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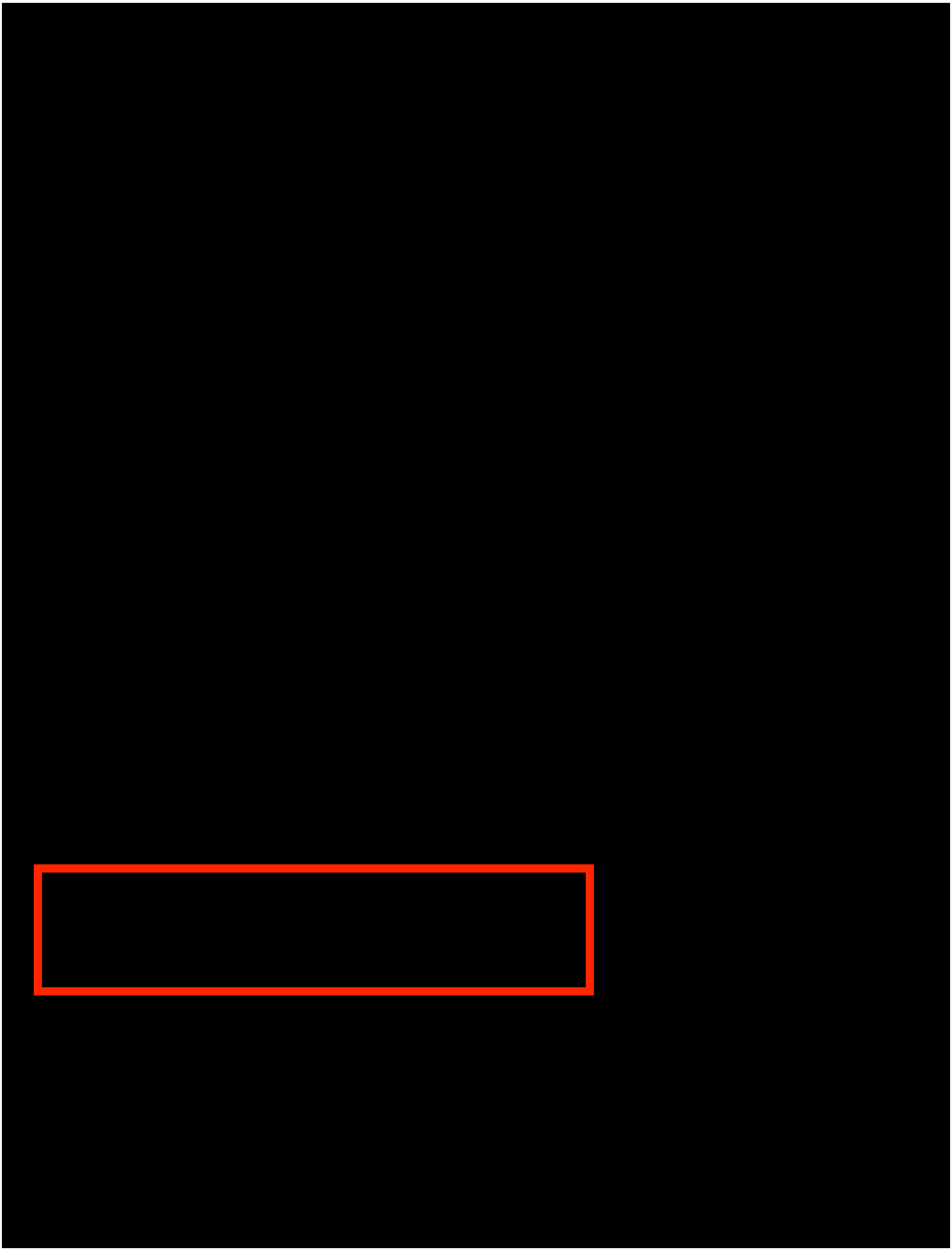

[Pengembangan Chatbot AI untuk Layanan Pelanggan PLN Menggunakan Algoritma Long Short Term Memory (LSTM)]

Universitas Negeri Gorontalo Jurnal Teknik Vol 23 No 1 (2025): Jurnal Teknik 59-75

2025 DOI: 10.37031/jt.v23i1.553 Accred : Sinta 3

[Analisis Dampak Lingkungan dan Sosial pada UMKM Menggunakan Metode Interpretive Structural Modeling]

Universitas Negeri Gorontalo Jurnal Teknik Vol 23 No 1 (2025): Jurnal Teknik 120-131

2025 DOI: 10.37031/jt.v23i1.558 Accred : Sinta 3

[Optimalisasi Kinerja Ruas Jalan Dengan Metode PKJI 2023 dan Aplikasi PTV Vissim]

Universitas Negeri Gorontalo Jurnal Teknik Vol 23 No 1 (2025): Jurnal Teknik 42-58

2025 DOI: 10.37031/jt.v23i1.607 Accred : Sinta 3

[Analisis Besaran Erosi dan Stabilitas Lereng dengan Perkuatan Soil Nailing]

Universitas Negeri Gorontalo Jurnal Teknik Vol 23 No 1 (2025): Jurnal Teknik 76-90

2025 DOI: 10.37031/jt.v23i1.614 Accred : Sinta 3

[Augmented Reality Sebagai Media Edukasi Pengenalan Anggota Keluarga Pada Anak: Studi Kasus Penggunaan Buku Interaktif]

Universitas Negeri Gorontalo Jurnal Teknik Vol 23 No 1 (2025): Jurnal Teknik 111-119

2025 DOI: 10.37031/jt.v23i1.622 Accred : Sinta 3

[Optimalisasi Kecepatan Kendaraan Angkutan Sampah di Kota Manado]

Universitas Negeri Gorontalo Jurnal Teknik Vol 23 No 1 (2025): Jurnal Teknik 91-102

2025 DOI: 10.37031/jt.v23i1.625 Accred : Sinta 3

Previous 1 2 3 4 5 Next

Page 2 of 13 | Total Records 123

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Analisis Keselamatan dan Kesehatan K Bidang Freight Forwader Menggunakan Metode HIRADC
Views: 32

Analisis Beban Kerja dan Jumlah Pekerj

Menggunakan Metode Workload Analys (Studi Kasus: PT. Metal Stamping)
Views: 31

KEYWORDS

INFORMATION

For Readers

For Authors

For Librarians

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Analysis of Preventive Maintenance on Heavy Dump Suspension Using Reliability-Centered Maintenance Method

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Abstrak

Sistem suspensi pada kendaraan Heavy Dump (HD) memegang peran krusial dalam menjaga stabilitas, kenyamanan, dan keandalan kendaraan saat digunakan di lingkungan berat. Pada kendaraan HD menerapkan suspensi hidrolik-pneumatik yang menggunakan gas nitrogen dan minyak untuk mengatasi beban dan getaran dari jalan. Suspensi penting untuk menjaga komponen kendaraan dan melindungi muatan, terutama saat melintasi jalur rusak atau bergelombang dengan kecepatan tinggi. Tujuan penelitian ini adalah untuk mengoptimalkan perencanaan *preventive maintenance* menggunakan metode *Reliability-Centered Maintenance* (RCM) serta menentukan kegiatan preventive dari sistem suspensi untuk mengurangi *breakdown*. Dalam merancang pemeliharaan preventif yang efektif, pendekatan RCM bersama dengan metode terkait seperti *Failure Modes and Effect Analysis* (FMEA) digunakan untuk mengidentifikasi mesin-mesin kritis sebagai fokus analisis. Selain itu, pendekatan distribusi statistika digunakan untuk menentukan interval kegiatan pemeliharaan yang optimal. Berdasarkan hasil analisis diperoleh bahwa data mengikuti distribusi lognormal di mana pengoptimalan preventive maintenance pada komponen suspensi yaitu setiap interval waktu 370 jam setiap mesin bekerja. Dengan dilakukan perubahan interval waktu, nilai reliabilitas sebelum dan sesudah pemeliharaan preventif meningkat dari 34.09% menjadi 93.60%. Kegiatan *preventive maintenance* dengan interval waktu 370 jam untuk mengurangi *unscheduled breakdown* berupa *adjusting* pada komponen suspensi.

Kata kunci: Downtime, FMEA, Pemeliharaan Preventif, RCM, Suspensi

Abstract

The suspension system on Heavy Dump (HD) vehicles is crucial in maintaining stability, comfort, and reliability when used in harsh environments. HD vehicles have a hydraulic-pneumatic suspension that uses nitrogen gas and oil to overcome the load and vibrations from the road. The suspension maintains vehicle components and protects the load, especially when crossing damaged or bumpy roads at high speed. This study aims to optimize preventive maintenance planning using the Reliability-Centered Maintenance (RCM) method and determine the suspension system's preventive activities to reduce breakdowns. In designing effective preventive maintenance, the RCM approach and related methods, such as FMEA, are used to identify critical machines as the focus of analysis. In addition, a statistical distribution approach is used to determine the optimal maintenance activity interval. Based on the analysis results, it was obtained that the data follows a lognormal distribution where the optimization of preventive maintenance on the suspension component is every 370-hour time interval for each machine working. Changing the time interval increased the reliability value from 34.09% to 93.60% before and after preventive maintenance. Preventive maintenance activities with a time interval of 370 hours to reduce unscheduled breakdowns in the form of adjusting suspension components

***Keywords**: Downtime, FMEA, Preventive Maintenance, RCM, Suspension*

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Introduction

Heavy equipment contracting companies play crucial roles in the mining industry by providing heavy equipment for excavation and material transportation, as well as planning and maintaining such equipment. The productivity and effectiveness of a company are parameters for measuring the company's success. To create and develop the effectiveness of work tools, you need a strategy to maintain, improve, and even increase the performance of the tools in the company. The contractor's work focuses more on activities on how to move coal cover material starting from the land clearing process, topsoil removal, overburden material removal, and coal transportation, to backfilling the area to the reclamation process (Sastradi & Dwi Putranta, 2023).

Decreased equipment efficiency can be influenced by downtime. The downtime factor causes a machine to not work optimally in a certain period. Reliability is the possibility of a machine working optimally at a particular time (Sajaradj et al., 2019). When a machine experiences unproductive performance, it will cause downtime, resulting in the production process being hampered (Frediansyah & Faritsy, 2023). Therefore, every heavy equipment contracting company in the mining world must develop a strategy to determine how maintenance must be carried out so that each machine works as effectively as possible.

The Heavy Dump (HD) truck suspension parts have the most downtime due to heavy loads, rough terrain, and poor maintenance. This research will focus on the suspension system, as the Komatsu 465 HD truck is not performing efficiently. To reduce downtime, we should improve preventive maintenance scheduling. According to (da Silva et al., 2023), the Reliability Centered Maintenance (RCM) method enables companies to develop maintenance plans that ensure asset reliability by assessing and prioritizing the risks related to potential functional failures. The researchers illustrate their proposed method using a case study of a hydroelectric power plant. Researchers demonstrate the ability of RCM to assist in developing and implementing reliability, risk, and cost-oriented maintenance plans. Furthermore, (Patil et al., 2022) researched the development of maintenance programs for steam boiler systems. This research identified the steam boiler system through Failure Modes and Effects Analysis (FMEA) of each component. Establishing a scheduled maintenance strategy and intervals is advised to ensure the system operates effectively. Applying the RCM method has proven to enhance the reliability and availability of the steam boiler system by 28.15%. Furthermore, by implementing a scheduled maintenance program guided by the FMEA method, annual maintenance costs can be reduced by as much as 20.32% (Patil & Bewoor, 2022).

The RCM method is closely related to FMEA. Both methods focus on identifying potential failures. The results of FMEA can be used as input in determining appropriate maintenance actions in RCM. Both methods aim to increase the system's reliability (Subriadi & Najwa, 2020). RCM does this through appropriate maintenance strategies, while FMEA does this through identifying failure risks. In addition, according to (Cahyono & Dwie Nurcahyanie, 2023) regarding risk identification and evaluation in logistics operations at PT. XYZ shows that there are 19 operational risks in the logistics section, with RPN values varying from the smallest value (12) to the largest value (729). Thus, the three highest operational risks were found to hamper work in the logistics section. The FMEA method is quite effective in determining the level of damage or defects in PT. XYZ logistics department.

Moreover, in this research, LTA will also be used to identify, analyze, and visualize the cause-and-effect relationships of various factors that can influence failure in a system (Hidayah, 2023). A study conducted by Prihananto using the FMEA and LTA methods revealed that improvements are needed in installing slew-bearing bolts due to a relatively high-Risk Priority Number (RPN) of over 125. Several recommendations were made to address this issue, including using a manipulator's arm with the torque tool and implementing a Manufacturing Execution System (MES). These changes can effectively reduce the RPN from above 125 to 28, indicating a significant improvement in the process (Prihananto & Sahroni, 2023).

Previous research on RCM-based preventive maintenance has been widely applied to mechanical systems such as turbines, boilers, or manufacturing systems. However, there is limited research specifically addressing the application of RCM to Heavy Dump (HD) suspension systems. Most studies tend to focus on powertrain or drivetrain systems. This study fills the gap in the study of reliability-based maintenance on the Heavy Dump suspension system, which has not been widely discussed in previous studies. We propose an innovative approach that combines RCM, Failure Mode and Effects Analysis (FMEA), and statistical distribution analysis, offering a more optimal solution than traditional maintenance methods. Therefore, our study aims to optimize preventive maintenance planning on critical components using the RCM method, compares reliability values before and after the analysis of preventive maintenance activities, and determines preventive activities of the suspension system on the HD unit to reduce breakdowns. Apart from that, FMEA will also function as an identifier for potential failure of components with critical status. Therefore, the goal is to reduce downtime, increase machine productivity, and decrease maintenance costs, ultimately positively impacting PT. XYZ.

Method

In this study, we are using the reliability-centered maintenance (RCM) approach, which aims to improve equipment reliability and maintainability. RCM is a crucial and highly effective method for evaluating and optimizing the maintenance requirements of plants and equipment while they are in operation.

The initial step in conducting an RCM analysis [CSN EN 60300-3-11] is to establish the necessity and extent of the investigation. Based on the data available in the maintenance management system, system/subsystem areas, such as spare parts or machine tools, are determined. In the second step, failures are analyzed based on operational data and test data obtained. The failure in question can be seen from the lack of functionality in components, monitoring the effectiveness of maintenance, and the performance of safety, operational, and economic objectives. The final step is implementation; the output is creating a maintenance program. Details about maintenance tasks will be expanded, such as information about processes and time performance, safety instructions, and spare parts at each maintenance point. The result of the analysis can be a large number of tasks with different frequencies (Opocenska & Hammer, 2016). This process involves using tools such as FMEA, which evaluates three parameters: severity (S), occurrence (O), and detection probability (D) (Wicaksono et al., 2023). The resulting Risk Priority Number (RPN) is used to prioritize the risks associated with a component. Additionally, a fishbone diagram illustrates the six major causes of problems: machine malfunction, procedures, materials, measurement processes, human resources, and environmental concerns (Neyestani, 2017).

The next step is to establish preventive maintenance procedures using the RCM Decision Worksheet. This worksheet determines preventive maintenance schedules based on specific time intervals calculated through a statistical analysis of data distribution. Begin by analyzing the downtime data for components by estimating the Time to Failure (TTF) and Time to Repair (TTR) for critical components. Then, process the Index of Fit data for TTF and TTR using distribution methods such as Weibull, exponential, lognormal, and normal distributions.

The lognormal distribution has significant applications in various fields, including economics, biology, and reliability engineering. It is a continuous probability distribution where the logarithm of the random variable follows a normal distribution. This distribution is often used to describe phenomena such as fatigue failure, failure rates, and other situations that involve a wide range of data (Maymon, 2018; Wang & Gui, 2020). The density function of the lognormal distribution is represented as (1), and the cumulative distribution function is expressed as (2).

$$f(t) = \frac{1}{t.s\sqrt{2\pi}} \exp\{-\frac{1}{2s^2}[In\frac{t}{t_{med}}]^2\} \quad (1)$$

$$F(t) = \emptyset\,(\frac{In(t)-\mu}{\sigma}) \quad (2)$$

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

To calculate the distribution results, use the largest fit value index to obtain a number applicable for Mean Time to Failure (MTTF) and Mean Time to Repair (MTTR) calculations. Once the values are determined, verify their goodness of fit using Minitab software. MTTF represents the average time until damage occurs. It measures the operational period of a component from the moment it is first used or activated until it becomes damaged. The calculation of MTTF varies depending on the type of damage distribution and each instance of damage data. On the other hand, MTTR indicates the average time required to repair a broken component. MTTR influences system availability by minimizing downtime; a lower MTTR means faster repairs and recovery (Fischer et al., 2012).

Data Collection

During our investigation, we analyzed the downtime data of components from January 1, 2022, to October 31, 2023. Our specific focus was on suspension. We identified the critical components for our research based on various characteristics. One crucial factor we considered was the component that experienced the most extended downtime due to unscheduled breakdowns. This was particularly important as it significantly impacted the plant's operations, highlighting the need for increased attention to this component.

The component with the highest damage frequency is a critical factor to consider. This implies the necessity for an examination to establish the most common sources of damage and to pay special attention to the equipment. Using SAP's historical data on equipment damage, we identified one component that required the aforesaid parameter. One component was chosen as the main object of research. The suspension contributed 1541 minutes of duration, and 21 failures occurred.

Results and Discussion

Results

This stage involves analyzing which probable failures occur more frequently in each of the previously designated essential components. FMEA calculates the RPN

(SxOxD), which includes severity, occurrence, and detection when determining the possible failure. The following explains the component failure modes based on the highest RPN value for each component. The suspension has the second greatest RPN (224), indicating that it is the most common cause of failure.

Root Cause Analysis

The root cause analysis stage determines the causes of failure in the component. A fishbone diagram is used to identify the source of failure. The fishbone diagram below shows the component's failure causes, as shown in Figure 1.

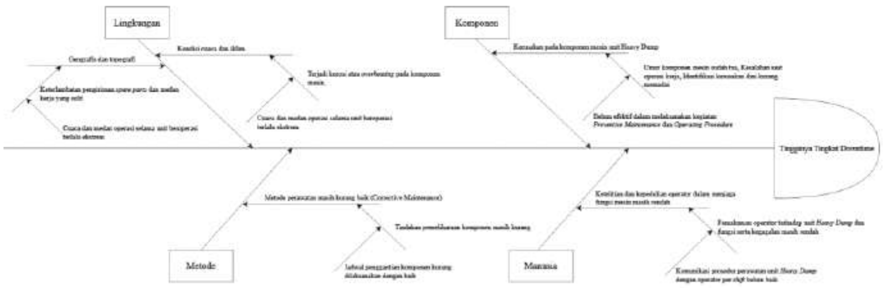

Figure 1. Fishbone Diagram for Suspension

RCM Worksheet and Distribution Identification

Based on the preceding study, deciding what steps will be made to limit the risk of damage is vital. The RCM Decision Worksheet, as previously mentioned, is used to determine actions that can be taken to address the causes of component damage to each piece of equipment. According to the RCM Decision Worksheet, the proposed task for the suspension is to load distribution and stability, absorb shock, increase traction and control, and improve operator safety.

The TTF (Time to Failure) and TTR (Time to Repair) data from the suspension will be analyzed using Minitab software to identify the most appropriate distribution. We will examine four distributions: Weibull, Exponential, Lognormal, and Normal. Figure 2 presents the TTF and TTR data's Anderson-Darling values and correlation coefficients.

Figure 2 shows that the lognormal distribution exhibited the highest correlation coefficient for the Time to Failure (TTF) data across all three pieces of equipment. Furthermore, the lognormal distribution recorded the lowest Anderson-Darling value. Based on these findings, the lognormal distribution is determined to be the best fit for the instruments' TTF data.

Distribution	Anderson-Darling (adj)	Correlation Coefficient
Weibull	1,398	0,961
Lognormal	0,766	0,993
Exponential	2,606	*
Normal	3,371	0,792

Distribution	Anderson-Darling (adj)	Correlation Coefficient
Weibull	1,208	0,963
Lognormal	1,080	0,975
Exponential	3,210	*
Normal	1,150	0,963

Figure 2. Index of Fit of TTF and TTR Data

The next step in identifying the distribution is to perform a goodness of fit test to ensure that the distribution determined by the index of fit is appropriate for use in the analysis. The goodness-of-fit test hypothesis is as follows:

H_0: The data follows the lognormal distribution.

H_1: The data does not follow the lognormal distribution.

The goodness of fit results in Figure 3 show that the most significant p-value and the smallest AD value are in the lognormal distribution. In addition, the p-value (0.0393) < α (0.05); therefore, the TTR suspension data analysis uses the smallest Anderson Darling (AD) value of the four distributions, namely 0.765 because the smaller the value of the Anderson Darling statistic, the closer the data follows the distribution. Based on the goodness of fit results, the lognormal distribution is the most suitable fit distribution, so the lognormal distribution was selected for further analysis.

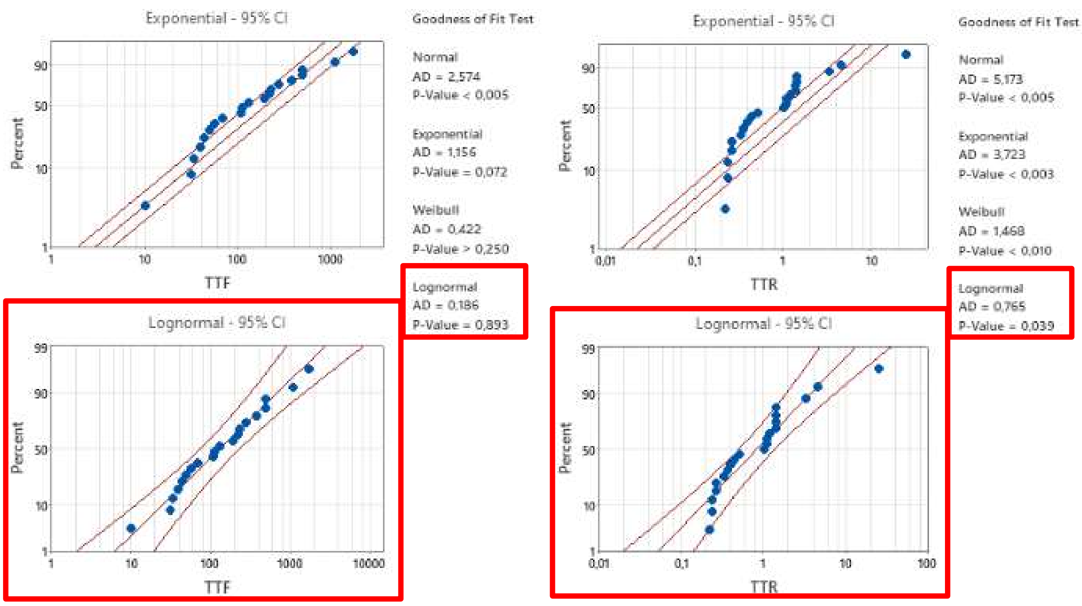

Figure 3. Goodness of Fit Test for Suspension TTF and TTR Data

Therefore, the MTTF and MTTR calculations will be conducted according to the lognormal distribution rule. To calculate the MTTF and MTTR, specific parameters must be determined by processing the data as follows:

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

$$\bar{t} = \sum_{i=1}^{n} \frac{In(ti)}{n}$$

$$= \frac{178,31}{20} = 8,92$$

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

$$= 7480,09$$

$$s = \sqrt{\frac{\sum_{i=1}^{n}(In\, t_i - \bar{t})^2}{n}}$$

$$= \sqrt{\frac{33,87}{20}} = 1,30$$

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

$$= 7480,09 \times e^{\frac{1,30^2}{2}}$$

$$= 17413,48\, menit = 290,22\, jam$$

Determination of Preventive Maintenance Interval

The determination of preventive maintenance intervals with checking activities for suspension first by calculating the average working hours in a month. Working hours in a month are 30 days, and working hours in a day are 20 hours, so the average working hours in a month are 30 days × 20 hours = 600 hours.

1. Failure frequency

Failure frequency in a period (10 months on 2023) = 21 times. Hence, average repair time:

$$\frac{1}{\mu} = \frac{MTTR}{\text{working hour average in a month}} = \frac{1,06}{600} = 0,002$$

$$\mu = \frac{1}{1/\mu} = 500\, minutes$$

2. Average check time

Duration for check activity t_i

$$\frac{1}{\mathrm{i}} = \frac{ti}{t} = \frac{average\ 1\ time\ checking}{\text{working hour average in a month}} = \frac{1}{600} = 0,0016$$

$$i = 625\, minutes$$

3. Average of failure and optimum check frequency

$$\mathrm{k} = \frac{failure\ frequency}{total\ of\ period} = \frac{21}{10} = 2,1$$

$$\mathrm{n} = \sqrt{\frac{k\ x\ i}{\mu}} = \sqrt{\frac{2,1 \times 625}{500}} = 1,62$$

4. Check activity interval

$$\frac{t}{\mathrm{n}} = \frac{average\ working\ hours}{n} = \frac{600}{1,62} = 370,37\, hours$$

Hence, the preventive maintenance interval for check activity is 370 hours or 15 days.

Discussions

Schedule Activity of Preventive Maintenance

Preventive Maintenance (PM) is included in maintenance that has been organized and implemented according to schedule. The benefits of PM activities are that the tools can work effectively and efficiently, minimize sudden damage, make the life of the tools more optimal, and guarantee the safety of the tools. PM activities include several things, such as checking, adjusting, lubricating, replacing, and testing. Before carrying out PM activities, it is also necessary to consider safety factors, divided into general precautions, preparations for work, and precautions during work.

The next step from the previous checking interval calculation is determining Preventive Maintenance (PM) activities with a time interval of every 370 working hours on the unit. When doing PM, mechanics have 5 work zones in 1 HD unit. The suspension is in work zone 1 (Left front suspension), work zone 3 (Right front suspension), and work zone 5 (Left and right rear suspension). The following are preventive maintenance activities with 500 hours of service optimized to 370 hours, as calculated from HM (Hour Meter).

1. Check suspension cylinder length and oil level (adjusting)
   When the engine runs, the uneven road surface can directly impact the chassis and differential, possibly causing the unit to float or the cylinder to hit the stopper.
2. When the unit is empty, make sure the bottom of the suspension cylinder cover is between the distance (A) indicated by the arrow on the sticker and a flat ground surface (see Figure 4).

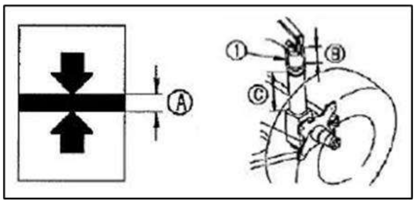

Figure 4. Check Length of the Front Suspension Cylinder

In addition, when the unit is empty, open cover (1) and measure the length (B) from the head of the suspension cylinder shoulder rod to the top surface of the flange. For standardization of front suspension cylinder length, see Table 1.

Table 1. Standard Length of Front Suspension Cylinder

(B)	237 to 257 mm (9.3 to 10.1 in)
Reference (C)	562 to 582 mm (22.1 to 22.9 in)

3. For Rear Suspension, as seen in Figure 5, measure the length (E) from the shoulder rod of the head suspension cylinder to the top surface of the flange. For standardization of rear suspension cylinder length is from 189 to 209 mm.

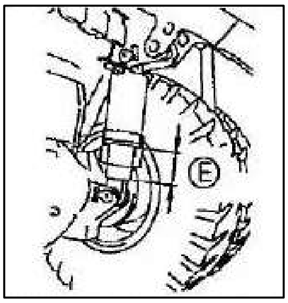

Figure 5. Check Length of Rear Suspension Cylinder

4. If suspension adjustments are needed, refer to the procedure in Table 2. The purpose of requiring preventive maintenance adjusting every 370 hours is to improve operator safety and comfort by reducing vibrations and shocks to the unit, increasing stability and control of the heavy equipment so that operations are more efficient, and reducing damage to mechanical components or the heavy equipment frame by effectively absorbing energy and shaking.

Table 2. Adjusting of Front and Rear Suspension Cylinder

Activity	Procedure	Tools
Adjust suspension level	1. Make sure there is no oil seepage in the suspension area. 2. Adjust the suspension with nitrogen gas and oil. 3. Open the cover on the suspension. 4. Loosen the bolt on the left valve core. 5. Install the nitrogen hose. 6. Set the nitrogen pressure to around ± 60 psi. 7. Make sure the nitrogen level matches the line level. 8. Make sure the valve core does not leak. 9. Reinstall the suspension cover	• Cartridge wrench • Double open-end wrench 24-26 mm • Double open-end wrench 16-17 mm • Double open-end wrench 14-15 mm • Sliding T-Handle ¾ • Ruler

Reliability Before and After Preventive Maintenance

Table 3. Reliability Before and After Preventive Maintenance

Reliability Before Preventive Maintenance	Reliability After Preventive Maintenance
- $T_{med} = \mu = 7480{,}09$	- $T_{med} = \mu = 7480{,}09$
- $\phi =$ Lognormal distribution value	- $\phi =$ Lognormal distribution value
- $t = \text{MTTF} = 17662{,}52$	- $R(T)^n = 1 - \phi\,(\frac{1}{2}\,In\frac{t}{\mu})^n$
- $R(t) = 1 - \phi\,(\frac{1}{2} \times In\frac{t}{\mu})$	$R(T)^n = 1 - \phi\,(0{,}5\,In\frac{370{,}37}{7480{,}09})^0$
$R(t) = 1 - \phi\left(0{,}5\,In\frac{17662{,}52}{7480{,}09}\right) = 33{,}35\%$	

$$R(t - nT) = 1 - \phi\,(\frac{1}{2} In \frac{t-nT}{\mu})$$

$$R(t - nT) = 1 - \phi\,(\frac{1}{2} In \frac{370{,}37-0 \times 370{,}37}{7480{,}09})$$

$$R(t - nT) = 1 - \phi\,(-1{,}50)$$

$$R(t - nT) = 0{,}933 = 93{,}3\%$$

To evaluate the effectiveness of preventive maintenance implementation, we can compare the reliability values of the component before and after the maintenance. As shown in Table 3, the reliability percentage increased significantly, rising from 33.35% before the preventive maintenance to 93.3% afterward, with the study focusing solely on data from suspension components of heavy equipment. The results are consistent with the assertion that the reliability function effectively demonstrates the enhancements achieved in machinery before and after maintenance activities. This assessment reflects the machine's reliability after the completion of preventive maintenance. Such maintenance contributes to increased reliability, resulting from the improvements made during the process. Thus, preventive maintenance is vital in enhancing machine reliability and extending the intervals between operational failures. This aligns with previous research indicating that the RCM method enhances reliability both before and after the implementation of a preventive maintenance program. Furthermore, by adopting preventive maintenance, the potential cost savings can be improved compared to the period before optimization (Cahyati et al., 2024).

Conclusions

Based on the analysis that has been carried out, several things can be concluded, including:

1. The FMEA method analysis showed that the suspension component had the second-highest value, 224.
2. Based on the selected distribution, the lognormal distribution with the largest P-value and the smallest Anderson Darling value, it was found that optimizing preventive maintenance of suspension components should be done every 370-hour time interval for each machine working.
3. By making changes to the time interval for carrying out preventive maintenance, it shows that the reliability value has increased to 93.3% from previously 33.35%, with the study focusing solely on data from suspension components of heavy equipment.

4. Our preventive maintenance activities, with a 370-hour time interval, have significantly reduced unscheduled breakdowns. In addition, the maintenance strategy enhances the reliability of the suspension system. It significantly improves work safety by minimizing the risk of suspension failures that could lead to accidents on rough terrain. Adhering to optimal maintenance intervals allows operators to work more safely, and vehicles can achieve greater stability in extreme operating conditions.
5. Further analysis is needed to identify the causes of frequent downtime and restore machine performance linked to the production process. This research can improve reliability and reduce the risk of failure in critical equipment.

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Analysis of Preventive Maintenance on Heavy Dump Suspension Using Reliability-Centered Maintenance Method

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Analysis of Preventive Maintenance on Heavy Dump Suspension Using Reliability-Centered Maintenance Method

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Abstrak

Sistem suspensi pada kendaraan Heavy Dump (HD) memegang peran krusial dalam menjaga stabilitas, kenyamanan, dan keandalan kendaraan saat digunakan di lingkungan berat. Pada kendaraan HD menerapkan suspensi hidrolik-pneumatik yang menggunakan gas nitrogen dan minyak untuk mengatasi beban dan getaran dari jalan. Suspensi penting untuk menjaga komponen kendaraan dan melindungi muatan, terutama saat melintasi jalur rusak atau bergelombang dengan kecepatan tinggi. Tujuan penelitian ini adalah untuk mengoptimalkan perencanaan *preventive maintenance* menggunakan metode *Reliability-Centered Maintenance* (RCM) serta menentukan kegiatan preventive dari sistem suspensi untuk mengurangi *breakdown*. Dalam merancang pemeliharaan preventif yang efektif, pendekatan RCM bersama dengan metode terkait seperti *Failure Modes and Effect Analysis* (FMEA) digunakan untuk mengidentifikasi mesin-mesin kritis sebagai fokus analisis. Selain itu, pendekatan distribusi statistika digunakan untuk menentukan interval kegiatan pemeliharaan yang optimal. Berdasarkan hasil analisis diperoleh bahwa data mengikuti distribusi lognormal di mana pengoptimalan preventive maintenance pada komponen suspensi yaitu setiap interval waktu 370 jam setiap mesin bekerja. Dengan dilakukan perubahan interval waktu, nilai reliabilitas sebelum dan sesudah pemeliharaan preventif meningkat dari 34.09% menjadi 93.60%. Kegiatan *preventive maintenance* dengan interval waktu 370 jam untuk mengurangi *unscheduled breakdown* berupa *adjusting* pada komponen suspensi.

Kata kunci: Downtime, FMEA, Pemeliharaan Preventif, RCM, Suspensi

Abstract

The suspension system on Heavy Dump (HD) vehicles is crucial in maintaining stability, comfort, and reliability when used in harsh environments. HD vehicles have a hydraulic-pneumatic suspension that uses nitrogen gas and oil to overcome the load and vibrations from the road. The suspension maintains vehicle components and protects the load, especially when crossing damaged or bumpy roads at high speed. This study aims to optimize preventive maintenance planning using the Reliability-Centered Maintenance (RCM) method and determine the suspension system's preventive activities to reduce breakdowns. In designing effective preventive maintenance, the RCM approach and related methods, such as FMEA, are used to identify critical machines as the focus of analysis. In addition, a statistical distribution approach is used to determine the optimal maintenance activity interval. Based on the analysis results, it was obtained that the data follows a lognormal distribution where the optimization of preventive maintenance on the suspension component is every 370-hour time interval for each machine working. Changing the time interval increased the reliability value from 34.09% to 93.60% before and after preventive maintenance. Preventive maintenance activities with a time interval of 370 hours to reduce unscheduled breakdowns in the form of adjusting suspension components

***Keywords**: Downtime, FMEA, Preventive Maintenance, RCM, Suspension*

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Introduction

Heavy equipment contracting companies play crucial roles in the mining industry by providing heavy equipment for excavation and material transportation, as well as planning and maintaining such equipment. The productivity and effectiveness of a company are parameters for measuring the company's success. To create and develop the effectiveness of work tools, you need a strategy to maintain, improve, and even increase the performance of the tools in the company. The contractor's work focuses more on activities on how to move coal cover material starting from the land clearing process, topsoil removal, overburden material removal, and coal transportation, to backfilling the area to the reclamation process (Sastradi & Dwi Putranta, 2023).

Decreased equipment efficiency can be influenced by downtime. The downtime factor causes a machine to not work optimally in a certain period. Reliability is the possibility of a machine working optimally at a particular time (Sajaradj et al., 2019). When a machine experiences unproductive performance, it will cause downtime, resulting in the production process being hampered (Frediansyah & Faritsy, 2023). Therefore, every heavy equipment contracting company in the mining world must develop a strategy to determine how maintenance must be carried out so that each machine works as effectively as possible.

The Heavy Dump (HD) truck suspension parts have the most downtime due to heavy loads, rough terrain, and poor maintenance. This research will focus on the suspension system, as the Komatsu 465 HD truck is not performing efficiently. To reduce downtime, we should improve preventive maintenance scheduling. According to (da Silva et al., 2023), the Reliability Centered Maintenance (RCM) method enables companies to develop maintenance plans that ensure asset reliability by assessing and prioritizing the risks related to potential functional failures. The researchers illustrate their proposed method using a case study of a hydroelectric power plant. Researchers demonstrate the ability of RCM to assist in developing and implementing reliability, risk, and cost-oriented maintenance plans. Furthermore, (Patil et al., 2022) researched the development of maintenance programs for steam boiler systems. This research identified the steam boiler system through Failure Modes and Effects Analysis (FMEA) of each component. Establishing a scheduled maintenance strategy and intervals is advised to ensure the system operates effectively. Applying the RCM method has proven to enhance the reliability and availability of the steam boiler system by 28.15%. Furthermore, by implementing a scheduled maintenance program guided by the FMEA method, annual maintenance costs can be reduced by as much as 20.32% (Patil & Bewoor, 2022).

The RCM method is closely related to FMEA. Both methods focus on identifying potential failures. The results of FMEA can be used as input in determining appropriate maintenance actions in RCM. Both methods aim to increase the system's reliability (Subriadi & Najwa, 2020). RCM does this through appropriate maintenance strategies, while FMEA does this through identifying failure risks. In addition, according to (Cahyono & Dwie Nurcahyanie, 2023) regarding risk identification and evaluation in logistics operations at PT. XYZ shows that there are 19 operational risks in the logistics section, with RPN values varying from the smallest value (12) to the largest value (729). Thus, the three highest operational risks were found to hamper work in the logistics section. The FMEA method is quite effective in determining the level of damage or defects in PT. XYZ logistics department.

Moreover, in this research, LTA will also be used to identify, analyze, and visualize the cause-and-effect relationships of various factors that can influence failure in a system (Hidayah, 2023). A study conducted by Prihananto using the FMEA and LTA methods revealed that improvements are needed in installing slew-bearing bolts due to a relatively high-Risk Priority Number (RPN) of over 125. Several recommendations were made to address this issue, including using a manipulator's arm with the torque tool and implementing a Manufacturing Execution System (MES). These changes can effectively reduce the RPN from above 125 to 28, indicating a significant improvement in the process (Prihananto & Sahroni, 2023).

Previous research on RCM-based preventive maintenance has been widely applied to mechanical systems such as turbines, boilers, or manufacturing systems. However, there is limited research specifically addressing the application of RCM to Heavy Dump (HD) suspension systems. Most studies tend to focus on powertrain or drivetrain systems. This study fills the gap in the study of reliability-based maintenance on the Heavy Dump suspension system, which has not been widely discussed in previous studies. We propose an innovative approach that combines RCM, Failure Mode and Effects Analysis (FMEA), and statistical distribution analysis, offering a more optimal solution than traditional maintenance methods. Therefore, our study aims to optimize preventive maintenance planning on critical components using the RCM method, compares reliability values before and after the analysis of preventive maintenance activities, and determines preventive activities of the suspension system on the HD unit to reduce breakdowns. Apart from that, FMEA will also function as an identifier for potential failure of components with critical status. Therefore, the goal is to reduce downtime, increase machine productivity, and decrease maintenance costs, ultimately positively impacting PT. XYZ.

Method

In this study, we are using the reliability-centered maintenance (RCM) approach, which aims to improve equipment reliability and maintainability. RCM is a crucial and highly effective method for evaluating and optimizing the maintenance requirements of plants and equipment while they are in operation.

The initial step in conducting an RCM analysis [CSN EN 60300-3-11] is to establish the necessity and extent of the investigation. Based on the data available in the maintenance management system, system/subsystem areas, such as spare parts or machine tools, are determined. In the second step, failures are analyzed based on operational data and test data obtained. The failure in question can be seen from the lack of functionality in components, monitoring the effectiveness of maintenance, and the performance of safety, operational, and economic objectives. The final step is implementation; the output is creating a maintenance program. Details about maintenance tasks will be expanded, such as information about processes and time performance, safety instructions, and spare parts at each maintenance point. The result of the analysis can be a large number of tasks with different frequencies (Opocenska & Hammer, 2016). This process involves using tools such as FMEA, which evaluates three parameters: severity (S), occurrence (O), and detection probability (D) (Wicaksono et al., 2023). The resulting Risk Priority Number (RPN) is used to prioritize the risks associated with a component. Additionally, a fishbone diagram illustrates the six major causes of problems: machine malfunction, procedures, materials, measurement processes, human resources, and environmental concerns (Neyestani, 2017).

The next step is to establish preventive maintenance procedures using the RCM Decision Worksheet. This worksheet determines preventive maintenance schedules based on specific time intervals calculated through a statistical analysis of data distribution. Begin by analyzing the downtime data for components by estimating the Time to Failure (TTF) and Time to Repair (TTR) for critical components. Then, process the Index of Fit data for TTF and TTR using distribution methods such as Weibull, exponential, lognormal, and normal distributions.

The lognormal distribution has significant applications in various fields, including economics, biology, and reliability engineering. It is a continuous probability distribution where the logarithm of the random variable follows a normal distribution. This distribution is often used to describe phenomena such as fatigue failure, failure rates, and other situations that involve a wide range of data (Maymon, 2018; Wang & Gui, 2020). The density function of the lognormal distribution is represented as (1), and the cumulative distribution function is expressed as (2).

$$f(t) = \frac{1}{t.s\sqrt{2\pi}} \exp\{-\frac{1}{2s^2}[In \frac{t}{t_{med}}]^2\} \quad (1)$$

$$F(t) = \emptyset\left(\frac{ln(t)-\mu}{\sigma}\right) \quad (2)$$

where Φ is the cumulative distribution function of the normal distribution.

To calculate the distribution results, use the largest fit value index to obtain a number applicable for Mean Time to Failure (MTTF) and Mean Time to Repair (MTTR) calculations. Once the values are determined, verify their goodness of fit using Minitab software. MTTF represents the average time until damage occurs. It measures the operational period of a component from the moment it is first used or activated until it becomes damaged. The calculation of MTTF varies depending on the type of damage distribution and each instance of damage data. On the other hand, MTTR indicates the average time required to repair a broken component. MTTR influences system availability by minimizing downtime; a lower MTTR means faster repairs and recovery (Fischer et al., 2012).

Data Collection

During our investigation, we analyzed the downtime data of components from January 1, 2022, to October 31, 2023. Our specific focus was on suspension. We identified the critical components for our research based on various characteristics. One crucial factor we considered was the component that experienced the most extended downtime due to unscheduled breakdowns. This was particularly important as it significantly impacted the plant's operations, highlighting the need for increased attention to this component.

The component with the highest damage frequency is a critical factor to consider. This implies the necessity for an examination to establish the most common sources of damage and to pay special attention to the equipment. Using SAP's historical data on equipment damage, we identified one component that required the aforesaid parameter. One component was chosen as the main object of research. The suspension contributed 1541 minutes of duration, and 21 failures occurred.

Results and Discussion

Results

This stage involves analyzing which probable failures occur more frequently in each of the previously designated essential components. FMEA calculates the RPN

(SxOxD), which includes severity, occurrence, and detection when determining the possible failure. The following explains the component failure modes based on the highest RPN value for each component. The suspension has the second greatest RPN (224), indicating that it is the most common cause of failure.

Root Cause Analysis

The root cause analysis stage determines the causes of failure in the component. A fishbone diagram is used to identify the source of failure. The fishbone diagram below shows the component's failure causes, as shown in Figure 1.

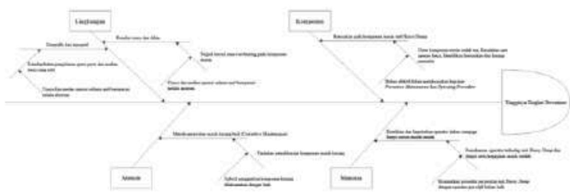

Figure 1. Fishbone Diagram for Suspension

RCM Worksheet and Distribution Identification

Based on the preceding study, deciding what steps will be made to limit the risk of damage is vital. The RCM Decision Worksheet, as previously mentioned, is used to determine actions that can be taken to address the causes of component damage to each piece of equipment. According to the RCM Decision Worksheet, the proposed task for the suspension is to load distribution and stability, absorb shock, increase traction and control, and improve operator safety.

The TTF (Time to Failure) and TTR (Time to Repair) data from the suspension will be analyzed using Minitab software to identify the most appropriate distribution. We will examine four distributions: Weibull, Exponential, Lognormal, and Normal. Figure 2 presents the TTF and TTR data's Anderson-Darling values and correlation coefficients.

Figure 2 shows that the lognormal distribution exhibited the highest correlation coefficient for the Time to Failure (TTF) data across all three pieces of equipment. Furthermore, the lognormal distribution recorded the lowest Anderson-Darling value. Based on these findings, the lognormal distribution is determined to be the best fit for the instruments' TTF data.

Goodness-of-Fit

Distribution	Anderson-Darling (adj)	Correlation Coefficient
Weibull	1,398	0,961
Lognormal	0,766	0,993
Exponential	2,606	*
Normal	3,371	0,792

Goodness-of-Fit

Distribution	Anderson-Darling (adj)	Correlation Coefficient
Weibull	1,208	0,963
Lognormal	1,080	0,975
Exponential	3,210	*
Normal	1,150	0,963

Figure 2. Index of Fit of TTF and TTR Data

The next step in identifying the distribution is to perform a goodness of fit test to ensure that the distribution determined by the index of fit is appropriate for use in the analysis. The goodness-of-fit test hypothesis is as follows:

H_0: The data follows the lognormal distribution.

H_1: The data does not follow the lognormal distribution.

The goodness of fit results in Figure 3 show that the most significant p-value and the smallest AD value are in the lognormal distribution. In addition, the p-value (0.0393) < α (0.05); therefore, the TTR suspension data analysis uses the smallest Anderson Darling (AD) value of the four distributions, namely 0.765 because the smaller the value of the Anderson Darling statistic, the closer the data follows the distribution. Based on the goodness of fit results, the lognormal distribution is the most suitable fit distribution, so the lognormal distribution was selected for further analysis.

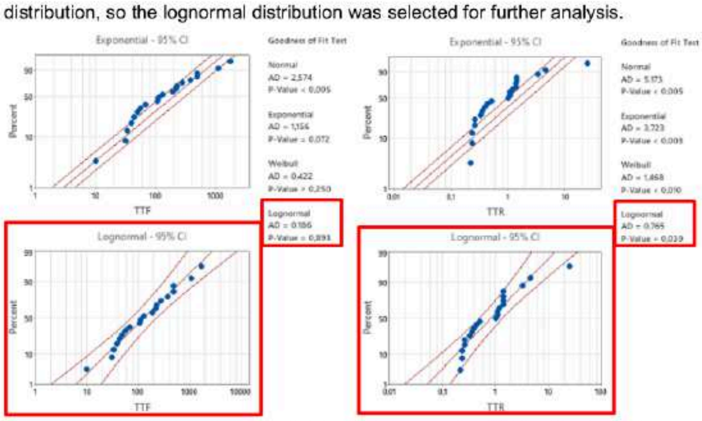

Figure 3. Goodness of Fit Test for Suspension TTF and TTR Data

Therefore, the MTTF and MTTR calculations will be conducted according to the lognormal distribution rule. To calculate the MTTF and MTTR, specific parameters must be determined by processing the data as follows:

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

$$\bar{t} = \sum_{i=1}^{n} \frac{In(ti)}{n}$$

$$= \frac{178{,}31}{20} = 8{,}92$$

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

$$= 7480{,}09$$

$$s = \sqrt{\frac{\sum_{i=1}^{n}(In\ t_i - \bar{t})^2}{n}}$$

$$= \sqrt{\frac{33{,}87}{20}} = 1{,}30$$

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

$$= 7480{,}09 \times e^{\frac{1{,}30^2}{2}}$$

$$= 17413{,}48\ menit = 290{,}22\ jam$$

Determination of Preventive Maintenance Interval

The determination of preventive maintenance intervals with checking activities for suspension first by calculating the average working hours in a month. Working hours in a month are 30 days, and working hours in a day are 20 hours, so the average working hours in a month are 30 days × 20 hours = 600 hours.

1. Failure frequency

Failure frequency in a period (10 months on 2023) = 21 times. Hence, average repair time:

$$\frac{1}{\mu} = \frac{MTTR}{\text{working hour average in a month}} = \frac{1{,}06}{600} = 0{,}002$$

$$\mu = \frac{1}{1/\mu} = 500\ minutes$$

2. Average check time

Duration for check activity t_i

$$\frac{1}{\mathrm{i}} = \frac{ti}{t} = \frac{average\ 1\ time\ checking}{\text{working hour average in a month}} = \frac{1}{600} = 0{,}0016$$

$$i = 625\ minutes$$

3. Average of failure and optimum check frequency

$$\mathrm{k} = \frac{failure\ frequency}{total\ of\ period} = \frac{21}{10} = 2{,}1$$

$$\mathrm{n} = \sqrt{\frac{k\ x\ i}{\mu}} = \sqrt{\frac{2{,}1 \times 625}{500}} = 1{,}62$$

4. Check activity interval

$$\frac{t}{\mathrm{n}} = \frac{average\ working\ hours}{n} = \frac{600}{1{,}62} = 370{,}37\ hours$$

Hence, the preventive maintenance interval for check activity is 370 hours or 15 days.

Discussions

Schedule Activity of Preventive Maintenance

Preventive Maintenance (PM) is included in maintenance that has been organized and implemented according to schedule. The benefits of PM activities are that the tools can work effectively and efficiently, minimize sudden damage, make the life of the tools more optimal, and guarantee the safety of the tools. PM activities include several things, such as checking, adjusting, lubricating, replacing, and testing. Before carrying out PM activities, it is also necessary to consider safety factors, divided into general precautions, preparations for work, and precautions during work.

The next step from the previous checking interval calculation is determining Preventive Maintenance (PM) activities with a time interval of every 370 working hours on the unit. When doing PM, mechanics have 5 work zones in 1 HD unit. The suspension is in work zone 1 (Left front suspension), work zone 3 (Right front suspension), and work zone 5 (Left and right rear suspension). The following are preventive maintenance activities with 500 hours of service optimized to 370 hours, as calculated from HM (Hour Meter).

1. Check suspension cylinder length and oil level (adjusting)
   When the engine runs, the uneven road surface can directly impact the chassis and differential, possibly causing the unit to float or the cylinder to hit the stopper.
2. When the unit is empty, make sure the bottom of the suspension cylinder cover is between the distance (A) indicated by the arrow on the sticker and a flat ground surface (see Figure 4).

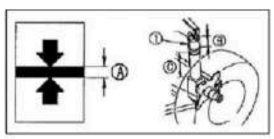

Figure 4. Check Length of the Front Suspension Cylinder

In addition, when the unit is empty, open cover (1) and measure the length (B) from the head of the suspension cylinder shoulder rod to the top surface of the flange. For standardization of front suspension cylinder length, see Table 1.

Table 1. Standard Length of Front Suspension Cylinder

(B)	237 to 257 mm (9.3 to 10.1 in)
Reference (C)	562 to 582 mm (22.1 to 22.9 in)

3. For Rear Suspension, as seen in Figure 5, measure the length (E) from the shoulder rod of the head suspension cylinder to the top surface of the flange. For standardization of rear suspension cylinder length is from 189 to 209 mm.

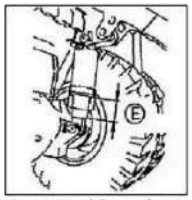

Figure 5. Check Length of Rear Suspension Cylinder

4. If suspension adjustments are needed, refer to the procedure in Table 2. The purpose of requiring preventive maintenance adjusting every 370 hours is to improve operator safety and comfort by reducing vibrations and shocks to the unit, increasing stability and control of the heavy equipment so that operations are more efficient, and reducing damage to mechanical components or the heavy equipment frame by effectively absorbing energy and shaking.

Table 2. Adjusting of Front and Rear Suspension Cylinder

Activity	Procedure	Tools
Adjust suspension level	1. Make sure there is no oil seepage in the suspension area. 2. Adjust the suspension with nitrogen gas and oil. 3. Open the cover on the suspension. 4. Loosen the bolt on the left valve core. 5. Install the nitrogen hose. 6. Set the nitrogen pressure to around ± 60 psi. 7. Make sure the nitrogen level matches the line level. 8. Make sure the valve core does not leak. 9. Reinstall the suspension cover	• Cartridge wrench • Double open-end wrench 24-26 mm • Double open-end wrench 16-17 mm • Double open-end wrench 14-15 mm • Sliding T-Handle ¾ • Ruler

Reliability Before and After Preventive Maintenance

Table 3. Reliability Before and After Preventive Maintenance

Reliability Before Preventive Maintenance	Reliability After Preventive Maintenance
- $T_{med} = \mu = 7480{,}09$	- $T_{med} = \mu = 7480{,}09$
- $\phi =$ Lognormal distribution value	- $\phi =$ Lognormal distribution value
- $t =$ MTTF $= 17662{,}52$	- $R(T)^n = 1 - \phi\,(\frac{1}{2}\,In\,\frac{t}{\mu})^n$
- $R(t) = 1 - \phi\,(\frac{1}{2} \times In\,\frac{t}{\mu})$	$R(T)^n = 1 - \phi\,(0{,}5\,In\,\frac{370{,}37}{7480{,}09})^0$
$R(t) = 1 - \phi\,\left(0{,}5\,In\,\frac{17662{,}52}{7480{,}09}\right) = 33{,}35\%$	

$$R(t-nT) = 1 - \phi\,(\tfrac{1}{2} ln \tfrac{t-nT}{\mu})$$

$$R(t-nT) = 1 - \phi\,(\tfrac{1}{2} ln \tfrac{370{,}37-0\times370{,}37}{7480{,}09})$$

$$R(t-nT) = 1 - \phi\,(-1{,}50)$$

$$R(t-nT) = 0{,}933 = 93{,}3\%$$

To evaluate the effectiveness of preventive maintenance implementation, we can compare the reliability values of the component before and after the maintenance. As shown in Table 3, the reliability percentage increased significantly, rising from 33.35% before the preventive maintenance to 93.3% afterward, with the study focusing solely on data from suspension components of heavy equipment. The results are consistent with the assertion that the reliability function effectively demonstrates the enhancements achieved in machinery before and after maintenance activities. This assessment reflects the machine's reliability after the completion of preventive maintenance. Such maintenance contributes to increased reliability, resulting from the improvements made during the process. Thus, preventive maintenance is vital in enhancing machine reliability and extending the intervals between operational failures. This aligns with previous research indicating that the RCM method enhances reliability both before and after the implementation of a preventive maintenance program. Furthermore, by adopting preventive maintenance, the potential cost savings can be improved compared to the period before optimization (Cahyati et al., 2024).

Conclusions

Based on the analysis that has been carried out, several things can be concluded, including:

1. The FMEA method analysis showed that the suspension component had the second-highest value, 224.
2. Based on the selected distribution, the lognormal distribution with the largest P-value and the smallest Anderson Darling value, it was found that optimizing preventive maintenance of suspension components should be done every 370-hour time interval for each machine working.
3. By making changes to the time interval for carrying out preventive maintenance, it shows that the reliability value has increased to 93.3% from previously 33.35%, with the study focusing solely on data from suspension components of heavy equipment.

4. Our preventive maintenance activities, with a 370-hour time interval, have significantly reduced unscheduled breakdowns. In addition, the maintenance strategy enhances the reliability of the suspension system. It significantly improves work safety by minimizing the risk of suspension failures that could lead to accidents on rough terrain. Adhering to optimal maintenance intervals allows operators to work more safely, and vehicles can achieve greater stability in extreme operating conditions.
5. Further analysis is needed to identify the causes of frequent downtime and restore machine performance linked to the production process. This research can improve reliability and reduce the risk of failure in critical equipment.

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PAGE 1

PAGE 2

PAGE 3

PAGE 4

PAGE 5

PAGE 6

PAGE 7

PAGE 8

PAGE 9

PAGE 10

PAGE 11

PAGE 12

PAGE 13