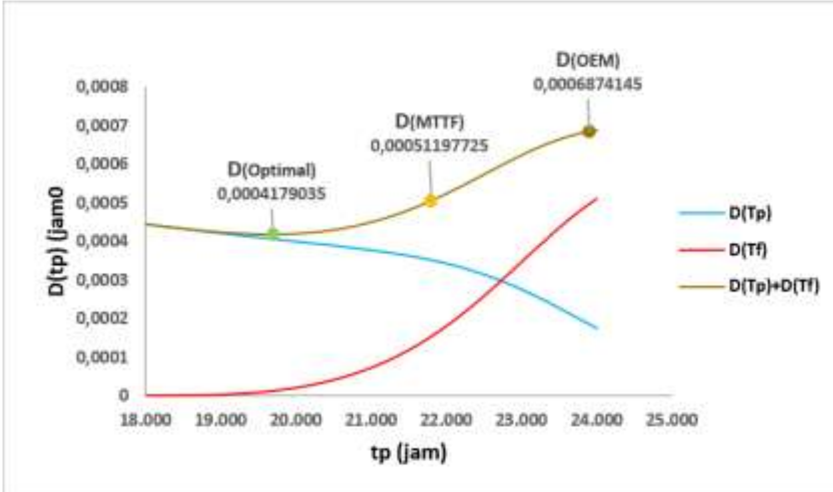

Figure 10 Expectations of the Curve Lays Downtime Radiator

Source: Data processing results using Relyence Weibull software (PT XYZ operational data, 2021-2025)

Based on Figure 10, the curve shows the expected average downtime per hour of operation for the Radiator components. Downtime due to preventive replacement is high in short (tp), while downtime due to damage increases in long (tp). The optimal interval was obtained at (tp) 19,664 hours with an expected downtime of 0.0004179035 hours per operating hour, lower than the OEM recommendation at (tp) 24,000 hours with an expected downtime of 0.0006874145 hours per operating hour and the existing condition of MTTF at (tp) 21,879 hours with an expected downtime of 0.00051197725 hours per operating hour.

Figures 6 to 10 show that the expected downtime at the optimal prevention interval is lower than the MTTF interval and the OEM recommendation for all critical components. D(Tp) prevention downtime decreases as the replacement interval increases, while D(Tf) damage downtime increases, so the total downtime curve has a minimum point set as the optimal prevention interval for each component.

optimal component replacement for the cost minimization criterion, which is 11,545 hours for Cylinder Boom components with a total cost expected value of IDR 24003.69; 16,820 hours for Turbocharger components with a total cost expected value of IDR 4,412.86; 7,366 hours for Water Pump components with a total cost expected value of IDR 6,100.00; 20,026 hours for Final Drive components with an expected value of total costs of IDR 37,793.31; and 19,624 hours for Radiator components with an expected total cost value of IDR 5,900.11.

Meanwhile, the optimal component replacement interval for the downtime minimization criterion is 10,690 hours for Cylinder Boom components with a total expected downtime value of 0.001048694 hours; 17,555 hours for Turbocharger components with a value of 0.0007242 hours; 8,618 hours for Water Pump components with a value of 0.0005946 hours; 19,643 hours for Final Drive components with a value of 0.0006272 hours; and 19,664 hours for Radiator components with a value of 0.000417904 hours.

PT XYZ is a company engaged in mineral and coal mining services, especially in the provision and rental of heavy equipment units for coal mining activities. The operation of the heavy equipment is used in the mine with the open pit method, which is greatly influenced by weather conditions. During the rainy season, mining activities are generally stopped, and after the rain subsides, additional time is needed for preparation before operations can resume.

In its implementation, this operational activity is regulated in a work contract between the contractor as the holder of a mining services business license (IUJP) and a mining business license holder (IUP). In the contract, the IUP owner, as the service user, sets certain performance targets, one of which is a high level of availability of the tool. PT XYZ, as a contractor, may be subject to a penalty if the availability value does not reach the agreed target. On the contrary, the ability to meet these targets will improve the company's reputation in the mining industry and open up opportunities for cooperation with other mine owners. The level of equipment availability is closely related to the total downtime in an operating period. The smaller the downtime, the higher the availability rate of the tool. Therefore, in determining maintenance policies, PT XYZ needs to prioritize efforts to minimize downtime without ignoring cost efficiency considerations.

Comparison of Total Costs and Total Downtime Based on Existing Component Replacement (MTTF) Policy, Dealer Recommendation (OEM), and Minimized Downtime

This comparison is carried out to evaluate whether each component is more appropriate for preventive replacement according to the predetermined interval. The evaluation was carried out by considering several factors, including component replacement time, labor costs, supporting equipment costs, lost production, and component prices at various interval conditions, namely the optimal preventive replacement interval (tp) obtained based on the criteria of cost minimization and minimization of downtime. existing conditions based on MTTF values, as well as preventive replacement intervals recommended by the dealer/OEM. The number of component replacements is calculated based on the PC2000-8 Excavator's operating life of 72,000 hours, during which period the unit is planned to be scrapped or resold. During the life of the operation, general overhaul activities are carried out every 24,000 hours. The replacement of components in this analysis is assumed to be carried out at the time the unit undergoes an overhaul in the first cycle, so that the frequency of subsequent replacement follows a predetermined replacement interval shows the total downtime and total cost of replacing critical components of the PC2000-8 Excavator based on existing methods (MTTF), dealer (OEM) recommendations, and minimizing downtime. For Cylinder Boom, MTTF produces 28 hours of downtime with a total cost of IDR 600,222,000, while OEM and minimum downtime both produce 16 hours of downtime with a total cost of IDR 385,906,000. Turbocharge has 15 hours of downtime and IDR 166,555,000 for MTTF, as well as 12 hours of downtime and IDR 70,540,000 for OEM, and minimized downtime. For Water Pump, MTTF 18 hours of downtime and IDR 214,250,800, OEM, and a minimum downtime of 12 hours of downtime each, with a total cost of IDR 120,554,700. Final Drive shows 18 hours of downtime and IDR 880,536,950 for MTTF, while OEM and minimum downtime both have 8 hours of downtime at IDR 732,830,950. For Radiators, MTTF has 14 hours of downtime and a total cost of IDR 219,942,200, while OEM and minimum downtime have 8 hours of downtime at IDR 112,784,200. Overall, the MTTF method has the highest downtime and total cost, while OEM and minimized downtime show similar results in terms of both downtime and cost. Thus, a follow-up review is needed to determine the method between OEM and downtime minimization that meets the reliability value according to company policy and has the highest reliability value.

Comparison of PC2000-8 Excavator Critical Component Reliability with Dealer Recommendation (OEM) Method, and Minimized Downtime

Reliability level (reliability) in each method is calculated to determine the ability of the components to operate without experiencing failure at a predetermined interval. Calculation of values' reliability for each critical component is based on a reliability function. In this study, the reliability is also compared to the company's policy, which is a minimum reliability level of 0.70. The value indicates that the component is expected to have a minimum probability of 70% remaining functional without experiencing failure until the set replacement interval. Thus, the interval preventive replacement. The proposed ones are not only assessed based on cost minimization and minimizing downtime, but must also meet the minimum limit reliability of the company, so that the component replacement policy remains operationally feasible. Value comparison results, reliability of each method is presented in Table 1.

Table 1 Comparison of Reliability Critical Components, Excavator PC2000-8, OEM Method and Minimization of Downtime

Components	Dealer Recommendations		Minimized Downtime	
	tp (hours)	Reliability	tp (hours)	Reliability
Cylinder Boom	12.000	0,71	10.690	0,80
Turbocharge	18.000	0,93	17.555	0,98
Water Pump	9.000	0,87	8.618	0,89
Final Drive	24.000	0,39	19.643	0,99
Radiator	24.000	0,39	19.664	0,99

Source: Data processing results with Microsoft Excel

Based on Table 1, for Cylinder Boom, the OEM method produces reliability by 0.71, while the minimization method downtime by 0.80; Both meet the minimum limit of 0.70, but the minimum method downtime is more recommended because it has a value reliability higher. On Turbocharge, both methods are above the minimum limit (OEM 0.93; minimum downtime 0.98), so the minimization method is chosen for providing higher reliability. Water Pump shows reliability OEM 0.87 and minimum downtime 0,89; Although both are policy-compliant, the higher value at the minimum downtime makes it a top choice. For Final Drive, the OEM method does not meet the minimum limit (0.39), while the minimum downtime of 0.99 meets the company's policy and is selected. Radiator also shows a similar pattern, with an OEM of 0.39 below the limit, while the minimized downtime of 0.99 meets the policy and is chosen as the optimal method. Minimization Method Downtime. It is chosen for all components because it provides a higher reliability value and is in accordance with the company's policy.

Comparison of PC2000-8 Excavator Critical Component Availability with Existing Method (MTTF) and Optimal Interval

Once the optimum replacement interval is known, it will compare the existing availability with the optimal replacement interval (tp). By using formula 2.27, the availability value presented in Table 2 is obtained.

Table 2. Comparison Availability Optimal existence and interval

Components	Existing (MTTF)		tp Optimum	
	tp (hours)	Avialibility	tp (hours)	Avialibility
Cylinder Boom	14.579,76	99,900%	10.690	99,925%
Turbocharge	20.709,62	99,929%	17.555	99,932%
Water Pump	12.052,14	99,922%	7.366	99,946%
Final Drive	23.466,53	99,903%	19.643	99,959%
Radiator	21.878,65	99,932%	19.664	99,959%

Source: Data processing results with Microsoft Excel

Based on Table 2, it can be seen that there is an increase in the availability value of each component after the implementation of the optimal preventive replacement interval (tp) compared to the existing condition (MTTF). Cylinder Boom components have increased their availability value from 99.900% to 99.924%. Turbocharger components have increased from 99.929% to 99.932%. Furthermore, the Water Pump component increased from 99.922% to 99.946%, the Final Drive component increased from 99.903% to 99.959%, and the Radiator component increased from 99.932% to 99.959%. The improvement shows that the implementation of optimal preventive replacement intervals is able to reduce downtime, thereby increasing equipment availability. With more precise replacement intervals, components can be replaced before a failure occurs, making the operation of the unit more reliable and efficient.

CONCLUSION

Based on the results of the data analysis, the critical components of the Komatsu PC2000-8 excavator at PT XYZ were identified as the boom cylinder, turbocharger, water pump, final drive, and radiator. The Age Replacement method demonstrated that the optimal preventive replacement intervals differed according to the optimization criterion. Under the cost-minimization criterion, the optimal replacement intervals were 11,545 operating hours for the boom cylinder, 16,820 hours for the turbocharger, 7,366 hours for the water pump, 20,026 hours for the final drive, and 19,624 hours for the radiator. Under the downtime-minimization criterion, the corresponding optimal replacement intervals were 10,690 operating hours for the boom cylinder, 17,555 hours for the turbocharger, 8,618 hours for the water pump, 19,643 hours for the final drive, and 19,664 hours for the radiator. Sensitivity analysis indicated that variations in maintenance cost and maintenance time influenced the optimal preventive replacement intervals, total maintenance cost, and equipment downtime. Among the evaluated variables, preventive replacement component cost was the most influential factor affecting total maintenance cost, with a sensitivity index of 0.5122. Therefore, controlling component replacement costs should be prioritized to optimize the maintenance costs associated with the critical components of the Komatsu PC2000-8 excavator at PT XYZ.

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