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OPTIMIZATION MAINTENANCE PERFORMANCE LEVEL THROUGH COLLABORATION OF OVERALL EQUIPMENT EFFECTIVENESS AND MACHINE RELIABILITY

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Maintenance performance level (MPL) is an important part of the key performance indicator (KPI) to improve the effectiveness of machine maintenance which includes factors of overall equipment effectiveness-machine effectiveness (OEE-ME) and machine reliability (MR). The purpose of this paper is to optimize the value of the maintenance performance level (MPL) through the collaboration of overall equipment effectiveness-machine effectiveness (OEE-ME) and machine reliability (MR). The study began with collecting research data, namely machine operation, preventive maintenance, and corrective maintenance. The data is processed using the Pareto principle to determine the critical system based on failure frequency. The selected critical system is tested for probability distribution and machine reliability (MR) assessment with several predetermined maintenance time interval scenarios. The main result of this research is the optimal maintenance time interval is a better criterion than other criteria. The optimal maintenance time interval was chosen because it can meet the requirements of overall equipment effectiveness-machine effectiveness (OEE-ME) at a world-class maintenance performance level (MPL) with a value of 90.43%, and the proposed machine reliability (MR) is better than the initial machine reliability (MR) based on the failure ratio value. Therefore, it can be boldly stated that the collaboration of overall equipment effectiveness-machine effectiveness (OEE-ME) and machine reliability (MR) can influence and optimize the value of maintenance performance level (MPL), which has a strong correlation and significant impact.

Keywords: machine effectiveness, machine reliability, maintenance performance level, mobile crane, overall equipment effectiveness, optimization

1 INTRODUCTION

Global competition is increasing, and all industries (such as the manufacturing industry, mining industry, and oil and gas industry) must develop strategies to ensure their business continuity. According to Bulut&Özcan (2021) [1] and Karevan et al. (2020) [2], maintenance has been an important factor in rapidly facing global business challenges. Furthermore, Wakiru et al. (2020) [3] explain that effective machine maintenance is important in ensuring machines' availability and optimal performance in an industry. In line with that, Farahani et al. (2020) [4] stated that maintenance is currently seen as a means to an end and contributes significantly to important company goals such as increasing machine reliability (MR) and effectiveness. Thus, an effective machine maintenance plan is very important for the company's long-term strategy to survive in the current or future global business competition.

Machine maintenance in an industry aims to repair or maintain machines in good and acceptable working conditions. The time-based machine maintenance category is divided into two main categories: corrective maintenance (CM) and preventive maintenance (PM). CM is generally carried out on machines or systems that fail, and then repairs are made so that the machine can return to normal [5]. CM is more appropriate for machines that have no significant impact on the overall operation. However, this will not be appropriate for applications on critical and critical machines. While PM is carried out before a machine or system is damaged and aims to reduce damaged machines and the risk of failure [6]. Therefore, PM can determine how long the reliability of a machine is [7].

Reliability and performance as an outcome of the effectiveness of machine maintenance are very important to be assessed using key performance indicators (KPI). One of the KPIs used in assessing the reliability and performance of machine maintenance is the maintenance performance level (MPL). MPL is obtained from 2 variables, namely machine's reliability (MR) and overall equipment effectiveness - machine's effectiveness (OEE-ME) [8]. Therefore, MPL is very appropriate for reliability and performance assessment, where MR is representative of reliability and OEE-ME is representative of performance.

Based on the results of previous research reviews, many researchers have taken measurements and tried to increase the OEE value in various types of machines and various industrial fields. Researchers use several methods and tools to assess and improve the value of OEE. The methods and tools used include the total productive maintenance (TPM) method for measuring OEE on the croissant production line [9], ice cream production line [10], limoncello production line [11], and in a salt company (Emisal) in Egypt [12]. Then, the TPM

method and the plan-do-check-act cycle were applied to Semiconductor Manufacturing Facilities in Malaysia [13] and press automotive machine component manufacturing companies in Indonesia [14] to calculate and increase the value of OEE. Furthermore, Pareto principle and fishbone diagrams are used to calculate OEE in the automotive industry [15].

In other industries, such as healthcare, the TPM method, Pareto principle, fishbone, and response surface method (RSM) are also applied [16] to measure OEE in pharmaceutical companies. In addition, the Effectiveness tool [17] was also used to measure OEE in the use of the dental chair unit at the Surabaya Mother and Child Hospital. Then in the mining industry, other studies have also developed an algorithm designed with the help of RStudio software [7] to measure OEE values. Several other tools and techniques have been used to measure OEE, such as the lean maintenance tool [18] applied to automotive companies, which can increase OEE by 8.3%, and the Maynard operation sequence technique (MOST) [19] to calculate OEE.

Similarly, in research related to reliability, the review results show that the qualitative reliability method is failure mode effect analysis (FMEA) to determine critical machines or components [20–22]. Other researchers also use FMEA to get machine availability values [23] and mean time to failure (MTTF) – mean time to repair (MTTR) [24]. The review results also show that the quantitative reliability method with the Weibull probability distribution is used to obtain the MTTF-MTTR values, availability, and maintainability [25], reliability, and MTTF [26]. The results of the following review show reliability analysis with several probability distributions (PD) used to obtain reliability, availability, and maintainability (RAM) and mean time between failure (MTBF)-MTTR [26], [27]. Calculation of RAM and MTBF-MTTR was also carried out using the expert judgment method [29] to support the lack of research data owned by researchers. Qualitative reliability (FMEA) and quantitative methods have also been used to obtain RAM and MTBF-MTTR [30].

The search and review results were carried out regarding the combination of qualitative reliability analysis and OEE. Some researchers also use the FMEA method to calculate OEE [29–33]. Other studies also use quantitative reliability analysis with PD to calculate OEE [34]. A different study was conducted by Samat et al. (2012) [8] by calculating the failure ratio and machine effectiveness to get the MR and OEE-ME values. Furthermore, the MR and OEE-ME values are interpreted into MPL using the health index. In previous studies, the increase in OEE and reliability values only based on the MTBF and MTTR intervals and RAM were analyzed. However, previous research results still have problems that have not been carried out, namely, by optimizing the maintenance time interval through the collaboration of overall equipment effectiveness and machine reliability. In addition, several results of calculations and the increase in the value of OEE in previous studies have also not reached the 85% benchmark [7],[9], [10],[17].

Referring research literature above, a problem not studied is optimization MPL through the collaboration of OEE-ME and MR. Therefore, we will do it through appropriate maintenance time intervals to increase OEE-ME and MR values. The increase in OEE-ME and MR values will affect maintenance performance, measured using a health index to determine MPL.

Furthermore, the results of increasing the OEE-ME and MR values to optimize MPL in this study can be used in the manufacturing industry, mining industry, and oil and gas industry to assess machine maintenance performance.

In addition, this study was conducted based on three hypotheses. Hypothesis one: there is an effect between maintenance time intervals on OEE-ME. Hypothesis two: there is an effect between maintenance time intervals on MR values. Hypothesis three: there is a significant effect between OEE-ME and MR collaboration on MPL optimization

2 MATERIAL AND THEORY

2.1 OEE-ME

OEE was developed by the Japan Institute of Plant Maintenance (JIPM) and proposed by Seiichi Nakajima in 1988. Initially, Seiichi Nakajima used OEE to measure the effectiveness of machines in the manufacturing industry. But today, as a performance indicator, OEE has been used in various industrial fields. OEE is obtained from the multiplication of availability, performance, and quality. Seiichi Nakajima presents indicators of ideal OEE conditions: availability of more than 90%, the performance of more than 95%, and quality of more than 99%. The indicator is equivalent to OEE ($0.90 \times 0.95 \times 0.99$) 85%, commonly referred to as a world-class industry. This indicator maximizes machine effectiveness by reducing six significant disadvantages: machine failure (breakdown), setting and adjustments, idling and minor stopping, reduced speed, scraps/rework, and reduced yield or process [35].

However, according to Samat et al. (2012) [8], the losses associated with the effectiveness of maintenance are only three significant losses directly related. The three losses in question include breakdown, set up & adjustment, and idling & minor stoppages. These three losses can be corrected and increased by effective maintenance activities. While losses caused by reduced speed, scraps/rework, and reduced yield or process are eliminated because these losses typically involve human error, material problems, or process requirements, they do not directly affect maintenance performance. So, by eliminating these three disadvantages, the quality level is also eliminated. Several studies [36], [37] also omitted quality to measure the actual level of maintenance performance.

Therefore, it is important to understand the OEE modification factors and their impact on machine performance measurement. Especially the use of OEE on lifting equipment in oil and gas companies and other industrial sectors that use lifting equipment. This study uses a mobile crane as the object of research, where the effectiveness of maintenance performance is not related to quality. Thus the formula in calculating OEE can eliminate quality and is called machine effectiveness. Losses that occur in mobile cranes are caused by two factors, namely PM and CM. PM itself is a planned downtime that is carried out periodically by the company. At the same time, CM is unplanned downtime or stoppage of mobile crane operation due to breakdown maintenance or minor stoppages. Losses caused by PM will affect the availability value. On the other hand, the loss caused by CM will affect the performance value.

OEE, which consists of availability and performance, is called OEE-ME. OEE-ME is obtained by multiplying availability by performance. Availability for OEE-ME is obtained by dividing the operating time by the total availability time. At the same time, performance is calculated by dividing the net operating time by the operating time. The OEE-ME rating on the machine has five levels. Each level indicates the machine's performance, with level 1 (effectiveness rating of 85-100%) being very good (world-class). Level 2 (effectiveness value 65-84%) is a good level (high-performance). Level 3 (effectiveness value 45-64%) is a fair level (typical). Level 4 (effectiveness score 25–44%) is poor (needs improvement), and level 5 (effectiveness score below 24%) is very poor (unacceptable). The following formula for OEE-ME [8]:

$$OEE - ME = Availability \times Performance \tag{1}$$

with:

$$Availability(A) = \frac{Operatingtime (OT)}{Totalavailabletime (TAT)} \times 100 \tag{2}$$

$$Performance(P) = \frac{Netoperatingtime (NOT)}{Operatingtime (OT)} \times 100 \tag{3}$$

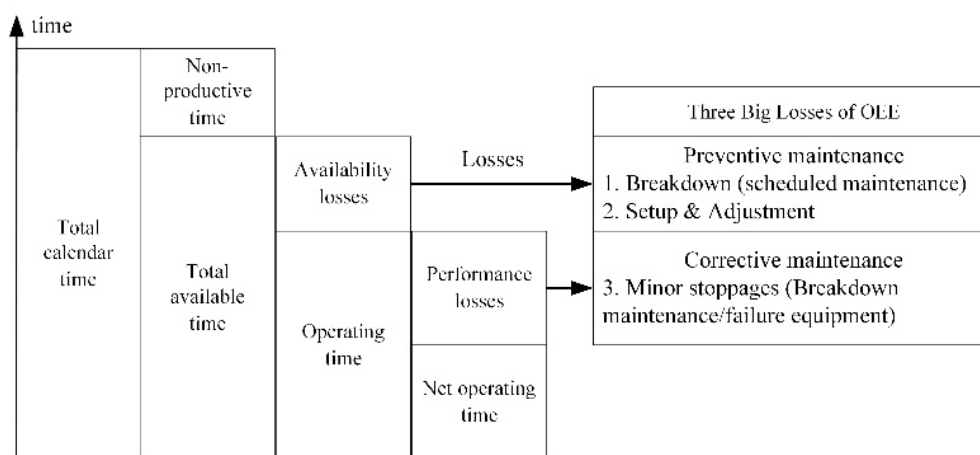


Figure 1. The concept of calculation time the OEE-ME [8]

In the past, MR was associated with sensitive and complex industries such as military, nuclear, and aerospace. Until now, MR has become a universal concern as one of the most important aspects of the quality of goods and services [38]. One way to maintain reliability is to perform machine or system maintenance [3], [39]. If there is a lack of reliability in the machine or system, it can cause irreparable damage to the machine or the system as a whole [20].

Reliability is the probability that a machine will perform its function satisfactorily for the desired period when used under certain conditions [40]. Analysis of the reliability of a complex system, a logical approach in reliability analysis is to apply a systematic approach to the reliability block diagram (RBD). RBD can be connected in series, parallel and combined series-parallel [41], [42]. In general, the reliability of a machine can be obtained using the following equation [27]:

$$R(t) = 1 - F(t) \tag{4}$$

with:

R(t) = reliability at time t,

F(t) = cumulative distribution function (CDF)

As for systems that are connected in series and parallel, follow the following equation [43]:

$$R_s(t) = R_1 \times R_2 \times R_3 \times R_n \leq \min\{R_1, R_2, R_3, R_n\} \quad (5)$$

$$R_{ps}(t) = 1 - (1 - R_1) \times (1 - R_2) \times (1 - R_3) \times (1 - R_n) \leq \min\{R_1, R_2, R_3, R_n\} \quad (6)$$

MR analysis is divided into 2, namely qualitative reliability analysis (FMEA) and quantitative reliability analysis (RAM). Qualitative MR analysis only discusses the possibilities of what, why, and how the failure of a machine/system can occur. However, it is impossible to answer when and how likely a machine/system failure could occur in the future. On the other hand, quantitative reliability analysis can answer it. Therefore, quantitative MR analysis is needed to analyze the possibility of machine/system failure in the future [44]. In addition, quantitative analysis of MR also needs to consider the distribution of its functions because if it is not taken into account, the calculation results will be inaccurate and unstable [45]. Therefore, to analyze the MR, this study uses four PD: normal distribution, lognormal, exponential, and Weibull. The selected PD has the smallest Anderson Darling value and the most significant correlation coefficient. Search PD and parameters for each system using Minitab 18 software [46]. System damage less than three during the study period will be determined as an exponential distribution.

Each selected PD has the formula to calculate the MR value. Furthermore, the results of the MR calculation are ranked/ranked. The MR rating on the machine has five levels. Each level shows MPL, with level 1 (failure ratio value 0-5%) being a very good/world-class level with routine maintenance recommendations. Level 2 (failure ratio value 6-10%) is a good performance level with routine maintenance recommendations + PM. Level 3 (failure ratio value 11-50%) is a moderate level (sufficient) with recommendations to improve failure analysis to identify possible corrective or replacement actions required, depending on the criticality. Level 4 (failure ratio value 51-90%) is a bad level with a recommendation to start the planning process to replace or rebuild, considering the risks and consequences of failure. Finally, level 5 (failure ratio value more than 90%) is very poor, with immediate recommendations to assess risk, replace, or maintain based on the assessment. The calculation of failure rate and failure ratio uses the following formula [8]:

$$\lambda(t) = \frac{f(t)}{R(t)} \quad (7)$$

$$Failure\ ratio(\zeta) = \frac{\lambda(t)}{T_\lambda} \times 100\% \quad (8)$$

with:

$f(t)$ = probability distribution function (PDF)

$\lambda(t)$ = machine or system failure rates

T_λ = total machine or system failure rate

2.1.1 Maintenance time intervals

The calculation of the maintenance time interval is to find and determine the ideal maintenance time interval. However, in the process, the reliability value is determined in advance according to the desired conditions to optimize machine performance. In this study, the calculation of the maintenance time interval is determined based on several criteria: "optimal criteria for MR with MPL level 1"; "the optimal standard for routine maintenance + PM with MPL level 2"; "criteria for an optimal maintenance time interval (the proposed failure ratio value is lower than the initial failure ratio value)"; "the current optimal standard of maintenance (maintenance time based on MTBF value)"; and "criteria based on optimal downtime value." The calculation of maintenance time intervals uses the equation used to calculate the expected downtime [47], [48]:

$$D(tp) = \frac{\text{Expected cycle time}}{\text{Total expected downtime per cycle}} \quad (9)$$

The formula for Total expected downtime per cycle and Expected cycle time is:

$$\text{Total expected downtime per cycle} = T_p \times R(tp) + T_f \times (1 - R(tp)) \quad (10)$$

$$\text{Expected cycle time} = (t_p + T_p) \times R(tp) + (M(tp) + T_f) \times (1 - R(tp)) \quad (11)$$

Then the total downtime per cycle $D(tp)$ is:

$$D(tp) = \frac{T_p \times R(tp) + T_f \times (1 - R(tp))}{(t_p + T_p) \times R(tp) + (M(tp) + T_f) \times (1 - R(tp))} \quad (12)$$

$$M(tp) = \frac{MTBF}{(1 - R(tp))} \quad (13)$$

with:

$D(tp)$ = total expected downtime per cycle.

- Tf (MTTR) = time to do damage repair.
- Tp (MTTR) = time to make preventive replacement.
- tp = preventive replacement interval.
- R(tp) = probability of occurrence of preventive replacement cycle at time tp.
- M(tp) = the expected value of the length of the breakdown cycle if a repair replacement is carried out.

The time interval between failures is calculated from the difference between the time the machine is repaired until the next machine failure is called time to failure (TTF). Meanwhile, the MTBF is the average time a machine can operate before a breakdown occurs. Therefore, the term MTBF is used for a machine that can be repaired, whereas MTTF indicates the expected failure time for a system that cannot repair. For initial MPL, MTTR is calculated by dividing downtime or time to repair (TTR) by the number of corrective actions. Then MTBF is uptime or TBF divided by the number of corrective actions [27].

Furthermore, for the optimization of OEE-ME and MR, the calculation of MTTR and MTBF follows the selected PD. Meanwhile, the mean time between maintenance (MTBM) includes PM and CM. MTBM is calculated by dividing the operating time by the total number of maintenance actions (PM+CM). Then, the mean maintenance time (MMT) is calculated by adding up the PM and CM times and dividing by the number of scheduled and unscheduled maintenance activities during the specified period. The formula for calculating inherent availability (Ai) and archive availability (Aa) [49]:

$$A_i = \frac{MTBF}{MTBF+MTTR} \quad (14)$$

$$A_a = \frac{MTBM}{MTBM+MMT} \quad (15)$$

2.2 Mobile crane (MC)

The object of this research is an all-terrain type mobile crane. A Mobile crane is lifting equipment that lifts and lowers material vertically and moves material horizontally. Mobile cranes are widely used in the assembly, repair, and material handling of steel and reinforced concrete structures. The advantages of mobile cranes are mobility, travel speed, and quick setup at the job site [50]. The mobile crane, the object of this research, is used in one Indonesian oil and gas company. Its main activity is loading and unloading materials with supply ships at Indonesia's Marunda Jetty. The details of the activities are shown in Figure 2.



Figure 2. Lifting activity mobile crane with supply boat at Marunda Jetty

The main system configuration of the mobile crane consists of the powertrain (PT), wheels, brake & steering system (WBS), carrier frame & suspension system (CFS), outrigger mechanism (OM), electrical devices (ED), safety devices (SD), swing mechanism (SM), boom mechanism (BM) and lifting device (LD). After knowing the configuration of the main mobile crane system, the next step is to sequence its activities to produce a product. The stages of mobile crane activities generally consist of 3 stages, namely: "The first stage is preparation and mobilization of mobile cranes to the lifting area (this activity involves PT, WBS, CFS, and ED)"; "The second stage is setting up the mobile crane to carry out lifting activities such as leveling and stability condition of the mobile crane as well as checking the function of security equipment such as anti-two block, load moment indicator, etc. (this activity involves OM and SD)"; "The third stage of lifting activity is carrying out loading and unloading activities by swinging mobile crane towards the material to be lifted, then adjusting the length of the boom, and booming the position with the boom up-down, then doing hoisting-lowering to pick up the load and lower the load (this activity

involves SM, BM, and LD). A function block diagram (FBD) is made based on the activity data. FBD is a functional relationship diagram showing the relationship between asset functions at the same level. FBD itself is used to describe the working system of a machine. In addition, the FBD represents the system's main functions in blocks containing the functions of each of the subsystems that make up the system. It is hoped that this FBD will make it easier when a failure occurs. FBD on mobile cranes can be modeled as shown in Figure 3. The making of this FBD refers to mobile crane activities in the field, which have been processed by researchers following the stages of mobile crane activity.

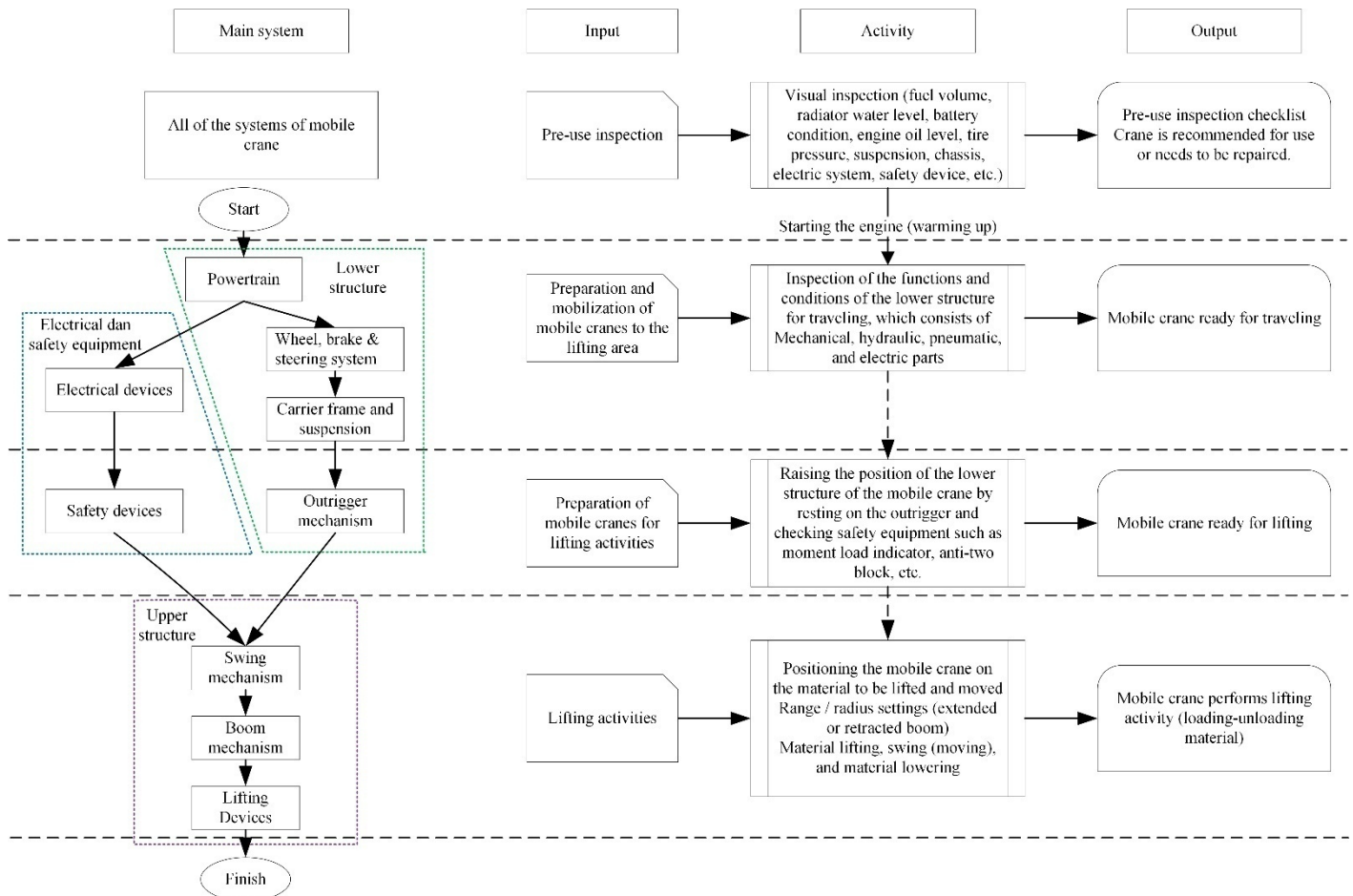


Figure 3. Function block diagram of the main system configuration model of the mobile crane

3 METHODOLOGY

3.1 Research design

This study will discuss maintenance performance with maintenance time intervals as the independent variable, namely the maintenance function. Then the maintenance time interval will be measured by OEE-ME and MR as the basis for machine performance and reliability. Finally, the measurement results will be interpreted using a health index to determine the MPL. The object of this research is a mobile crane (lifting equipment) unit. Therefore, to complete this research, the researcher uses a research design that is quantitative reliability analysis (RAM). Quantitative reliability analysis will get the probability of machine/system failure in the future. In addition, by using quantitative reliability analysis, scheduled maintenance time intervals that result in downtime can be intervened or adjusted to the set targets. Thus, the target is to optimize the OEE-ME, MR, and MPL values.

3.2 Research stages

This research begins with collecting data on machine operation, PM data records, and CM data records obtained from company records stored in the maintenance department, direct daily observations by researchers, and interviews with the Performing Authority (foreman level position) and Area Authority (supervisor level position). Then based on these data, the initial OEE-ME, MR, and MPL calculations were performed. Furthermore, the critical system is selected based on the frequency of damage using the Pareto principle. The selected critical system will then be reviewed for failure frequency data in TBF and TTR. If the frequency does not reach three times during the study period, it will be included in the exponential distribution. Meanwhile, a PD test will be conducted for systems that fail three or more times during the study period.

After getting the results of the PD of each system and its parameters, make an RBD calculate the RAM of the entire system. The next step is to perform maintenance time interval scenarios with predetermined criteria. Next, based on the criteria, the new OEE-ME and MR values were assessed. The new OEE-ME and MR values were then interpreted with the health index to determine the results and compared with the initial MPL.

After all optimization processes are carried out and obtained. Then hypothesis testing is carried out, namely the maintenance time interval to OEE-ME, the maintenance time interval to MR, and collaboration between OEE-ME and MR to MPL. Testing this hypothesis uses a regression test to see the magnitude of the effect and a correlation test to see the significance of each research variable. The next stage is to conclude from the results of the study and suggestions for further research. The flowchart of this research is shown in Figure 4.

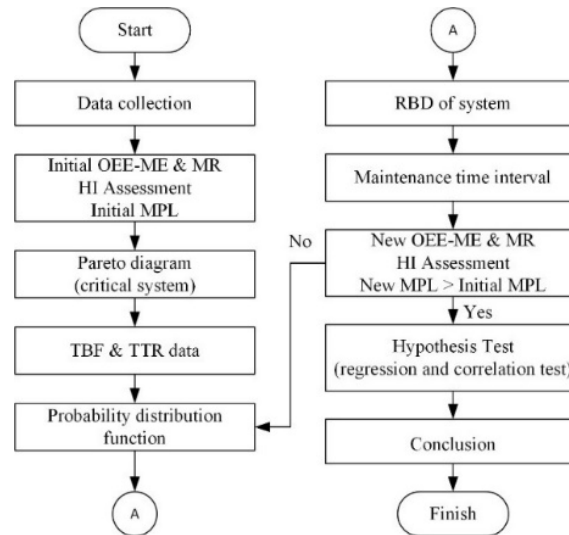


Figure 4. Research flowchart

3.3 Data and data collection methods

This section begins by collecting historical data on the operation, maintenance, and main system's configuration. Data collection starts from January 1, 2019, to June 17, 2021.

The policy rules for the company carry out work activities every day from 07.00 to 16.00, with working hours shown in table 1.

Table 1. Daily work activity

Activity	Working hours	Time (minutes)
Start	07.00	0
All Crew morning meeting	07.00-07.30	30
Toolbox talk crew lifting	07.30-07.45	15
Pre-use inspection mobile crane	07.45-08.00	15
Lifting activity	08.00-09.30	90
Morning coffee time	09.30-09.45	15
Lifting activity	09.45-12.00	135
Lunch	12.00-13.00	60
Lifting activity	13.00-14.30	90
Afternoon coffee time	14.30-14.45	15
Lifting activity	14.45-15.45	60
Housekeeping	15.45-16.00	15

Based on these data (table 1), can make calculations:

Mobile crane operation by adding up the lifting activity time, namely: $90+135+90+60 = 375$ minutes.

Total working time for a day = $30+15+15+90++15+135+60+90+15+60+15 = 540$ minutes.

Total time: period January 1, 2019 to June 17, 2021 = 899 days, so Total calendar time = $899 \times 540 = 485460$ minutes.

Non-productive time per day = $30+15+15+15+60+15+15 = 165$ minutes, so the total Non-productive time during the study period = $899 \times 165 = 148335$ minutes.

Total available time = $485460 - 148335 = 337125$ minutes or $375 \times 899 = 337125$ minutes.

It is known that the mobile crane (MC) used in this study is a machine that operates 375 minutes per day and operates every day. Therefore, in two and a half years, the total available time (TAT) data is 337125 minutes. The assumption used is that the standby time of the machine is considered uptime because the machine is in a

condition ready for operation (available). Information data was obtained from company records, direct daily observations by researchers, and interviews with the Performing Authority (foreman level position) and Area Authority (supervisor level position) at the research location.

Meanwhile, downtime starts from the cessation of machine operation until maintenance is completed and the machine is declared ready to operate. Daily periodic checks before and after the operation are not considered to affect machine time. The results of the data collection consist of: total calendar time (TCT) during the period, total nonproductive time (NPT: meeting all crew, lifting team talk box talk, lunch break inspection before use, coffee time in the morning and evening), PM, frequency of PM, CM, and the CM frequency. Furthermore, the data is processed as shown in table 2.

An important goal of good maintenance is so that the mobile crane can work in prime condition as the backbone of operational activities at the Indonesian Marunda Jetty. For maintenance to be more effective, the maintenance policy must consider the interactions between the various components of the system. Currently, the company is implementing a mobile crane maintenance strategy using PM and CM methods. PM mobile crane data is shown in table 3. In general, PM activities are routine maintenance carried out periodically by the company, including visual inspection and cleaning, lubricating, greasing, set up and adjustment, etc. Meanwhile, CM activities are non-routine maintenance and are carried out when the mobile crane fails, or breakdown maintenance is called minor stoppages.

Table 2. Mobile crane operation and maintenance data for the period January 1, 2019 to June 17, 2021

Total calendar time (TCT) (minutes)	Non-productive time (NPT) (minutes)	Total available time (TAT) (minutes)	Planned downtime/preventive maintenance (PM) (minutes)	PM frequency	Operating time (OT) (minutes)	Unplanned downtime/corrective maintenance (CM) (minutes)	CM frequency	Net operating time (NOT) (minutes)
485460	148335	337125	48925	129	288200	9230	32	278970

Table 3. Mobile crane preventive maintenance data for the period January 1, 2019, to June 17, 2021

No	TBF	TTR	No	TBF	TTR
1	3375	375	79	1125	375
2	2250	375	80	2250	375
3	2250	375	81	2250	375
4	2250	375	82	2250	375
5	2625	375	83	2250	375
6	1875	375	84	4875	500
7	2250	375	85	2125	375
8	1500	375	86	2625	375
9	3375	375	87	1875	375
10	1875	375	88	2250	375
...
53	750	375	119	2250	375
54	2250	375	120	1875	550
55	5250	375	121	2450	375
56	750	375	122	2250	375
57	1125	375	123	2250	375
58	2250	375	124	3000	375
59	2250	375	125	1500	375
60	2625	375	126	2625	375
61	2250	375	127	1875	600
62	2250	375	128	2025	225
...	129	2400	375

4 RESULT AND DISCUSSION

4.1 Initial OEE-ME, MR, and MPL

The results of optimization and analysis begin with the initial calculation of OEE-ME, MR, and MPL. Based on PM and CM mobile crane data, the initial calculations for OEE-ME, MR, and MPL are shown in table 4.

Table 4. Calculation of mean time between maintenance (MTBM), mean maintenance time (MMT), archive availability (Aa), availability (A), performance (P), and OEE-ME assessment

Variable	Value	Indicator OEE-ME	Result	MPL level
MTBM (minutes)	1732,73			
MMT (minutes)	361,21			
Aa	82,75%	90%	Need to be improved	
A	85,49%	90%	Need to be improved	
P	96,80%	95%	Achieved	
OEE-ME	82,75%	85%	Need to be improved	2

Then calculate MTBF, MTTR, failure rate (λ), failure ratio (ζ), and MR assessment. MR is obtained from three main system configurations, namely lower structure configurations such as powertrain (PT), wheels, brake & steering system (WBS), carrier frame & suspension system (CFS), outrigger mechanism (OM). Configuration of electrical & safety equipment such as electrical devices (ED) and safety devices (SD). Configuration of upper structure such as swing mechanism (SM), boom mechanism (BM), and lifting device (LD). The MR assessment of the main system is carried out partially (each system) based on CM data. The configuration of the main mobile crane system, as illustrated in the RBD, is shown in Figure 6. The results of the initial MR and MPL calculations are shown in table 5.

Table5. Calculation of MTBF, MTTR, inherent availability (A_i), failure rate (λ), failure ratio (ζ), and assessment of MR

System	TAT	Uptime/TBF	Downtime/TTR	Fail	MTBF	MTTR	A_i	λ	ζ	MPL level
PT	337125	335070	2055	5	67014	411	99,39%	0,000015	15,65%	3
WBS	337125	336255	870	3	112085	290	99,74%	0,000009	9,36%	2
CFS	337125	336810	315	1	336810	315	99,91%	0,000003	3,11%	1
OM	337125	336180	945	3	112060	315	99,72%	0,000009	9,36%	2
ED	337125	335235	1890	7	47890,71	270	99,44%	0,000021	21,90%	3
SD	337125	336235	890	4	84058,75	222,5	99,74%	0,000012	12,48%	3
SM	337125	337125	0	0	∞	0	100,00%	0,000000	0,00%	1
BM	337125	336910	215	1	336910	215	99,94%	0,000003	3,11%	1
LD	337125	335075	2050	8	41884,38	256,25	99,39%	0,000024	25,04%	3
Total		327895	9230	32				0,000095	100%	

Based on the calculations in table 3, the availability value is 85.49%, the performance value is 96.80%, the OEE-ME value is 82.75%, and the initial MPL is at level 2. Therefore, the availability and OEE-ME values need to be increased to achieve MPL level 1. Then, the initial MPL assessment in table 4 is based on the calculation of the failure ratio, or MR obtained partial system values at different levels. CFS, SM, and BM systems at MPL level 1. WBS and OM systems at MPL level 2 and PT, ED, SD, and LD systems at MPL level 3.

4.2 Pareto principle

Furthermore, CM data processing is carried out using the Pareto principle to determine the critical system on the mobile crane. The Pareto principle highlights the most significant loss among the data set shown in the Pareto diagram. The losses associated with critical OEE-ME elements are ranked according to their impact on OEE-ME performance in a Pareto diagram. It provides an overview of the severity of the loss to the maintenance department to prioritize the elimination of losses. By focusing on the main disadvantages of OEE-ME, the maintenance department can leverage improvement efforts and ensure the effective use of limited resources [13]. The results of data processing on the Pareto principle are shown in Figure 5, namely systems with cumulative failures of 93.8% are LD, SD, ED, OM, PT, and WBS. Then the system is declared as a critical system.

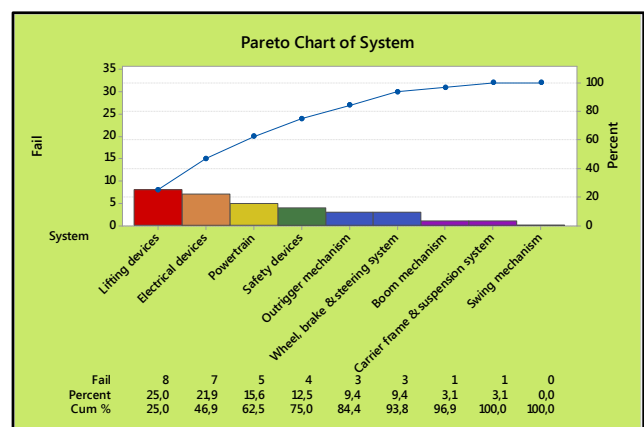


Figure 5. Pareto diagram for a critical system on a mobile crane

4.3 TBF and TTR of a critical system, PD, and Parameter

After knowing the critical system of the mobile crane, TBF and TTR data from the critical system will be searched for PD and its parameters. TBF and TTR data for the mobile crane system are shown in table 6.

Table 6. TBF and TTR data of the mobile crane system.

PT		WBS		OM	
TBF minutes	TTR minutes	TBF minutes	TTR minutes	TBF minutes	TTR minutes
55875	375	72870	255	127500	375
114570	180	98685	315	3060	315
87000	375	128700	300	197370	255
39375	750	CFS			
13875	375	230685	315	LD	
ED		SD		8715	285
13950	300	131125	125	60500	250
23385	240	28560	315	29340	285
43305	195	28620	255	78435	315
45900	225	94305	195	36870	255
62325	300	SM		32700	300
51870	255	BM		37425	75
38625	375	261535	215	48090	285

Furthermore, the parameters of each system are searched using TBF and TTR data. Before looking for parameters, first look for PD using Anderson Darling and the correlation coefficient. The results of the PD test on a critical system show that all TBF data are normally distributed. At the same time, the PD of the TTR data is different. TTR-PT and TTR-ED are Lognormally distributed. TTR-WBS and TTR-LD Weibull distributed, TTR-OM and TTR-SD Normal distribution. For mobile cranes with PM, TBF is normally distributed, and TTR is lognormally distributed.

After knowing the PD, the next step is to find the parameter value. The system's TBF and TTR parameter values are based on CM data, while the mobile crane parameter values are based on PM data. Therefore, the TBF and TTR parameter values for each system are shown in table 7 and table 8, while the TBF and TTR parameter values for mobile cranes are shown in table 9.

Table 7. TBF parameter values for each system

System (TBF)	PD	Parameter		
		Failure rate (λ)	Mean (μ)	StDev ($\sigma=s$)
PT	Normal		62139	45362,4
WBS	Normal		10008	34009,8
CFS	Exponential	0,000003		
OM	Normal		10931	118367
ED	Normal		39908,6	18218,1
SD	Normal		70652,5	56190,5
SM	There is no failure			
BM	Exponential	0,000003		
LD	Normal		41509,4	22783,2

Table 8. TTR parameter values for each system

TTR	PD	Parameter	
		Scale (α)	Median (t_{med})
PT	Lognormal	0,534785	371,951
ED	Lognormal	0,240222	264,523
		μ	$\sigma=s$
OM	Normal	315,00	73,10
SD	Normal	222,50	95,84
		Shape (β)	Scale (α)
WBS	Weibull	8,94	304,04

TTR	PD	Parameter	
		Scale (α)	Median (tmed)
LD	Weibull	2,83974	285,797
		λ	
CFS	Exponential	0,000003	
BM	Exponential	0,000003	
SM	There is no failure		

Table 9. Parameter values of TBF and TTR of mobile crane

MC	PD	Parameter			
		Scale (α)	Mean (μ)	StDev ($\sigma=s$)	Median (tmed)
TBF	Normal		2225,20	693,91	
TTR	Lognormal	0,037521			377,956

4.4 Reliability block diagram (RBD) of mobile crane

Furthermore, from FBD in Figure 3, RBD is made to analyze the reliability of each system that has been created. The RBD method is a method that applies a function equation or failure logic to each element and is represented in the form of a block diagram. The block diagram states the process between the main parts consisting of input, process, and output. The overall RBD of the mobile crane system is shown in Figure 6.

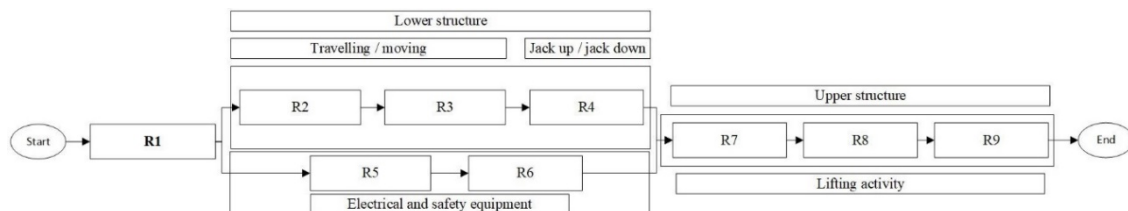


Figure 6. Reliability block diagram of mobile crane

4.5 Optimization maintenance time interval

In this section, we will analyze the calculation of MTBF, MTTR, reliability (R), probability distribution function (PDF), cumulative distribution function (CDF), failure rate (λ), maintainability (M), downtime (D), and A_i at each system to obtain optimal maintenance time intervals. The calculation is determined based on several criteria. Optimal criteria for MR with MPL level 1. Optimal criteria for routine maintenance + PM with MPL level 2. Criteria for an optimal maintenance time interval (the proposed failure ratio value is lower than the initial failure ratio value). Current criteria (maintenance time based on MTBF value) and criteria based on optimal downtime value. The calculation results are shown in Tables 10 to 12. The calculation of maintenance time intervals uses the equation (12) used in calculating the expected downtime.

Table 10. MTBF, MTTR, and Maintainability (M) of system mobile crane

System/Machine	PT	WBS	OM	ED	SD	LD	MC
MTBF	62139	100085	109310	39908,6	70652,5	41509,4	36858,3
MTTR	429,13	287,84	315	272,27	222,5	254,63	378,22
M	60,54%	99,98%	50%	54,78%	50%	92,03%	83,94%

The MTBF assessment showed the ED system with the lowest score of 39908.6 minutes and the highest OM system of 109310 minutes. On the other hand, the MTTR assessment in the SD system with the lowest value was 222.5 minutes, and the highest was in the PT system, which was 429.13 minutes. Then, using the MTTR value, the maintainability calculation is carried out. The OM and SD systems with the lowest maintainability are 50%, and the highest in the WBS system, 99.98%.

Based on each system's MTBF and MTTR values, A_i and system availability (A system) values are obtained.

Table 11. A_i value and availability system

Ai									A system
PT	WBS	CFS	OM	ED	SD	SM	BM	LD	
99,31%	99,71%	99,91%	99,71%	99,32%	99,69%	100%	99,94%	99,39%	98,64%

In the calculation results, the Ai value for all systems is greater than 99%, and the calculation for the A system value is 98.64%.

Table 12. The optimal maintenance time interval of system mobile crane

TP						WBS					
Assessment	MPL level 1	MPL level 2	new ζ < initial ζ	MTBF	Optimal downtime	Assessment	MPL level 1	MPL level 2	new ζ < initial ζ	MTBF	Optimal downtime
tp	6000	31500	52500	62139	70500	tp	51000	66000	69000	90000	100085
R (tp)	89,21 %	75,03 %	58,41 %	50,00 %	42,69%	R (tp)	92,55%	84,19%	81,96%	61,66%	50,00%
PDF (tp)	4,E-06	7,E-06	9,E-06	9,E-06	9,E-06	PDF (tp)	4,E-06	7,E-06	8,E-06	1,E-05	1,E-05
CDF (tp)	0,1079	0,2497	0,4159	0,5	0,5731	CDF (tp)	0,0745	0,1581	0,1804	0,3834	0,5
M(tp)	575690	248852	149422	124278	108423	M(tp)	1343900	632965	554924	261038	200170
D (tp)	0,63%	0,57%	0,46%	0,46%	0,46%	D (tp)	0,20%	0,18%	0,18%	0,18%	0,19%
A (tp)	99,37 %	99,43 %	99,54 %	99,54 %	99,54%	A (tp)	99,80%	99,82%	99,82%	99,82%	99,81%
λ	5,E-06	9,E-06	2,E-05	2,E-05	2,E-05	λ	4,E-06	8,E-06	9,E-06	2,E-05	2,E-05
ζ	4,81%	9,79%	15,44 %	18,45 %	21,25%	ζ	4,69%	8,85%	9,89%	19,10%	24,61%
OM						ED					
Assessment	MPL level 1	MPL level 2	new ζ < initial ζ	MTBF	Optimal downtime	Assessment	MPL level 1	MPL level 2	new ζ < initial ζ	MTBF	Optimal downtime
tp	61500	109310	148500	166500	168000	tp	7500	15000	25500	36000	39908,6
R (tp)	65,69 %	50,00 %	37,03 %	31,45%	31,00%	R (tp)	96,24%	91,42 %	78,55 %	58,49 %	50,00%
PDF (tp)	3,E-06	3,E-06	3,E-06	3,E-06	3,E-06	PDF (tp)	5,E-06	9,E-06	2,E-05	2,E-05	2,E-05
CDF (tp)	0,3431	0,5	0,6297	0,6855	0,69	CDF (tp)	0,0376	0,0858	0,2145	0,4151	0,5
M(tp)	318560	218620	173587	159458	158422	M(tp)	1060660	465274	186052	96151	79817
D (tp)	0,21%	0,19%	0,19%	0,19%	0,19%	D (tp)	0,57%	0,51%	0,45%	0,44%	0,45%
A (tp)	99,79 %	99,81 %	99,81 %	99,81%	99,81%	A (tp)	99,43%	99,49 %	99,55 %	99,56 %	99,55%
λ	5,E-06	7,E-06	9,E-06	1,E-05	1,E-05	λ	5,E-06	9,E-06	2,E-05	4,E-05	4,E-05
ζ	4,96%	7,07%	9,04%	10,00%	10,09%	ζ	4,91%	9,87%	21,39 %	38,38 %	45,94%
SD						LD					
Assessment	MPL level 1	MPL level 2	new ζ < initial ζ	MTBF	Optimal downtime	Assessment	MPL level 1	MPL level 2	new ζ < initial ζ	MTBF	Optimal downtime
tp	10500	45000	58500	70652,5	90000	tp	3000	13500	31500	39000	41509,4
R (tp)	85,78 %	67,60 %	58,56 %	50,00%	36,53%	R (tp)	95,45%	89,05 %	66,98 %	54,39 %	50,00%
PDF (tp)	4,E-06	6,E-06	7,E-06	7,E-06	7,E-06	PDF (tp)	4,E-06	8,E-06	2,E-05	2,E-05	2,E-05
CDF (tp)	0,1422	0,324	0,4144	0,5	0,6347	CDF (tp)	0,0455	0,1095	0,3302	0,4561	0,5
M(tp)	496871	218060	170499	141305	111317	M(tp)	912502	379209	125706	91000	83019
D (tp)	0,28%	0,22%	0,21%	0,21%	0,21%	D (tp)	0,57%	0,47%	0,41%	0,40%	0,61%
A (tp)	99,72 %	99,78 %	99,79 %	99,79%	99,79%	A (tp)	99,43%	99,53 %	99,59 %	99,60 %	99,39%
λ	5,E-06	9,E-06	1,E-05	1,E-05	2,E-05	λ	4,E-06	9,E-06	2,E-05	3,E-05	4,E-05
ζ	4,90%	9,93%	12,42 %	14,89%	19,21%	ζ	4,61%	9,69%	24,90 %	33,57 %	36,74%

The optimal maintenance time interval of the mobile crane system shows that the MPL level 1 criterion has the shortest maintenance time interval. While the maintenance time interval with optimal criteria for downtime with the longest maintenance time interval. OEE-ME, MR will assess the ideal maintenance time interval and MPL, discussed in the following subsection. The results of comparing the maintenance time interval of the mobile crane system are as shown in Figure 7

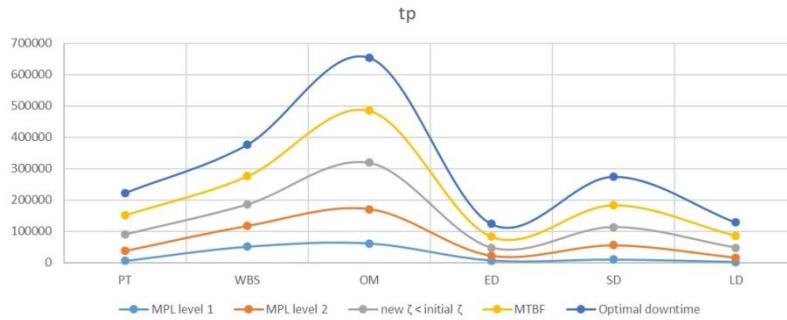


Figure 7. Comparing the maintenance time interval of the mobile crane system

4.6 New OEE-ME, MR, and MPL vs. initial MPL

Furthermore, the calculation of availability, performance, and OEE-ME is carried out. In addition, an MR assessment is also carried out referring to the failure ratio of each system. From the day of data processing, we can also find out the value of Aa. Then the MPL is assessed based on the health index to determine the system's condition if maintenance is carried out with predetermined time intervals and criteria. The results of data processing as shown in table 13 to table 17.

Table 13. Optimal MR – MPL level 1

System	Total available time	Uptime	Downtime	Fail	λ	ζ	MPL Level 1	R (t)
PT	337125	313013	24112	56	0,000005	4,81%	0-5% = Very good	89,21%
WBS	337125	335222	1903	7	0,000004	4,69%	0-5% = Very good	92,55%
CFS	337125	336810	315	1	0,000003	3,11%	0-5% = Very good	36,79%
OM	337125	335398	1727	5	0,000005	4,96%	0-5% = Very good	61,89%
ED	337125	324887	12238	45	0,000005	4,91%	0-5% = Very good	96,24%
SD	337125	329981	7144	32	0,000005	4,90%	0-5% = Very good	85,78%
SM	337125	337125	0	0	0,000000	0,00%	0-5% = Very good	100%
BM	337125	336910	215	1	0,000003	3,11%	0-5% = Very good	36,79%
LD	337125	313013	24112	112	0,000004	4,61%	0-5% = Very good	95,45%
TCT	NPT	TAT	PM	PM Frequency	OT	CM	CM Frequency	NOT
6750	375	337125	18750	50	318375	71765	260	246610
Improve OEE-ME								
Variabel	Value	Indicator ME	MPL Result		MTBM	MMT	Aa	Result
A	94,44%	90%	Achieved		796,26	292,26	73,15%	Need to be improved
P	77,46%	95%	Need to be improved					
OEE-ME	73,15%	85%	Need to be improved					

The maintenance time interval based on the optimal MR shows that the MPL is level 1. Still, the performance, OEE-ME, and Aa values are below world-class standards, so it is necessary to improvise to increase these values

Table 14. Optimal normal maintenance + PM – MPL level 2

System	Total available time	Uptime	Downtime	Fail	λ	ζ	MPL Level 2	R (t)
PT	337125	332532	4593	11	0,000009	9,79%	6-10% = Good	75,03%
WBS	337125	335719	1406	5	0,000009	9,89%	6-10% = Good	81,96%
CFS	337125	336810	315	1	0,000003	3,11%	6-10% = Good	36,79%
OM	337125	336487	638	2	0,000010	10,00%	6-10% = Good	31,45%
ED	337125	331006	6119	22	0,000009	9,87%	6-10% = Good	91,42%
SD	337125	335458	1667	7	0,000009	9,93%	6-10% = Good	67,60%
SM	337125	337125	0	0	0,000000	0,00%	6-10% = Good	100%
BM	337125	336910	215	1	0,000003	3,11%	6-10% = Good	36,79%
LD	337125	330766	6359	25	0,000009	9,69%	6-10% = Good	89,05%
TCT	NPT	TAT	PM	PM Frequency	OT	CM	CM Frequency	NOT
6750	375	337125	18750	50	318375	21312	75	297063

Improve OEE-ME								
Variabel	Value	Indicator ME	MPL Result		MTBM	MMT	Aa	Result
A	94,44%	90%	Achieved		2385,06	321,65	88,12%	Need to be improved
P	93,31%	95%	Need to be improved					
OEE-ME	88,12%	85%	Achieved					

The maintenance time interval based on optimal normal maintenance + PM shows that the MPL value is level 2. Still, the performance and Aa values are below world-class standards, so it is necessary to improvise to increase these values.

Table 15. Optimal downtime

System	Total available time	Uptime	Downtime	Fail	λ	ζ	MPL	R (t)
PT	337125	335073	2052	5	0,000020	21,25%	11-50% = Fair	42,69%
WBS	337125	336047	1078	4	0,000018	19,10%	11-50% = Fair	61,66%
CFS	337125	336810	315	1	0,000003	3,11%	0-5% = Very good	36,79%
OM	337125	336493	632	2	0,000010	10,09%	11-50% = Fair	31,00%
ED	337125	334575	2550	9	0,000037	38,38%	11-50% = Fair	58,49%
SD	337125	336292	833	4	0,000018	19,21%	11-50% = Fair	36,53%
SM	337125	337125	0	0	0,000000	0,00%	0-5% = Very good	100%
BM	337125	336910	215	1	0,000003	3,11%	0-5% = Very good	36,79%
LD	337125	334924	2201	9	0,000032	33,57%	11-50% = Fair	54,39%
TCT	NPT	TAT	PM	PM Frequency	OT	CM	CM Frequency	NOT
6750	375	337125	18750	50	318375	9877	34	308498
Improve OEE-ME								
Variabel	Value	Indicator ME	MPL Result		MTBM	MMT	Aa	Result
A	94,44%	90%	Achieved		3660,00	339,62	91,51%	Achieved
P	96,90%	95%	Achieved					
OEE-ME	91,51%	85%	Achieved					

The maintenance time interval based on the optimal downtime shows that the MPL value in each system varies according to the interval. The assessment results show that the proposed failure ratio is higher than the initial failure ratio, so it is necessary to improvise the maintenance time interval. Meanwhile, the availability, performance, OEE-ME, and Aa values have reached world-class standards.

Table 16. Current (maintenance time based on MTBF value)

System	Total available time	Uptime	Downtime	Fail	λ	ζ	MPL	R (t)
PT	337125	334797	2328	5	0,000018	18,45%	11-50% = Fair	50,00%
WBS	337125	336155	970	3	0,000023	24,61%	11-50% = Fair	50,00%
CFS	337125	336810	315	1	0,000003	3,11%	0-5% = Very good	36,79%
OM	337125	336154	971	3	0,000007	7,07%	6-10% = Good	50,00%
ED	337125	334825	2300	8	0,000044	45,94%	11-50% = Fair	50,00%
SD	337125	336063	1062	5	0,000014	14,89%	11-50% = Fair	50,00%
SM	337125	337125	0	0	0,000000	0,00%	0-5% = Very good	100%
BM	337125	336910	215	1	0,000003	3,11%	0-5% = Very good	36,79%
LD	337125	335057	2068	8	0,000035	36,74%	11-50% = Fair	50,00%
TCT	NPT	TAT	PM	PM Frequency	OT	CM	CM Frequency	NOT
6750	375	337125	18750	50	318375	10229	35	308146
Improve OEE-ME								
Variabel	Value	Indicator ME	MPL Result		MTBM	MMT	Aa	Result
A	94,44%	90%	Achieved		3615,95	340,05	91,40%	Achieved
P	96,79%	95%	Achieved					
OEE-ME	91,40%	85%	Achieved					

The current optimal standard of maintenance (maintenance time based on MTBF value) shows that the MPL value in each system varies according to the interval. The assessment results show that the proposed failure ratio is higher than the initial failure ratio, so it is necessary to improvise the maintenance time interval. Meanwhile, the availability, performance, OEE-ME, and Aa values have reached world-class standards.

Table 17. The optimal maintenance time interval

System	Total available time	Uptime	Downtime	Fail	λ	ζ	MPL	R (t)
PT	337125	334369	2756	6	0,000015	15,44%	11-50% = Fair	58,41%
WBS	337125	335655	1470	5	0,000008	8,85%	6-10% = Good	84,19%
CFS	337125	336810	315	1	0,000003	3,11%	0-5% = Very good	36,79%
OM	337125	336154	971	3	0,000009	9,04%	6-10% = Good	37,03%
ED	337125	333525	3600	13	0,000020	21,39%	11-50% = Fair	78,55%
SD	337125	335843	1282	6	0,000012	12,42%	11-50% = Fair	58,56%
SM	337125	337125	0	0	0,000000	0,00%	0-5% = Very good	100%
BM	337125	336910	215	1	0,000003	3,11%	0-5% = Very good	36,79%
LD	337125	334400	2725	11	0,000024	24,90%	11-50% = Fair	66,98%
TCT	NPT	TAT	PM	PM Frequency	OT	CM	CM Frequency	NOT
6750	375	337125	18750	50	318375	13334	46	305041
Improve OEE-ME								
Variabel	Value	Indicator ME	MPL Result		MTBM	MMT	Aa	Result
A	94,44%	90%	Achieved		3167,63	333,17	90,48%	Achieved
P	95,81%	95%	Achieved					
OEE-ME	90,48%	85%	Achieved					

The maintenance time interval based on the optimal maintenance time interval shows that the MPL value in each system varies according to the interval. The assessment results show that the proposed failure ratio value is lower than the initial failure ratio value. Meanwhile, the availability, performance, OEE-ME, and Aa values have reached world-class standards. Details of the differences in each maintenance time interval as shown in Figure 8.

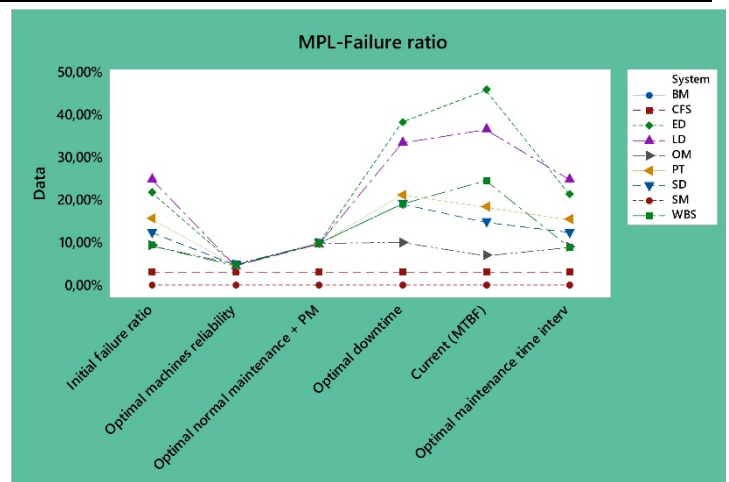


Figure 8. Graph of differences in each maintenance time interval

The final part of this optimization compares the initial OEE-ME, MR, and MPL with the new OEE-ME, MR, and MPL. Referring to the analysis of the optimization assessment, the researcher suggests the company carry out maintenance actions for mobile cranes based on the optimal maintenance time interval (the proposed failure ratio value is lower than the initial failure ratio value). These criteria are selected to get the value of new OEE-ME, failure ratio or MR and MPL is better than initial OEE-ME, initial failure ratio or MR and initial MPL. Figure 9 (a) shows the comparison of the new OEE-ME value with the initial OEE-ME, and Figure 9 (b) shows the comparison of the selected new failure ratio value with the initial failure ratio. Furthermore, Figure 10 shows the new MPL values based on the collaboration of OEE-ME and MR.

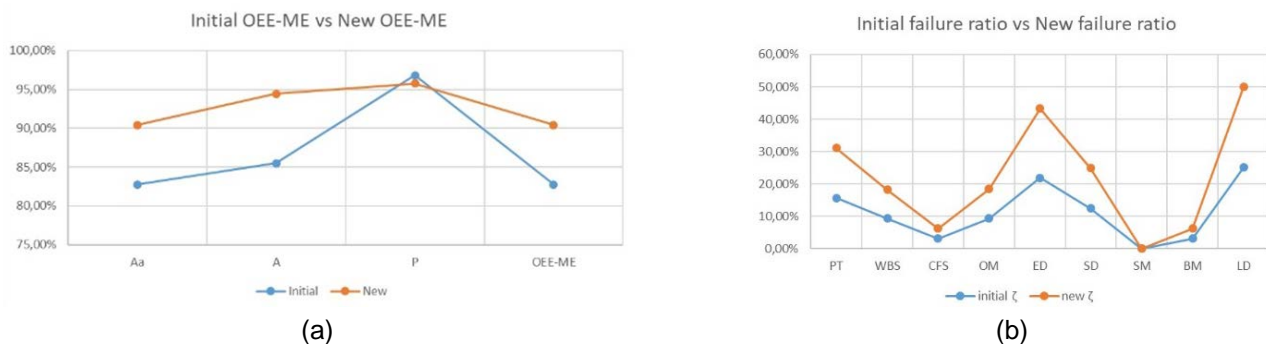


Figure 9. Comparison of new OEE-ME and new failure ratio values with initial OEE-ME and initial failure ratio.



Figure 10. The new MPL is based on the collaboration of OEE-ME and MR.

The results of the collaboration between OEE-ME and MR resulted in better OEE-ME values and achieved world-class MPL. Then the new MR and initial MR values are at the same MPL level. However, the new MR value is better than the initial MR based on the failure ratio.

4.7 Hypothesis test

After all optimization processes are carried out, and results are obtained, the next step is to test the truth of the hypotheses built. The true test of the hypothesis in this study will go through a regression test to see the magnitude of the effect and a correlation test to see the significance of each research variable. Correlation assessment is based on five categories with a range of 0-1. Category one is very low, with an R square value of 0.00-0.199. The second category is low, with an R square value of 0.20-0.399. The third category is moderate, with an R square value of 0.40-0.599. The fourth category is strong, with an R square value of 0.60-0.799. Finally, category five is very strong, with an R square value of 0.80-1.00. Regression and correlation tests in this study used the Minitab 18 software. The test was carried out by taking 50 samples, increasing a maintenance time interval of 1500 minutes starting from the 4500th minute to the 78000th minute. The results of hypothesis testing with regression and correlation are as shown in Tables 17 to 19 for the significance test value with 95% confidence level and 5% alpha.

4.8 Maintenance time interval to OEE-ME

The first hypothesis test was conducted to see the effect of maintenance time interval on OEE-ME. The results of the calculation of the hypothesis test are shown in Table 18, and the Residual Normplot for OEE-ME is shown in Figure 11.

Table 18. Regression Analysis: OEE-ME on tp-MC

Model Summary				
P-Value	S	R-sq	R-sq (adj)	R-sq (pred)
0,000	0,0827079	75,07%	74,55%	67,26%
Regression Equation				
OEE-ME = -2,178 + 0,1965 tp-MC				

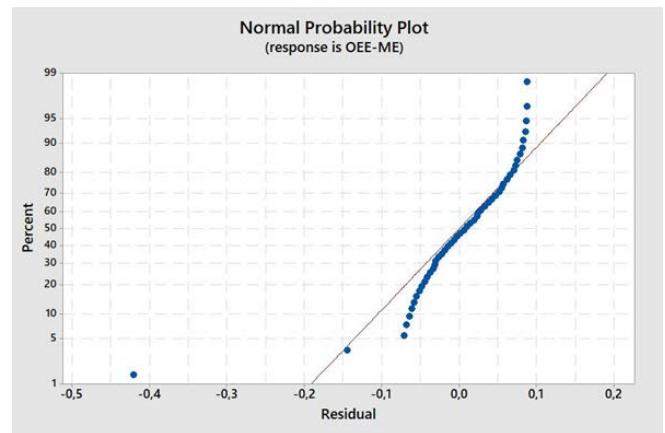


Figure 11. Normplot of Residuals for OEE-ME

Based on the results of the correlation and regression tests in Table 18, it can be stated that the correlation value between the maintenance time interval (tp-MC) and OEE-ME is in the strong category with an R square value of 75.07%. Then the coefficient of determination adjusted R square is 74.55% which means that the maintenance time interval (tp-MC) can explain OEE-ME by 74.55%, while other factors influence the remaining 25.45%. Furthermore, because the P-Value (0.000) is smaller than the alpha value of 0.05, it can be concluded that there is a significant effect between the maintenance time interval (tp-MC) and OEE-ME. As for the regression equation, it is $OEE-ME = -2.178 + 0.1965 tp-MC$.

4.9 Maintenance time interval to MR

The second hypothesis test was conducted to see the effect of maintenance time interval on MR or ζ . The results of the calculation of the hypothesis test are shown in Table 19, and the Normplot Residuals for MR are shown in Figure 12.

Based on the results of the correlation and regression tests in table 19, it can be stated that the correlation value between the maintenance time interval (tp-MC) and the failure ratio (ζ) is in the very strong category with an R square value of 94.34%. Then the coefficient of determination adjusted R square is 94.22%, which means that the maintenance time interval (tp-MC) can explain the failure ratio (ζ) of 94.22%, while other factors influence the remaining value of 5.78%.

Furthermore, because the P-Value (0.000) is smaller than the alpha value of 0.05, it can be concluded that there is a significant effect between the maintenance time interval (tp-MC) and the failure ratio (ζ). As for the regression equation is $\zeta = -12.555 + 0.9959 \text{ tp-MC}$.

Table 19. Regression Analysis: MR or ζ on tp-MC

Model Summary				
P-Value	S	R-sq	R-sq (adj)	R-sq (pred)
0,000	0,178106	94,34%	94,22%	93,17%
Regression Equation				
$\zeta = -12,555 + 0,9959 \text{ tp-MC}$				

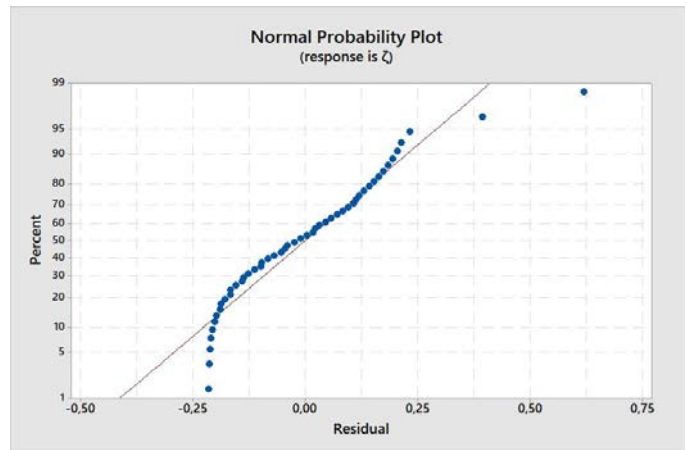


Figure 12. Normplot of Residuals for MR or ζ

4.10 OEE-ME and MR to MPL

The third hypothesis test was conducted to see the effect of OEE-ME collaboration and MR or on MPL. The results of the calculation of the hypothesis test are shown in table 20, and the Normplot Residuals for MR are shown in Figure 13.

Table 20. Regression Analysis: MPL-MC versus MR or failure ratio (ζ); OEE-ME

Model Summary				
P-Value	S	R-sq	R-sq (adj)	R-sq (pred)
0,000	0,0845023	67,13%	65,73%	63,96%
Regression Equation				
$\text{MPL-MC} = 1,0068 + 0,2345 \zeta - 0,791 \text{ OEE-ME}$				

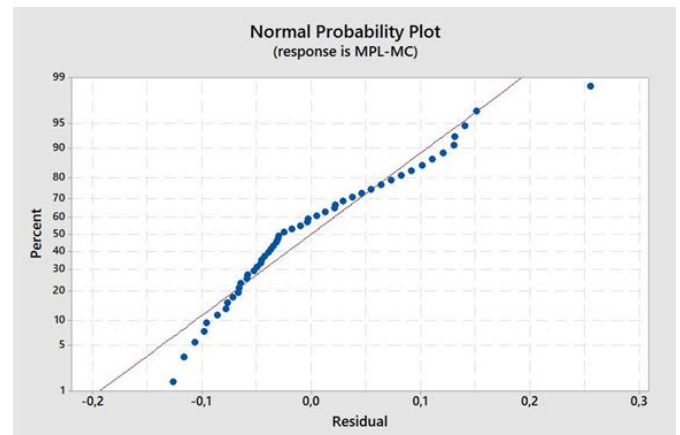


Figure 13. Normplot of Residuals for MPL-MC

Based on the results of the correlation and regression tests in table 20, it can be stated that the correlation value between failure ratio (ζ) and OEE-ME with MPL-MC is included in the strong category with an R square value of 67.13%. Then the coefficient of determination adjusted R square is 65.73% which means that the failure ratio (ζ) and OEE-ME can explain MPL-MC by 65.73%, while other factors influence the remaining value of 34.27%. Furthermore, because the P-Value (0.000) of the failure ratio (ζ) and OEE-ME is smaller than the alpha value of 0.05, it can be concluded that there is a significant effect between the failure ratio (ζ) and OEE-ME with MPL-MC. The regression equation is $\text{MPL-MC} = 1.0068 + 0.2345 \zeta - 0.791 \text{ OEE-ME}$.

CONCLUSION

Determining proper maintenance time intervals for machines is very important in all areas of industry. Errors in determining the maintenance schedule can result in considerable losses. To overcome these problems can be done by carrying out adequate planned maintenance. MPL can assess the success of maintenance activities. MPL is a function of OEE-ME and MR. This paper examines the optimization of MPL through the collaboration of OEE-ME and MR. The contribution of this study is (1) to analyze the significant effect of maintenance time intervals in optimizing the OEE-ME value. This contribution is a solution to the problem of OEE-ME analysis with the objective

function of availability and performance rate. (2) Analyzing the significant effect of maintenance time interval in optimizing the MR value. This contribution is a solution to the problem of MR analysis with the objective functions of reliability, availability, maintainability, failure rate, and failure ratio. (3) Analyzing the significant effect of optimizing OEE-ME and MR collaboration on optimizing MPL values. The collaboration results were interpreted with maintenance effectiveness using five health index levels as the basis for the objective function.

Based on the results of data processing and analysis, we can draw the following conclusions:

- Based on the Pareto principle, critical systems with cumulative failure of 93.8% are LD, SD, ED, OM, PT, and WBS.
- To optimization maintenance time intervals on each system through five proposed criteria, namely optimal MR, optimal normal maintenance + PM, optimal maintenance time interval, current (MTBF), and optimal downtime. The analysis results show that the optimal maintenance time interval is a better criterion than other criteria because it can meet the requirements of world-class OEE-ME and the proposed MR or new failure ratio is lower than the initial failure ratio.
- Based on the correlation and regression tests results, between maintenance time intervals (tp-MC) with MR or failure ratio (ζ) has a very strong correlation, and the effect is significant. Then the maintenance time interval (tp-MC) can explain the MR or failure ratio (ζ) of 94.22%.
- The correlation and regression test results showed that the maintenance time interval (tp-MC) with OEE-ME was strongly correlated and had a significant effect. Then the maintenance time interval (tp-MC) can explain OEE-ME by 74.55%.
- Based on the correlation and regression tests results, the collaboration of MR or failure ratio (ζ) and OEE-ME with MPL-MC has a strong correlation, and the effect is significant. Then the collaboration of MR or failure ratio (ζ) and OEE-ME can explain MPL-MC by 65.73%.

Further research is needed to extend the proposed policy to other assumptions such as imperfect inspection, replacement, and maintenance. In addition, machines that are repaired and replaced do not return to their new condition. Different assumptions can also be made, such as random machine failure every time.

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