RELIABILITY, AVAILABILITY, AND MAINTAINABILITY (RAM) ANALYSIS FOR PERFORMANCE EVALUATION OF POWER GENERATION MACHINES

Analisis Reliability, Availability, dan Maintainability (RAM) untuk Evaluasi Kinerja Mesin Pembangkit Listrik

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Abstrak

This paper presents a reliability, availability, and maintenance (RAM) analysis framework to evaluate the performance of Power Generation Machines (MPL) as part of office infrastructure. MPL performance is evaluated by calculating maintenance performance, including Mean Time Between Failures (MTBF) to see reliability aspects, Mean Time to Repair (MTTR) to see maintainability aspects, and availability to see its operational availability. This research used data as maintenance log sheet data from three MPLs from January to September 2021. The results showed that MPL1 had the most optimal condition with an availability value of 93.48%, MPL2 was 82.19%, and MPL3 was 70.55%. Root cause analysis was carried out using Fishbone Diagram. It was able to identify the main problems in the machine's age and the procedure for submitting maintenance. Maintenance performance improvement is very much needed, especially the availability aspect for MPL2 and MPL3, as well as the valuation of existing preventive care. In addition, determining qualification standards for availability, MTBF, and machine MTTR needs to be carried out as a quantitative consideration in making MPL replacement decisions.

Keywords: Maintenance, performance, reliability, maintainability, availability, Power Generation Machine

Abstract

Makalah ini menyajikan kerangka analisis keandalan, ketersediaan, dan pemeliharaan (RAM) untuk mengevaluasi kinerja Mesin Pembangkit Listrik (MPL) sebagai bagian dari infrastruktur kantor. Performa MPL dievaluasi dengan menghitung performa maintenance, antara lain Mean Time Between Failures (MTBF) untuk melihat aspek reliability, Mean Time to Repair (MTTR) untuk melihat aspek maintainability, dan availability untuk melihat ketersediaan operasionalnya. Penelitian ini menggunakan data sebagai data log sheet pemeliharaan dari tiga MPL periode Januari hingga September 2021. Hasil penelitian menunjukkan bahwa MPL1 memiliki kondisi paling optimal dengan nilai ketersediaan sebesar 93,48%, MPL2 sebesar 82,19%, dan MPL3 sebesar 70,55%. Analisis akar penyebab dilakukan dengan menggunakan Fishbone Diagram. Mampu mengidentifikasi masalah utama pada usia mesin dan prosedur pengajuan perawatan. Peningkatan kinerja perawatan sangat diperlukan, terutama aspek ketersediaan untuk MPL2 dan MPL3, serta valuasi perawatan preventif yang ada. Selain itu, penentuan standar kualifikasi availability, MTBF, dan MTTR mesin perlu dilakukan sebagai pertimbangan kuantitatif dalam pengambilan keputusan penggantian MPL.

Kata kunci: *Pemeliharaan, kinerja, keandalan, pemeliharaan, ketersediaan, Mesin Pembangkit Listrik*

1. INTRODUCTION

The development progress of a country depends on the production, use, and storage of its energy (Zazoum, 2022). In Indonesia, the increase in national economic growth is one of the triggers for increasing electricity consumption (Muchlis & Permana, 2003). Economic growth indicators are also shown by the development of office buildings in various areas with various types of businesses in them, both as commercial areas, hotel businesses, offices, and financial services, including banking. (Aribowo et al., 2020). The need for electricity supply is the primary need for offices to carry out their business activities. This dependence is increasing with technological advances and industrial growth (Zazoum, 2022). The power generating machine (MPL) is essential to ensure the availability of electricity supply when there is a problem with the electricity supply from the government. The amount of electricity a power-generating machine produces is strongly influenced by its type and capacity. Aribowo et al. (2020) mention the factors that affect the production of electricity per type of power plant, among others, the loading capacity both as a base load and a peak load, the loading characteristics, and the operating time of the power generating unit.

In the era of global competition and increasing stakeholder demands, fundamental business demands exist to improve industry performance. Industry performance and competitiveness depend on the reliability and productivity of their production facilities (Muchiri et al., 2011). Previous research has concluded that equipment maintenance and system reliability are important factors affecting an organization's ability to provide quality and timely services to customers and to stay ahead of the competition (Muchiri et al., 2011; Arias Velásquez & Mejía Lara, 2018; Dachyar et al., 2018; Corvaro et al., 2017; Guo et al., 2007). Therefore, the maintenance function is crucial for the continuous performance of any manufacturing plant.

As an effort to determine the level of maturity in carrying out asset management in an organization, Cahyo et al. (2021) have proposed the asset management maturity model, which combines an approach based on SAM+ for ISO 55001:2014 and risk management to determine the maturity level of asset management in an organization. The research assessed maturity using the Self-Assessment Methodology Plus (SAM +) software on ISO 55001: 2014 developed by The IAM. Equipment maintenance management must be able to assist management in achieving its operational performance goals. Equipment performance significantly affects organizational performance (Dachyar et al., 2018). Various methodologies and equipment accompany maintenance activities to maintain productive process continuity. Complexity ranges from simple repairs to complex managerial tasks, where the main goal is failure prevention (Corvaro et al., 2017). Maintenance is the sum total of all technical and administrative actions aimed at maintaining an object or returning it to a state where it can perform its required functions (BSI, 1984; Pintelon & Puyvelde, 2006). Maintenance management in an organization at least ensures asset functionality, including product availability, reliability, and quality. In addition, maintenance ensures the organization reaches the planned service life, ensures environmental safety, and efficient use of resources (Muchiri et al., 2011; Nurcahyo et al., 2019).

In several case studies (Table 1), RAM analysis has been used to evaluate system and subsystem performance (Simon et al., 2014; Ahmadi et al., 2019; Cevasco et al., 2021; Kumar et al.,, 2022; Corvaro et al., 2017; Leite et al., 2022; Jagtap et al., 2021; Arias Velásquez & Mejía Lara, 2018). A reliability study on a series capacitor bank to be located at the Cotaruse 220 kV substation in Peru implemented calculations divided into forced and scheduled blackouts (Arias Velásquez & Mejía Lara, 2018). Drilling machine reliability, maintainability, and availability for earth pressure balance tunnels were investigated by Agrawal et al., (2019) and resulted in an availability rate of 61%, increasing to 70% with proper maintenance and planning. Jagtap et al. (2021) revealed that the proposed RAM framework helps decision-makers to plan maintenance activities according to subsystem criticality levels and allocate resources accordingly.

Cevasco et al. (2021) present a comprehensive review and discussion of identifying critical components of offshore wind turbines, presenting recommendations on feasible efforts to improve the prediction of future offshore project performance. The RAM factor is a strategic approach to integrate reliability, availability, and maintenance, using methods, tools, and engineering techniques (Mean Time to Failure, Equipment down Time and System Availability values) to identify and measure equipment and system failures that prevent the achievement of productive goals (Corvaro et al., 2017). Unplanned failures can result in high costs, especially when machines are challenging to repair, or parts are far away (Simon et al., 2014). The reliability of each subsystem is determined by the best probability distribution function (Ahmadi et al., 2019).

Table 1 Previous research.

Author	Research object
(Arias Velásquez & Mejía Lara, 2018)	capacitor bank
(Agrawal et al., 2019)	tunnel boring machine operating
(Jagtap et al., 2021)	a circulation system of water
(Leite et al., 2022)	railway locomotive bogies
(Cevasco et al., 2021)	trends in offshore wind energy applications
(Corvaro et al., 2017)	reciprocating compressors API 618
(Ahmadi et al., 2019)	conveyor system in mechanized tunneling
(Simon et al., 2014)	the main conveyor in the Svea Coal Mine

This study will explore the performance of an organization's vital infrastructure in the electrical aspect, namely the power generator machine (MPL), by calculating the Reliability, Availability, and Maintainability (RAM). The object of research is a machine that has been operating since 1995 and is a reasonably vital infrastructure. Equipment life influences maintenance activities because of the higher potential for damage (Nurcahyo et al., 2016). Analysis of the results of the maintenance of power plant machines is needed to maintain or improve the quality that has been previously owned.

2. LITERATURE REVIEW

In production systems, the device's functionality is measured once the system is up and running. In addition to normal wear and tear, other failures may occur, mainly due to equipment exceeding design limits or operating errors. Factory downtime, quality problems, slowdowns, safety risks, or environmental pollution are apparent consequences. All these consequences can negatively impact critical performance requirements such as operating costs, profitability, customer satisfaction, and productivity. Maintenance management must make decisions about maintenance targets and the strategies that need to be implemented to ensure that the plant operates at the required conditions while meeting production targets at optimal cost (Muchiri et al., 2011).

Maintenance work is seen as a reactive task, which requires repairing and replacing spare parts or simply repairing damaged equipment (Nurcahyo et al., 2019). Maintenance activities are viewed as non-productive, non-core support functions that add little value to the business. However, the role of maintenance is very supportive of the manufacturing department, and to meet maintenance objectives, the maintenance team needs to involve trained operators in routine maintenance (Lazim & Ramayah, 2010)

Corder et al. (1992) divide maintenance activities into four types: planned maintenance, preventive maintenance, corrective maintenance, and emergency maintenance. Furthermore, the British national standards body (BSI) further classifies maintenance activities according to Figure 1.

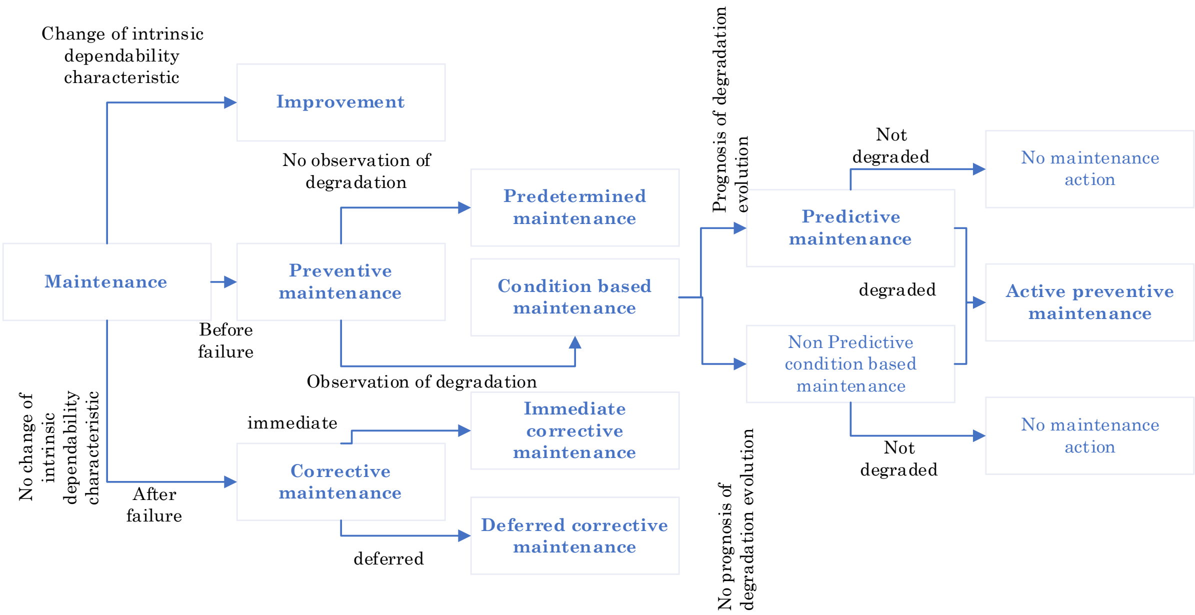

Figure 1 Type and classification of maintenance (BSI, 2017).

BS EN 13306 establishes general terms and definitions for the technical, administrative, and managerial maintenance fields. Maintenance is carried out when there is a change in the intrinsic dependent characteristics to improve the performance of the equipment. On the other hand, preventive maintenance is scheduled before a failure occurs, and repair maintenance is scheduled when a failure occurs. Preventative maintenance increases asset life and avoids unscheduled maintenance activities (Dachyar et al., 2018). In preventive maintenance, predictive maintenance is the most suitable method to be implemented in the industry (Nurcahyo et al., 2018).

Reliability engineering is not new method (Kumar et al., 2022). Like other engineering systems, the failure of one or more units of a function in an industry will disrupt processes that should run properly. Reliability engineering is relevant to all aspects of plant design and operation, applying reliability analysis and prediction techniques early, greatly assisting the design team in selecting the technology to be used (Al-Douri et al., 2021).

Reliability

Reliability is defined as the ability of the system to perform tasks under certain conditions and at certain time intervals (BSI, 2017). When a system can perform the specified job more quickly, it is more reliable (Modarres et al., 2016; (Ahmadi et al., 2019). Mean Time Between Failures (MBTF) is an indicator to measure the reliability of a machine. MBTF is the average time between one failure and the next on a machine. Failure is due to the inability of a part of the system or equipment to operate under certain conditions, where the leading causes of loss include poor or incomplete design, manufacturing defects, incorrect use, improper placement and installation, wear, and failure in other parts of the system. The system, and a gradual decline in operation (Ahmadi et al., 2019).

To calculate the Mean Time Between Failures (MTBF), first, the Actual Operating Time of the three Power Generation Machines that are used as research objects are calculated. Calculations are carried out using the Equation:

$$Actual\ operating\ time = specified\ operating\ time - (preventive + corrective\ maintenance) \quad (1)$$

The following Equation can calculate the MTBF value:

$$Mean\ Time\ Between\ Failures = \frac{actual\ operating\ time}{breakdown\ frequency} \quad (2)$$

(Dervitsiotis, 1981)

Availability

Availability is the probability that the device/system will function properly at time t when used in an ideal environment under certain conditions. Intrinsic availability is the most commonly used definition in the reliability literature (Simon et al., 2014). Measuring the value of the availability of an item requires data on when the item can operate and when the item is processed. The following Equation can calculate the availability value:

$$Availability = \frac{Actual\ operating\ time}{specified\ operating\ time} \quad (3)$$

(Dervitsiotis, 1981)

Maintainability

Maintainability is the probability that a failed system/equipment/item will be returned to a satisfactory operating condition over time t by applying maintenance (Dhillon, 2006; Ahmadi et al., 2019). Maintainability, which is also defined as the ability of an item to be maintained or recovered to a condition where the item can function when maintenance is carried out following existing procedures, can be measured by an indicator called the Mean Time to Repair (MTTR). This indicator is the average time that shows how long it takes an item from breakdown until it can operate again. The equation can calculate the MTTR value:

$$Mean\ time\ to\ repair = \frac{breakdown\ time}{breakdown\ frequency} \quad (4)$$

(Dervitsiotis, 1981)

3. METHODS

BS EN 133006 defines maintenance as a combination of all technical, administrative, and managerial actions during the life cycle of an item. This action is intended to maintain or restore the function of the item so that it can carry out the required process. This study conducted RAM analysis based on the definition set out in BS EN 13006 as well as other studies that have been completed (Ahmadi et al., 2019; Arias Velásquez & Mejía Lara, 2018; Corvaro et al., 2017; Jagtap et al., 2021; Kumar et al., 2022; Leite et al., 2022).

3.1 Research stage

Power generation machines are fundamental to ensure that an office building continues operating during working hours, even 24 hours. It concerns the needs of the structure consisting of 23 floors and a server or data centre that must be continuously used because, in this case, the office of a company engaged in the banking sector. This research was conducted with three electric generating machines with a capacity of 1,500 kVA for each machine. The machine was manufactured in 1991 with a frequency of 50 Hz, a rotational speed of 1,500 RPM, type 4 stroke, and several cylinders, namely 16. The study was carried out according to the steps shown in Figure 2.

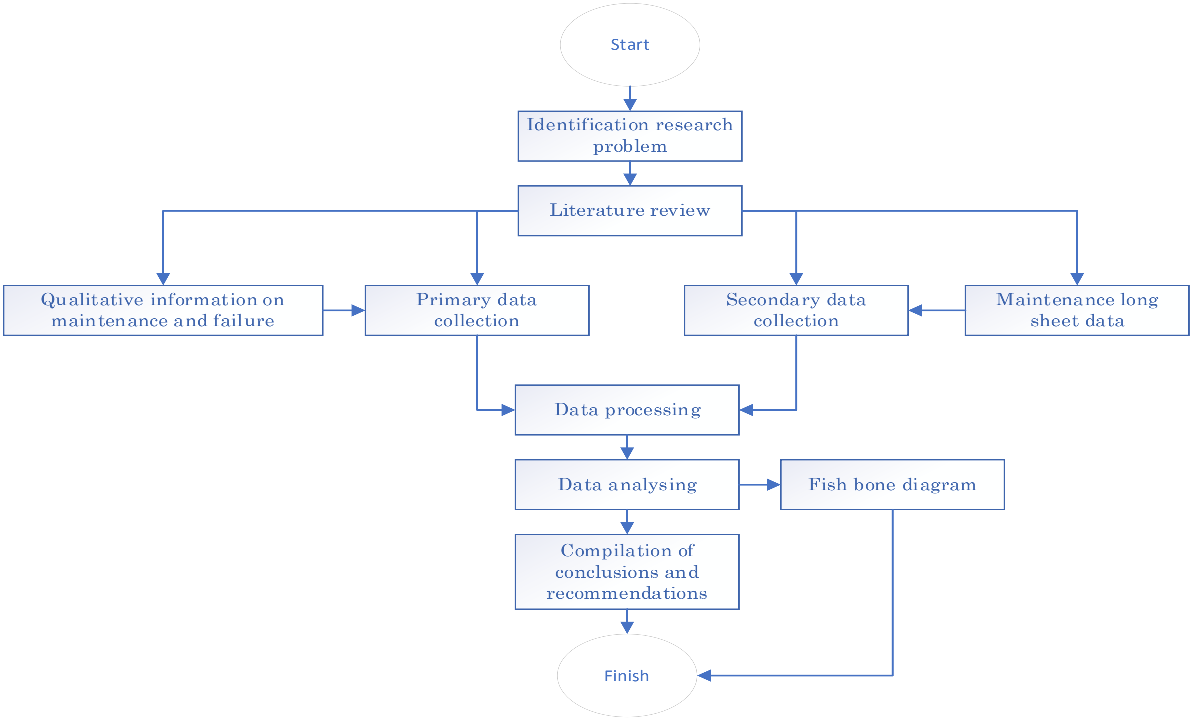

Figure 2 Research steps.

This research was conducted in September 2021. Figure 2 presents the research steps that begin with problem identification. This study identifies the condition of the availability of machines available to support building operations and finds out the leading causes of failure of the power plant engine. Support for literature studies is carried out by searching the results of research that has been carried out related to RAM analysis on several research objects. Secondary data is obtained from the maintenance log sheet of three Power Generation Machines (MPL) in an office building from a company engaged in banking from January 2021 to September 2021.

Researchers collected data by identifying maintenance records, including oil pressure, water temperature, components on the battery (Accu water, connecting battery), engine RPM, hours meter, and load (frequency, voltage, current). The assumption is that if the notes on the sheet are in normal condition, it indicates the machine can operate adequately. The data from the log sheet are machine operating time data, machine breakdown time, damage frequency, and causes of machine damage. In addition to secondary data collection, primary data collection was conducted through interviews with employees who are responsible and directly involved in maintenance activities to obtain qualitative information. The information needed is in the form of how the maintenance activities are already running, including the cause of the failure of the power plant engine.

Data processing is carried out to get the maintenance performance of the three machines at a predetermined period. The calculation of engine reliability, availability, and maintainability are based on equations (1), (2), and (3), which are then analyzed for data and problems using Fishbone Diagram/Root Cause Analysis to get to the root of the problem. The preparation of conclusions and recommendations in this study is intended to assist office owners or building managers in monitoring the condition of the availability of machines that support building operations and find out the leading causes of failure of power plant machines through the analysis carried out. It can also be considered as information on whether a machine or equipment can still be maintained as infrastructure in an office or the need for overhaul or procurement of new machines/equipment.

4. RESULT AND DISCUSSION

Analysis of the characteristics of RAM on a power plant engine affects the effectiveness of the engine's performance. This analysis is used to find critical subsystems to facilitate the development of appropriate maintenance strategies; RAM is a valuable tool for finding essential subsystems. It helps in deciding the proper maintenance strategy.

Reliability

The failure and repairable data from the power generation engine are used for continuous analysis. In this case, the primary data sources, in the form of reports recorded in the log sheet and various qualitative sources, have been used.

Based on the log-sheet data and Equation (1), the actual operating time values in January – September range of the three machines are shown in Table 2.

Table 2 Data on the actual operating time of power plant machines in 2021 (January-September).

Month	MPL1 (hour)	MPL2 (hour)	MPL3 (hour)
January	740	668	740
February	308	668	668
March	740	740	740
April	716	716	716
May	739	739	740
June	716	524	716
July	740	0	140
August	740	596	0
September	716	716	140
Total	**6155**	**5367**	**4600**

The existence of Actual Operating Time is strongly influenced by several indicators, namely Specified Operating Time, which is machine operating time 24 hours a day; preventive maintenance, where the average value for each month is 4 hours; and corrective maintenance time that varies each month according to the machine conditions. Table 3 shows the MTBF calculation using this indicator.

Table 3 Mean Time Between Failures (MTBF) data for power generation machines in 2021 (January-September).

Month	MPL1 (hour)	MPL2 (hour)	MPL3 (hour)
January	185	167	185
February	77	167	167
March	185	185	185
April	179	179	179
May	184,75	184,75	185
June	179	131	179
July	185	0	35
August	185	149	0
September	179	179	35
Total	**1538,75**	**1341,75**	**1150**
Average	**307,75**	**268,35**	**230**

The reliability value is used to predict system availability. In addition, it helps in recognizing the functionality of the equipment/subsystem/system (Jagtap et al., 2021). Economic reasons from manufacturers have historically driven reliability requirements or objectives. These requirements are usually expressed by a reliability number assigned over the life period, or by Mean Time To Failure, Mean Time Between Failure, Mean Time To the First Failure (one shot devices), MTBF for repairable systems/products, or Mean Time to a Critical Failure or between critical failures (Krasich, 2009). Table 3 shows the widely varying MTBF values from MPL1, MPL2, and MPL3. The more excellent MTBF value generated by the machine shows the machine has better performance. The engine tends to be longer for the interval between failures. Vice versa, the lower the value of the resulting MTBF, the worse the machine's performance. It is in line with the research of Cevasco et al. (2021); Harman et al. (2008), which state that higher reliability will lead to generally higher technical availability. Table 3 shows that MPL1 performs better than the other two machines, with an average MTBF of 307,75 hours.

Maintainability

Equipment maintenance is expressed in probabilities. Probability shows the equipment's working condition after being repaired within the specified time interval. Data on equipment repair time were used for maintenance analysis (Jagtap et al., 2021). Table 4 shows the results of the MTTR calculation for the three power plant engines in the January – September period.

Table 4 Mean Time to Repair (MTTR) data for power generation machines in 2021 (January-September).

Month	MPL1 (hour)	MPL2 (hour)	MPL3 (hour)
January	0	72	0
February	360	0	0
March	0	0	0
April	0	0	0
May	1	1	0
June	0	192	0
July	0	744	600
August	0	144	744
September	0	0	576
Total	**361**	**1153**	**1920**
Average	**40,11**	**128,11**	**213,33**

As with the MTBF value in the reliability analysis, the MTTR value generated from the three machines also varies greatly. Mean Time To Repair (MTTR) is a performance indicator used to determine an asset's maintenance (Ragala, 2022). The higher the MTTR value of a machine, the longer it will take for the machine to be operated again after a failure, and vice versa. Management of maintenance activities is based on close monitoring of maintenance performance indicators. MTTR is considered one of the key metrics to monitor. MTTR measures critical system shutdown times. A high MTTR equates to a business being vulnerable to major outages when an outage occurs, which can lead to severe business disruption, customer dissatisfaction, and lost revenue (Raouhi et al., 2020)(Ragala, 2022). Table 4 shows that MPL1 has the best maintainability level compared to the other two MPLs.

Availability

The availability of each power-generating machine is calculated using Equation (3). Table 5 shows the availability value of each power plant engine for the January – September period. System availability is defined as the ready status of a device both in quantity (quantity) and quality according to the needs used to carry out the operation process (Pratama et al., 2019)(Tripathi et al., 2011). This availability can be used to assess the success or effectiveness of the maintenance activities (Tripathi et al., 2011).

Table 5 Data on the availability of power generation machines in 2021 (January - September).

Month	MPL1	MPL2	MPL3
January	99,46%	89,78%	99,46%
February	45,83%	99,40%	99,40%
March	99,46%	99,46%	99,46%
April	99,44%	99,44%	99,44%
May	99,33%	99,33%	99,46%
June	99,44%	72,78%	99,44%
July	99,46%	0,00%	18,82%
August	99,46%	80,11%	0,00%
September	99,44%	99,44%	19,44%
Total	**841,32%**	**739,74%**	**634,92%**
Average	**93%**	**82%**	**71%**

MPL1 has the highest availability value among the other two machines, which shows the machine's availability in the best condition and most feasible to operate.

The RAM analysis method is capable of estimating a system's production availability by identifying failure modes, failure rates, and consequences while considering the effect on production. RAM analysis can evaluate equipment performance and simulate the lifetime performance of an asset to increase system productivity and overall profit and reduce lifecycle costs (including losses in production costs, maintenance costs, operating costs, and so on). MPL 1 has the best MTBF, MTTR, and availability values compared to the other two machines, and this can be used as a guide in conducting further analysis to improve the performance of MPL 2 and MPL 3.

A follow-up analysis was carried out to determine the main reason for the failure that occurred in each machine. This analysis uses a Pareto diagram for each machine based on the losses and damage shown. Pareto analysis allows identifying problem areas that must be analyzed as widely as possible using statistical methods (Ahmadi et al., 2019). The availability indicator accumulates the types of causes of the most extended downtime and the duration of damage that occurs in power plants. Figure 3 shows a diagram of the type and time of MPL damage.

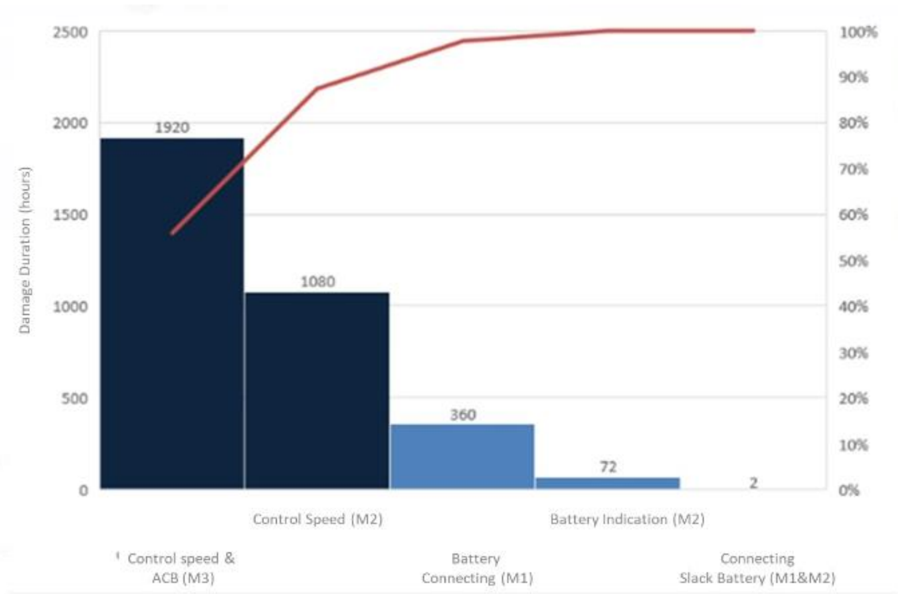

Figure 3 Types and duration of power plant machine damage (January - September 2021).

Figure 3 illustrates 80% of the total duration of MPL damage caused by control speed damage that occurs in MPL2 and MPL3. In addition, there is damage to the Air Circuit Breaker (ACB) on the MPL3. Meanwhile, the damage in MPL1 was caused by connecting the battery.

After prioritizing 80% of the existing problems, root cause analysis is needed to find out the origin of the cause of the damage. Primary data from interviews with employees who understand and are directly responsible for MPL are used in this analysis. The tool used is a Fishbone Diagram to find the root of the problem, divided into three aspects: Materials, Machines, and Methods. The fishbone diagram, often referred to as a cause-and-effect diagram, is a tool used to identify the root cause of a problem that represents the effect and the factors or causes that influence it. This tool is a template for brainstorming possible reasons for a result. With no limit to the identified causes, this tool helps determine the root cause in a structured and precise way (Shinde et al., 2018) (Coccia, 2018).

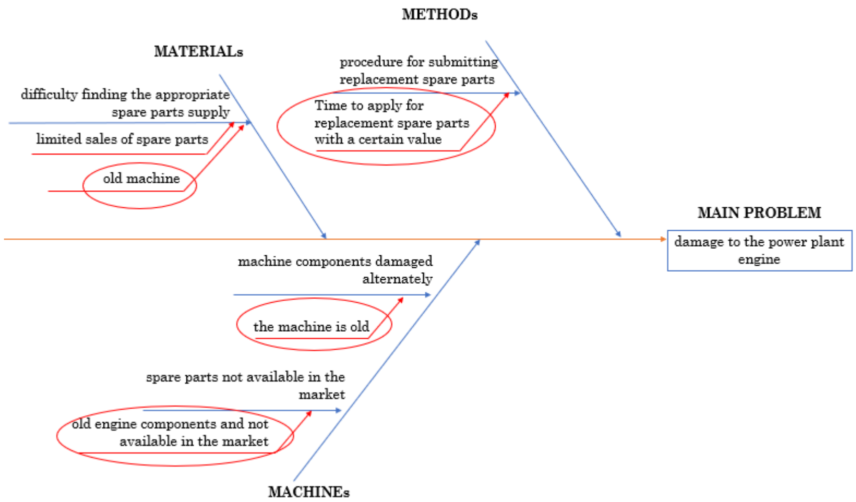

Figure 4 Analysis of the Root Problem of Power Plant Machine Damage Using Fishbone Diagram.

Figure 4 informs that the leading causes of damage to the Control Speed and Air Circuit Breaker components that cause MPL damage for a long time are the machine's age and the procedures' existence. The old age of the engine causes some engine parts to no longer be able to provide the required performance. In addition, the procedure for submitting machine repairs and renewals takes a long time. Due to the significant value of the submission, it must go through a separate process.

Furthermore, it is necessary to formulate and develop strategies, as well as follow up to solve the problems that have been identified. A maintenance planning strategy can be prepared by dividing it into two levels, namely short-term and medium-term (Nurcahyo et al., 2018). The short-term strategy that can be taken is to increase the availability of MPL2 and MPL3 by evaluating existing preventive maintenance activities. Furthermore, the medium-term strategy can be set for activities to analyze the planning for procuring new MPL. Thus, new MPLs can be available when needed. In addition, it is also necessary to implement a strategy so that the procedure for assessing submissions from the building management by building owners for maintenance with a particular value can be accelerated, especially for MPL, to shorten the downtime period and return to the status available to operate.

5. CONCLUSION

This paper evaluates the reliability, availability, and maintenance of power plant machines in an office building. There are three machines considered, namely MPL1, MPL2, and MPL3. The best probability distribution function determines the reliability of each machine. Based on the results, MPL1 shows the highest level of reliability. MPL1 also has more maintenance than other MPLs. MPL1 also showed the highest eligibility level compared to the other two MPLs. The condition of MPL1, which has an availability performance of up to 93.48%, indicates that this machine has the best and most prime condition. MPL2 is detected to have a condition that is not too good, with an availability performance of 82.19%, so more attention is needed regarding its maintenance to increase engine performance so that it does not continue to decline significantly. Meanwhile, MPL3 has a fairly bad condition with an availability performance of 70.55%, so evaluation and special attention are needed in its maintenance.

The root of the problem from the leading cause lies in the age of the old machine (operating since 1995), and the procedure that takes quite a while to apply to maintain a particular value is quite large. The queue procedure that places MPL 3 in the final order causes its performance to be no better than the other two MPLs. Replacement procedures take a long time due to the availability of spare parts in the market, which are difficult to find, causing long queues for replacement of spare parts also in MPL 3. The short-term strategy that can be developed is to improve the availability performance of MPL2 and MPL3 by evaluating the existing preventive maintenance for building management. The mid-term strategy that can be determined is to analyze the planning for procuring a new MPL. The procedure for proposing new MPL maintenance and procurement needs to be evaluated by shortening the procurement process.

The limitation of this study is that no further analysis has been carried out regarding the proposed strategy, and other research is needed to analyze the life cycle costs of the three existing MPLs as a consideration for the company's future strategy, especially in the financial aspect.

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REFERENCES

Agrawal, A. K., Murthy, V. M. S. R., & Chattopadhyaya, S. (2019). Investigations into reliability, maintainability and availability of tunnel boring machine operating in mixed ground condition using Markov chains. *Engineering Failure Analysis*, *105*, 477-489. https://doi.org/10.1016/j.engfailanal.2019.07.013

Ahmadi, S., Moosazadeh, S., Hajihassani, M., Moomivand, H., & Rajaei, M. M. (2019). Reliability, availability and maintainability analysis of the conveyor system in mechanized tunneling. *Measurement*, *145*, 756-764.. https://doi.org/10.1016/j.measurement.2019.06.009

Al-Douri, A., Kazantzi, V., Currie-Gregg, N., & El-Halwagi, M. M. (2021). Integrating

uncertainty quantification in reliability, availability, and maintainability (RAM) analysis in the conceptual and preliminary stages of chemical process design. *Chemical Engineering Research and Design*, *167*, 281-291.
https://doi.org/10.1016/j.cherd.2021.01.014

Velásquez, R. M. A., & Lara, J. V. M. (2018). Reliability, availability and maintainability study for failure analysis in series capacitor bank. *Engineering Failure Analysis*, *86*, 158-167.
https://doi.org/10.1016/j.engfailanal.2018.01.008

Aribowo, D., Desmira, D., & Fauzan, D. A. (2020, November). Sistem Perawatan Mesin Genset Di PT (Persero) Pelabuhan Indonesia II. In *Prosiding Seminar Nasional Pendidikan FKIP* (Vol. 3, No. 1, pp. 580-594).

BSI. (1984). British Standard Glossary of Maintenance Management Terms in Terotechnology. In *British Standard Institution, London*.

BSI. (2017). BS EN 13306:2017 Maintenance - Maintenance Terminology. *British Standards Institution*.

Cahyo, W. N., Hadiyanto, H., & Fiantama, N. N. (2021). PROPOSED RISK MITIGATION IN ASSET MANAGEMENT SYSTEM BASED ON SELF ASSESSMENT METHODOLOGY PLUS (SAM+) FOR ISO 55001: 2014 AND RISK MANAGEMENT APPROACH. *Jurnal Standardisasi*, *23*(3), 313-322. https://js.bsn.go.id/index.php/standardisasi/article/view/855

Cevasco, D., Koukoura, S., & Kolios, A. J. (2021). Reliability, availability, maintainability data review for the identification of trends in offshore wind energy applications. *Renewable and Sustainable Energy Reviews*, *136*(October 2020), 110414. https://doi.org/10.1016/j.rser.2020.110414

Coccia, M. (2018). The Fishbone diagram to identify, systematize and analyze the sources of general purpose Technologies. *Journal of Social and Administrative Sciences*, *4*(4), 291-303.

Corder, Antony, S., & Hadi, K. (1992). Teknik manajemen pemeliharaan. *Jakarta: Erlangga*.

Corvaro, F., Giacchetta, G., Marchetti, B., & Recanati, M. (2017). Reliability, Availability, Maintainability (RAM) study, on reciprocating compressors API 618. *Petroleum*, *3*(2), 266-272.
https://doi.org/10.1016/j.petlm.2016.09.002

Dachyar, M., Nurcahyo, R., & Tohir, Y. (2018). Maintenance strategy selection for steam power plant in range of capacity 300-625 MW in Indonesia. *ARPN Journal of Engineering and applied Sciences*, *13*(7), 2571-2580.

Dervitsiotis, K. N. (1981). Operations management. *New York : McGraw-Hill*.

Dhillon, B. S. (2006). *Maintainability, maintenance, and reliability for engineers*. CRC press.

Guo, Y., Lim, A., Rodrigues, B., & Yu, S. (2007). Machine scheduling performance with maintenance and failure. *Mathematical and computer modelling*, *45*(9-10), 1067-1080.
https://doi.org/10.1016/j.mcm.2006.09.018

Harman, K., Walker, R., & Wilkinson, M. (2008, April). Availability trends observed at operational wind farms. In *European Wind Energy Conference* (pp. 1-8).

Jagtap, H. P., Bewoor, A. K., Kumar, R., Ahmadi, M. H., Assad, M. E. H., & Sharifpur, M. (2021). RAM analysis and availability optimization of thermal power plant water circulation system using PSO. *Energy Reports*, *7*, 1133-1153.
https://doi.org/10.1016/j.egyr.2020.12.025

Krasich, M. (2009, January). How to estimate and use MTTF/MTBF would the real MTBF please stand up?. In *2009 Annual Reliability and Maintainability Symposium* (pp. 353-359). IEEE.
https://doi.org/10.1109/RAMS.2009.4914702

Kumar, N. H., Manjunath, C., John, R. P., Chand, R. P., Madhusudhana, S., & Venkatesha, B. K. (2022). Reliability, availability and maintainability study of 6.5 cubic meters shovel and 60 tone dumper in a surface limestone mine. *Materials Today: Proceedings*, *54*, 199-204.https://doi.org/10.1016/j.matpr.2021.08.292

Mad Lazim, H., & Ramayah, T. (2010). Maintenance strategy in Malaysian manufacturing companies: a total productive maintenance (TPM) approach. *business strategy series*, *11*(6), 387-396.

https://doi.org/10.1108/17515631011093098

Leite, M., Costa, M. A., Alves, T., Infante, V., & Andrade, A. R. (2022). Reliability and availability assessment of railway locomotive bogies under correlated failures. *Engineering Failure Analysis*, *135*, 106104.

https://doi.org/10.1016/j.engfailanal.2022.106104

Modarres, M., Kaminskiy, M. P., & Krivtsov, V. (2016). Reliability Engineering and Risk Analysis: A Practical Guide, Third Edition 3rd Edition. *CRC Press*.

Muchiri, P., Pintelon, L., Gelders, L., & Martin, H. (2011). Development of maintenance function performance measurement framework and indicators. *International Journal of Production Economics*, *131*(1), 295-302.

https://doi.org/10.1016/j.ijpe.2010.04.039

Muchlis, M., & Permana, A. D. (2003). Proyeksi Kebutuhan Listrik PLN 2003 s.d. 2020. *Pengembangan Sistem Kelistrikan Dan Menunjang Pembangunan Nasional Jangka Panjang*, 11 Halaman. http://www.oocities.org/markal_bppt/publish/slistrk/slmuch.pdf

Nurcahyo, R., Darmawan, D., Jannis, Y., Kurniati, A., & Habiburrahman, M. (2018, December). Maintenance Planning Key Process Area: Case Study at Oil Gas Industry in Indonesia. In *2018 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)* (pp. 1704-1708). IEEE.

https://doi.org/10.1109/IEEM.2018.8607527

Nurcahyo, R., Kurniarso, A., & Farizal. (2018). Maintenance program selection in cigarette manufacturing industry with multi-criteria decision-making method. *4th IEEE International Conference on Engineering Technologies and Applied Sciences, ICETAS 2017*, *2018-Janua*, 1–5. https://doi.org/10.1109/ICETAS.2017.8277891

Nurcahyo, R., Rachman, A., & Agustino, T. (2016). Production efficiency improvement through preventive maintenance and production scheduling optimization. *Proceedings of the International Conference on Industrial Engineering and Operations Management*, *8-10 March*(March), 1028–1032.

Pintelon, L., & Puyvelde, F. van. (2006). Maintenance decision making. *Acco, Leuven, Belgium*, *1st edisio*.

Pratama, D. Y., Sukadarmika, G., & Sastra, N. P. (2019). Analisis Availability Metrics Webserver Penyedia Website Program Studi Teknik Elektro Fakultas Teknik Universitas Udayana. *Jurnal SPEKTRUM Vol*, *6*(3).

Ragala, Z. (2022). *MTTR Prediction of railway rolling stock using regression algorithms*. 0–5.

Ragala, Z., Retbi, A., & Bennani, S. (2022, May). MTTR Prediction of railway rolling stock using regression algorithms. In *2022 International Conference on Intelligent Systems and Computer Vision (ISCV)* (pp. 1-6). IEEE.

Raouhi, E. M., Lachgar, M., & Kartit, A. (2020). Comparative Study of Regression and Regularization Methods: Application to Weather and Climate Data. *Proceedings of the 6th International Conference on Wireless Technologies, Embedded, and Intelligent Systems. Lecture Notes in Electrical Engineering 745*, 233.

Shinde, D. D., Ahirrao, S., & Prasad, R. (2018). Fishbone diagram: application to identify the root causes of student–staff problems in technical education. *Wireless personal communications*, *100*, 653-664.

Simon, F., Javad, B., & Abbas, B. (2014). Availability analysis of the main conveyor in the Svea Coal Mine in Norway. *International Journal of Mining Science and Technology*, *24*(5), 587-591.

https://doi.org/10.1016/j.ijmst.2014.07.004

Tripathi, S., Abbas, & Rizwan Beg. (2011). Availability metrics: under controlled environments for web services. *International Journal on Web Service Computing*, *2*(3), 1–9. https://doi.org/10.5121/ijwsc.2011.2301

Zazoum, B. (2022). Solar photovoltaic power prediction using different machine learning methods. *Energy Reports*, *8*, 19–25. https://doi.org/10.1016/j.egyr.2021.11.183.