Maintenance Analysis Based on Reliability of Main Engine Lubrication System with Markov Method

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(Received: 19 September 2022 / Revised: 17 December 2022 / Accepted: 17 December 2022)

***Abstract*— maintenance of the main engine lubrication system determines the engine's performance and components based on the standard of Japan Institute of Plant Maintenance. The purpose of the system analysis is to determine the critical components and evaluate every lubrication system component as a base on maintenance planning as a preventive measure to avoid downtime during ship operations. Data needed are the ship's motion, damage frequency, components' downtime, and lubrication system diagram. Data was analyzed qualitatively with Failure Mode and Effect Analysis and Fault Tree Analysis as well as quantitatively with Overall Equipment Effectiveness, Markovian Decision Process, and damage distribution. Results show that LO filter crisis components with 120 RPN and LO Pump (standby) with 105 RPN. FTA analysis results there are 3 lost types cause happening failure system that is pressure oil low , overheating of the oil , and there is pollution in oil. At its steady-state conditions, have a probability of 0.45 to experience moderate damage and 0.55 to be severe damage. Therefore, it is recommended to carry out maintenance before passing the MTTF value of each component so that the system can work optimally.**

Keywords—reliability, qualitative and quantitative analysis, lubrication system main engine, JIPM.

I. Introduction

Tug Boat is a boat that functions to push, pull, drag, and help ships that will go out or in the port[1]. To fulfill the function of a tugboat using a diesel engine as the main mover. The main engine is equipped with a support system in order to have a good operation without interference.

The lubrication system is one of the main engine support systems and keeps the engine's endurance by giving lubrication [2]. The appliance of the lubricating oil is done between two intersecting surfaces with pressure and moves to each other [3]. Lubricating becomes important because internal combustion cannot work if the moving metal component is not given a lubricating layer. High friction could cause an increase in engine temperature. This can cause damage which results in component replacement. In operating, all of the moving engine's parts have to be lubricated continuously. In order to support the distribution of the lubrication well, it is required to do routine checks and maintenance.

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Table 1 shows the breakdown that happened caused by damages, repair, and maintenance which affected the ship's utilization. If the main engine can't operate optimally, utilization will decrease. This would cause a big loss for the company since if the utilization decreases, then the company's income will also decrease. Also, the company has to incur a cost for the damaged component's repair.

Seeing this impact, the author wants to analyze the condition of the main engine lubrication system. The purpose is to determine the lubrication system's critical component. Planning the maintenance schedule for the lubrication system components.

Research involving failure and maintenance in the lubricating system has been done with Failure Mode and Effect Analysis method. Results of critical component analysis with the highest RPN include lubricating oil pump, filter, LO Cooler, and transfer pump[4–6]. The method was also used simultaneously with Weibull's distribution. The result from the Transfer Pump as a critical component analysis shows mean time to failure scored 1096 operational hours[7]. Calculation score availability using simulation *Monte Carlo* obtained results of 0.702[8]. Based on past research, suggestions for maintenance systems ware based on the risk level of each component. In other words, the method was not considering time and engine conditions to evaluate a maintenance system.

Aiming at previous research, the writer wants to use the Markovian Decision Process method. This method is frequently used in calculating transition probability between differences in engine status[9], and maintenance system evaluation was taken based on state system probability that will happen in the future. Engine state can be determined using the Overall Equipment Effectiveness method based on the condition and performance of the engine. The advantage of this method is that it can schedule the system maintenance regularly and knows which maintenance type is suitable for the engine condition. Qualitative analysis was also done in components using the Failure Mode and Effect Analysis and Fault Tree Analysis methods.

TABLE 1.
DAMAGE AND AVAILABILITY CAUSED DOWN ON SYSTEM LUBRICATION

Month	Possible Time (hour)	Availability (hour)	Breakdown (hour)	Downtime system (hour)	Utility (hour)
Jan	744	720.67	23.33	4.67	485.67
Feb	696	654.08	41.92	5.08	407.75
Mar	744	725.08	18.92	6.58	475.08
Apr	720	680.08	39.92	4.50	407.80
May	744	614.83	129.17	15.50	302.33
Jun	720	691.08	28.92	7.75	377.92
Jul	744	721.25	22.75	10.08	407.33
Aug	744	729.00	15.00	3.17	414.08
Sep	720	706.33	13.67	3.00	366.25
Oct	744	714.50	29.50	1.25	326.17
Nov	720	225.33	494.67	0.33	80.92
Dec	*Docking*	*Docking*	*Docking*	*Docking*	*Docking*

II. METHOD

In this study, the data collection process was carried out using a literature study on maintaining the main engine lubrication system. In addition, qualitative data collection was also carried out, such as system diagrams, ship motion reports, and a list of damage that occurred to the lubrication system with the object of research on the harbor tugboat KT Batavia III.

A. *Qualitative Analysis*

Qualitative analysis was done based on data found in the field. In this research, the Failure Mode and Effect Analysis (FMEA) and Fault Tree Analysis (FTA) methods were used.

1) *Failure Mode and Effect Analysis*

The use of the FMEA method is a beginning step to determining the choice of maintenance based on its critical components. Data on the frequency of damage and the length of time the component is damaged are required, as shown in Table 2. FMEA can evaluate components in the system, thus able to reduce the risk and effects caused by damages[10]. Using a system's records, every possibility of failure mode and effects was based on three factors which are severity, occurrence, and detection. FMEA analysis was written in the form of an FMEA worksheet.

TABLE 2.
COMPONENT DAMAGES RECAPITULATION

No	Parts	Frequency	Downtime (hour)
1	Lubricating Oil purifier	2	4 – 8
2	LO Tank PS	-	No damaged
3	LO Tank SB	-	No damaged
4	LO Pump (Standby) PS	7	4 – 8
5	LO Pump (Standby) SB	4	4 – 8
6	LO Filter PS	12	1 – 4
7	LO Filter SB	9	1 – 4
8	LO Pump PS	5	4 – 8
9	LO Pump SB	6	4 – 8
10	LO Cooler PS	9	4 – 8

11	LO Cooler SB	9	4 – 8
12	LO PRV PS	2	1 – 4
13	LO PRV SB	4	1 – 4
14	LO Purifier Pump	2	4 – 8

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Oct	744	714.50	29.50
Nov	720	225.33	494.67
Dec	*Docking*	*Docking*	*Docking*

2) Fault Tree Analysis

Fault Tree Analysis (FTA) starts with identifying the top event in a system. In this analysis, a lubrication system workflow is needed, obtained from the system diagram. The system was analyzed to find a basic event that led to the top event, as shown in Figure 1. Based on the fault tree diagram, the minimum cut set can be calculated. A minimum cut set is a bunch of sets that could cause failures[10]. Criticalities on the cut set can be looked at based on orders. Basic events which have smaller orders have a higher probability as a cause of system damage. If a cut set has more than one basic event, then all the basic events must happen simultaneously for a top event to happen. TopEvent FTA was used for this analysis. Stages in Fault Tree Analysis include identifying the top event and basic events that caused the top event, making the Fault Tree diagram, and determining the minimum cut set.

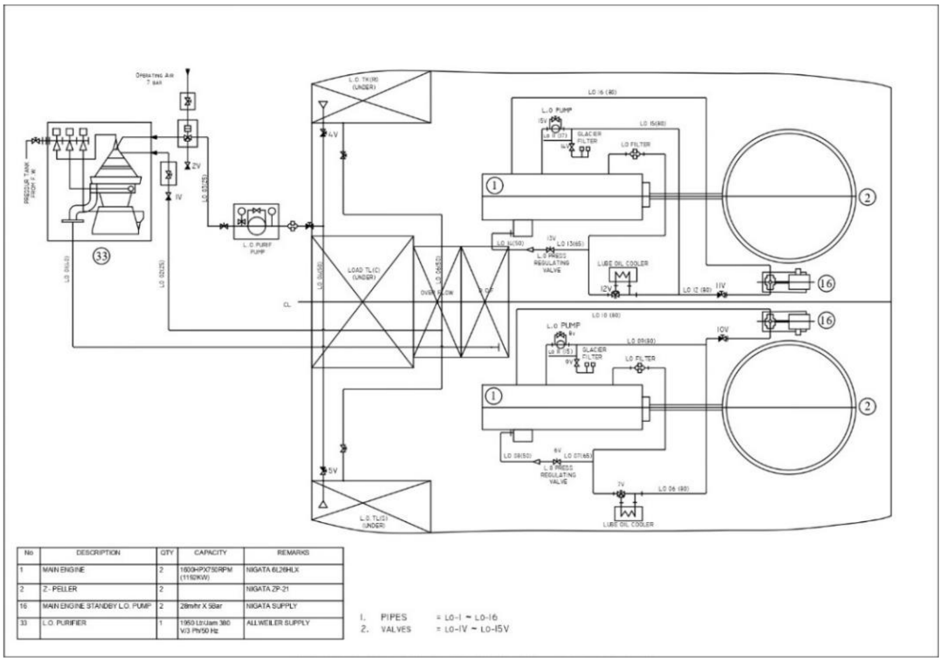

Figure. 1. Lubrication System Diagram of KT Batavia III

B. Quantitative Analysis

When analyzing system reliability, probability distribution from time to time is used as a random variable. The random variable is a value that is measured in the data processing. Parameters that would be measured are component error level, component frequency, and other parameters needed[11].

1) Overall Equipment Effectiveness

Overall Equipment Effectiveness is the result stated as a ratio of output from a system divided by the maximum output system with the optimum performance condition [12]. OEE scoring is based on 3 main ratios, which are availability, performance efficiency, and rate of quality product [13].

a) Availability Ratio

Availability Ratio is a use of time provided for a system to operate. Equation used in calculation.

$$A = \frac{operation\ time}{loading\ time} \quad (1)$$

where operation time is the operational time of the ship and loading time is time provided reduced by planned downtime.

b) Performance Efficiency

Performance efficiency is a ratio which represents the efficiency of engine performance during the cycle. Performance ratio can be calculated through equation 2.

$$P = \frac{processed\ amount\ \times ideal\ cycle\ time}{operation\ time} \quad (2)$$

where processed amount is the amount of ship's movement and ideal cycle time is the ideal time for every ship's movement which is 1,25 hours/move.

c) Rate of Quality Product

Rate of quality product is a ratio which describe a system's ability to operate suited to the standard. It can be calculated with equations 3.

$$Q = \frac{processed\ amount - defect\ amount}{processed\ amount} \quad (3)$$

Due to the object examined being a tugboat, where in its operational it is not physically defected. Therefore, it used the comparison between system's capability or utility with ship's availability which affected by system downtime to calculate the quality rate score.

$$Q = \frac{utility}{(0{,}7\ \times possible\ time) - downtime\ system} \quad (4)$$

OEE score obtained by multiplying all of the main three ratios. OEE could be calculated with equations 5.

$$OEE = A \times P\ \times Q \quad (5)$$

As shown in Table 1, there are data on vessel availability, planned breakdown, downtime due to the lubrication system, and vessel operating hours to calculate the Overall Equipment Effectiveness value.

2) Markovian Decision Process

Markovian Decision Process is a Markov chain with condition transition involving the current condition. This process is used to calculate decisions which is going to be used to increase utility considering the advantages[14].

Generally, Markov can be classified into discrete and continuous. Discrete Markov is when a displacement in a situation happens in a constant discrete time interval. It can be called continuous when displacement in a situation happens over a period of time with a continuous random variable[15].

To get a probability on every state, a stochastic transitional probability matrix was made to describe displacement from one state to another[11]. Matrix was transitioned until it reached steady state, where the condition shows the value of probability transition matrix did not change. POM QM software for Windows 5 was used as a support tool in STP Matrix transition calculation.

3) Reliability Score Calculation

Reliability is the operating component's or system's probability according to its function in a certain period and in certain operating conditions. Due to the reliability score being a probability, the score will be on the range of 0 to 1[16].

If R(t) states component's reliability function to time function, R(t) and distribution of cumulative damage could be calculated with equations 7.

$$R(t) = 1 - F(t) = \Pr(T \geq t) \quad (6)$$

$$R(t) = 1 - \int_0^t f(t)dt \quad (7)$$

Where F(t) is the cumulative function from time (t). Pr(T>t) is a component's probability function above period (t), and f(t) is a probability density function from (t).

4) Damage Distribution

Damage distribution is fundamental information about a component's lifetime[16]. When calculating the cumulative distribution function, the median rank approach method is used in order to give a better result for damage distribution that has skewed distribution[17]. F(t) value was obtained through the equation 8.

$$F(t_i) = \frac{i - 0.3}{n + 0.4} \quad (8)$$

Where t shows time of the damage number 1, the orders in time between damages was annotated with (t) which ordered based on smallest value. Meanwhile (n) shows the amount of data being processed.

a) Weibull's Distribution

This distribution uses two parameters: Ƞ (scale parameter) and β (shape parameter)[17]. Density probability function could be calculated with equations 9.

$$F(t) = \frac{\eta}{\beta}\left(\frac{t}{\beta}\right)^{\eta-1} e^{\left[-\frac{t}{\beta}\right]^{\eta}} \quad (9)$$

for Ƞ >0, β>0 and t>0

Reliability function in Weibull's Distribution:

$$R(t) = e^{-\left(\frac{t}{\beta}\right)\beta} \quad (10)$$

Mean Time to Failure in Weibull's Distribution:

$$MTTF = Ŋ\Gamma\,(1 + \frac{1}{\beta}) \quad (11)$$

Where R(t) is the reliability function with time (t) that has the value more or equal to 0. Shape parameter (β) and scale parameter (Ŋ) has the value more than 0.

b) Normal Distribution

Normal distribution or Gaussian is used by many reliability analysis[17]. If component's failure time (t) distributed normally, then the density probability function can be define by:

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{\left[\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2\right]} \quad (12)$$

Cumulative distribution function:

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{t} e^{\left[\frac{(t-\mu)^2}{2\sigma^2}\right]} dt \quad (13)$$

Reliability function:

$$R(t) = 1 - \emptyset\left(\frac{t-\mu}{\sigma}\right) \quad (14)$$

MTTF score using normal distribution:

$$MTTF = \mu \quad (15)$$

Where (σ) is a standard deviation and (μ) is average of time.

c) Exponential Distribution

Parameters used in exponential distribution are damage speed (λ) and scale parameter (γ)[17]. Reliability function in exponential distribution, density probability function:

$$F(t) = \lambda e^{-\lambda t}\ ;\ t > 1 \quad (16)$$

Cumulative density function:

$$F(t) = 1 - e^{(-\lambda t)} \quad (17)$$

Reliability function:

$$\lambda\, R(t) = e^{(-\lambda t)} \quad (18)$$

MTTF score in exponential distribution:

$$MTTF = \gamma + \frac{1}{\lambda} \quad (19)$$

Where testing time (t), damage speed (λ), and scale parameter (γ) have to be more or equal to 0.

d) Lognormal Distribution

Similar to Weibull's Distribution, lognormal distribution has many forms[16]. Density probability function in lognormal distribution is defined by equation 20.

$$f(t) = \frac{1}{t\alpha\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\ln(t)-\mu}{\sigma}\right)^2} \quad (20)$$

Reliability function R(t) in lognormal distribution:

$$R(t) = \phi\left(\frac{\mu - \ln t}{\sigma}\right) \quad (21)$$

Mean Time to Failure:

$$MTTF = \exp\left(\mu + (0{,}5 \times s^2)\right) \quad (22)$$

for s>0, $t_{med} > 0$ and t > 0.

5) Best Fit Distribution Identification

Best Fit Distribution Identification could be made using the least square method. The most common linear correlation used between two variables is the correlation coefficient. The correlation coefficient or Index of Fit shows the linear relationship between X and Y. One of the criterias to identify a distribution is to choose the largest Index to Fit to determine the data distribution type[16].

$$r = \frac{n\sum x_i y_i - (\sum x_i \sum y_i)}{\sqrt{[(n\sum xi^2) - (\sum xi)^2][(n\sum yi^2) - (\sum yi)^2]}} \quad (23)$$

6) Maximum Likelihood Estimate

Some of the parameters are needed to test failure time data and repair time. Generally, maximum likelihood is found on probability distribution with complete data[16]. The function of maximum likelihood estimate for unknown parameters $\theta_1, \theta_2, \ldots, \theta_k$ as in equation 24.

$$L(\theta_1, \ldots, \theta_k) = \prod_{i=1}^{n} f(t_i|\theta_1, \ldots, \theta_k) \quad (24)$$

The purpose is to determine the estimator value, which gives the maximum value based on data on $t_1, \ldots, t_n$.

Best fit distribution calculation, parameter determination with MLE, and reliability score on each component are used as supporting tools in Relyence software.

III. Results and Discussion

A. Qualitative Analysis

Qualitative analysis was done based on data found on field. In this research, the Failure Mode and Effect Analysis (FMEA) and Fault Tree Analysis (FTA) methods were used.

1) Failure Mode and Effect Analysis

FMEA method was used to identify severity detection and occurrence in each component. The three values were multiplied to obtain the Risk Priority Number score.

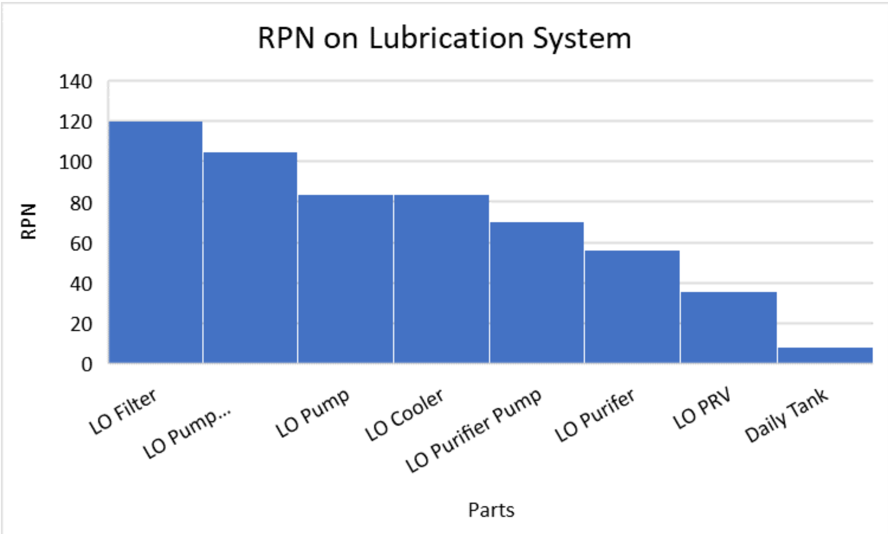

Figure. 2. RPN on Lubrication System of KT Batavia III

On the lubrication system of KT Batavia III, it is known that failure mode on the filter, which is damage caused by lifetime filter and filter clogging. This caused a decline in components' function and hindered the oil tract. For failure mode in the pumping system, it is a leak on the pump and low pressure. This is due to the damage to the pump seal and damage to the electromotor.

Failure in heat exchange is a leak on the gasket. This is caused by the presence of corrosion. So that the heat exchanger's capability to cool down the oil is reduced. Meanwhile, in the Pressure Regulating Valve, damage happened to the valve due to leaks and sticking on the valve; therefore, the pressure output was not suitable. It is also known that the failure mode on the purifier component has excess dirt on its purifier bowl and seal ring that was worn off. Effects caused are the decreasing lubricant quality and the presence of a pollutant in oil.

Results of RPN calculation shows that 4 critical components with the highest score are LO Filter PS/SB with 120 RPN, LO Pump (Standby) PS/SB with 105 RPN, LO Pump PS/SB with 84 RPN, and LO Cooler PS/SB with 84 RPN.

2) Fault Tree Analysis

The lubrication system's work is described based on the initial design. On the lubrication system of KT Batavia III, there are 3 interferences that could cause failures which are low pressure on oil (lost type 1), oil overheating (lost type 2), and the presence of a pollutant in oil (lost type 3). The creation of diagrams and calculation of the cut set was supported by TopEvent FTA software.

Lost type 1 or low pressure can be caused by a clogged filter, damage to the seal, damage to the electromotor, or sticking to the valve. On lost type 2 or the oil overheating, the cause of failure is overflow in the purifier or leakage in the cooler gasket. Clogged filter and purifier overflow can also cause lost type 3 or discovery of pollutants in the oil.

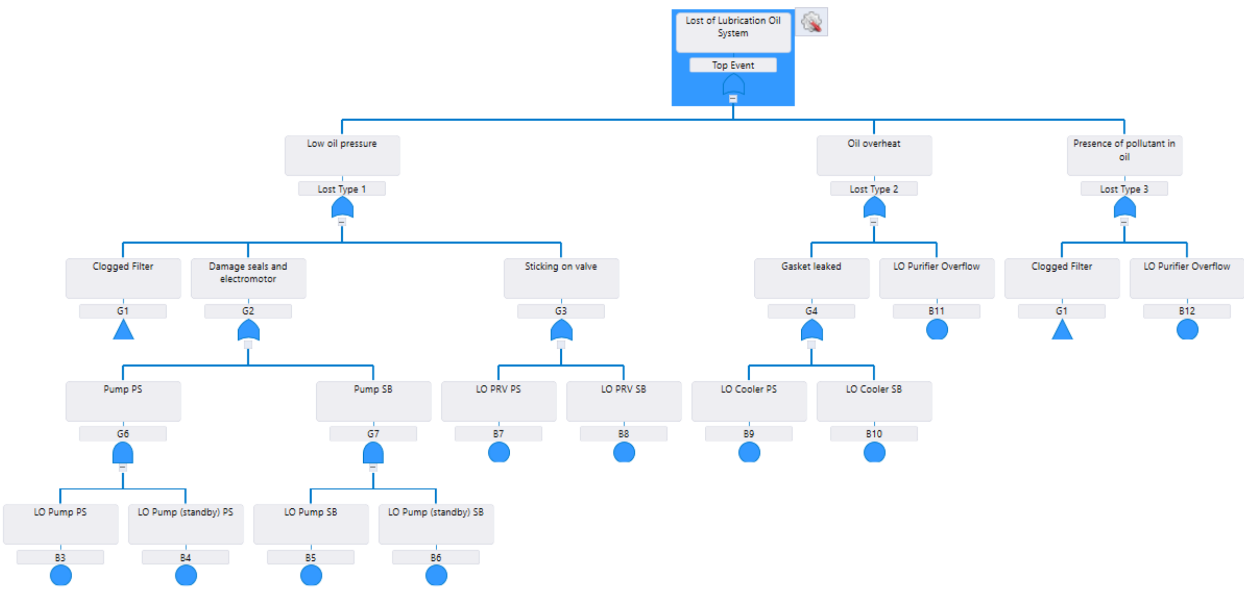

Figure. 3. Fault Tree Analysis of Lubrication System

The minimum cut set was calculated, and it was found that the components of LO Filter PS, LO Filter SB, LO PRV PS, LO PRV SB, LO Purifier, LO Cooler PS, and LO Cooler SB are in order 1. the occurrence of top events. Components {B3, B4} are LO Pump PS, and LO Pump (standby) PS, {B5, B6} are LO Pump SB, and LO Pump (standby) SB are on order 2.

B. *Quantitative Analysis*

1) *Analysis with Overall Equipment Effectiveness*

Overall Equipment Effectiveness (OEE) is a score that shows the measure of the system's effectiveness. There are four stages in OEE scores that describe the engine's condition[13]. The engine's status classification is set as a standard by the Japan Institute of Plant Maintenance (JIPM). To get an OEE score, a calculation for three ratios has to be done.

Calculation of availability ratio or the ratio that describes utilization of the available time from the system. It uses the equation 25.

$$A = \frac{utility}{0.7 \times possible\ time - downtin} \quad (25)$$

Ship's daily motion target was used which has the value of 0,7 or 16,25 hours to 17,5 hours from the available time per available time which is 24 hours.

Subsequently, the calculation was done on Performance efficiency or ratio that describes the ability of the system to work. Also, calculating Rate of Quality or ratio of the amount of the operational hours with the ship's availability target, which is affected by the system's downtime. After obtaining those three values, OEE calculation was done. OEE scores were classified based on a standard set by the Japan Institute of Plant Maintenance.

TABLE 3.
OEE CLASSIFICATION

Month	Availability	Performance Rate	Rate of Quality Product	OEE	Status	Condition
Jan	96%	83%	94%	75%	2	light damage
Feb	89%	80%	85%	60%	2	light damage
Mar	94%	84%	92%	72%	2	light damage
Apr	86%	82%	82%	58%	3	moderate damage
May	70%	81%	60%	34%	4	severe damage
Jun	78%	88%	76%	53%	3	moderate damage
Jul	81%	89%	80%	57%	3	moderate damage
Aug	81%	92%	80%	60%	3	moderate damage
Sep	74%	89%	73%	48%	3	moderate damage
Oct	65%	86%	63%	35%	4	severe damage
Nov	51%	85%	16%	7%	4	severe damage
Dec	0%	0%	0%	0%	4	severe damage

OEE scores in the lubrication system of KT Batavia III has an average of 47%. This shows the system is situated under the standard score which is 85%. This was caused by the low quality of product score.

2) *Analysis using Markovian Decision Process*

Based on the Overall Effective Equipment analysis of three states in the lubrication system of KT Batavia III, which are light damage (X1), moderate damage (X2), and severe damage (X3). A transition that happened from condition X1 to X1 found 2, from X1 to X2 found 1, and there was no transition found from X1 to X3. Subsequently, there is also no transition found from state X2 to X1. There are three transitions from X2 to X2 and two transitions from X2 to X3. There was also no transition found from X3 to X1. However, for X3 to X2, there is a time transition found, and from X3 to X3, two transitions were found. The total amount of transitions that happened in the lubrication system of KT Batavia III from January 2020 to December 2020 was recorded 11 times.

The STP matrix was made to describe the displacement probability between states[12]. An initial probability matrix is needed that can be calculated through the equation 26.

$$Po(n) = \frac{transition\ from\ state\ n}{total\ transition\ state} \quad (26)$$

Initial probability matrix is obtained as follows:

$$Po = [0.273 \quad 0.455 \quad 0.273]$$

The transition probability matrix was made ($P_x n_n$) by calculating the probability that happened from condition n to status n to total transition from condition n. The value of B^1:

$$B^1 = \begin{bmatrix} 0.67 & 0.33 & 0 \\ 0 & 0.6 & 0.4 \\ 0 & 0.33 & 0.67 \end{bmatrix}$$

Calculation of the B^n transition probability matrix was done until the steady state condition where the value of the probability matrix does not experience changes or the same on certain n. Probability transition was calculated using the equation 27.

$$B^n = B^{n-1} \times B' \tag{27}$$

The transition matrix and probability values are calculated using POM QM software. The matrix transition stops at the value of n = 15 because the matrix values at n = 15 and n = 16 are the same, which means the system is in a steady state.

$$B^{15} = \begin{bmatrix} 0 & 0.45 & 0.55 \\ 0 & 0.45 & 0.55 \\ 0 & 0.45 & 0.55 \end{bmatrix}$$

Referring to the steady state condition matrix, the probability for X1 (light damage) is 0, X2 (moderate damage) is 0.452, and X3 (severe damage) is 0.548.

Based on these calculations, it is recommended to do corrective maintenance for several components in the form of repair and replacement. Then do preventive maintenance regularly, such as periodic inspection and cleaning of all lubrication system components, preventing components from being severely damaged.

3) Best Fit Distribution Analysis and Parameters

Best fit distribution determination was done using Index of Fit. The distribution was selected based on the highest Index of Fit. Parameters determination was done using the Maximum Likelihood method for every used distribution. Calculation was done with the help Relyence software.

TABLE 4.
BEST FIT DISTRIBUTION AND COMPONENTS PARAMETER

No	Parts	Distribution	λ	η	γ	μ	σ	β	I(θ)
1	Lubricating Oil Purifier	Exponential -2P	9.09 e-004	1099.35	926.30	-	-	-	-16.005
2	LO Pump (Standby) PS	Weibull – 2P	-	648.76	-	-	-	3.13	-47.23
3	LO Pump (Standby) SB	Weibull – 2P	-	903.89	-	-	-	5.87	-26.55
4	LO Filter PS	Weibull – 2P	-	379.88	-	-	-	2.06	-78.39
5	LO Filter SB	Exponential -2P	0.0030	332.18	114	-	-	-	-61.25
6	LO Pump PS	Exponential -2P	0.0035	286.6	231	-	-	-	-33.29
7	LO Pump SB	Exponential -2P	0.0032	319.83	231.08	-	-	-	-40.61
8	LO Cooler PS	Normal	-	-	-	425.44	207.93	-	-60.81
9	LO Cooler SB	Weibull – 2P	-	505.70	-	-	-	1.91	-61.80
10	LO PRV PS	Exponential -2P	0.0015	671.50	689	-	-	-	-15.02
11	LO PRV SB	Exponential -2P	0.0019	503.08	473.25	-	-	-	-28.88
12	LO Purifier Pump	Exponential -2P	0.0033	306.34	1719.33	-	-	-	-13.45

4) Calculation of Mean Time to Failure Value

After knowing the value of the parameter of each component, the Mean Time to Failure can be calculated for every one of the components. The calculation was done using the help of the Relyence software.

The results of the mean time to failure value for 14 lubrication system components of KT Batavia III are shown in Table 5. There are two components that do not have damage records, and those are LO Tank PS and TO Tank SB, therefore the MTTF value for both components cannot be calculated.

TABLE 5.
MTTF COMPONENT VALUE IN LUBRICATION SYSTEM

No	Parts	Distribution	MTTF (hour)
1	Lubricating Oil purifier	Exponential -2P	2025
2	LO Pump (Standby) PS	Weibull – 2P	580.447
3	LO Pump (Standby) SB	Weibull – 2P	837.5
4	LO Filter PS	Weibull – 2P	336.517

5	LO Filter SB	Exponential -2P	446.18
6	LO Pump PS	Exponential -2P	517.6
7	LO Pump SB	Exponential -2P	550.91
8	LO Cooler PS	Normal	425.44
9	LO Cooler SB	Weibull – 2P	448.64
10	LO PRV PS	Exponential -2P	1360.5
11	LO PRV SB	Exponential -2P	976.325
12	LO Purifier Pump	Exponential -2P	2025.66

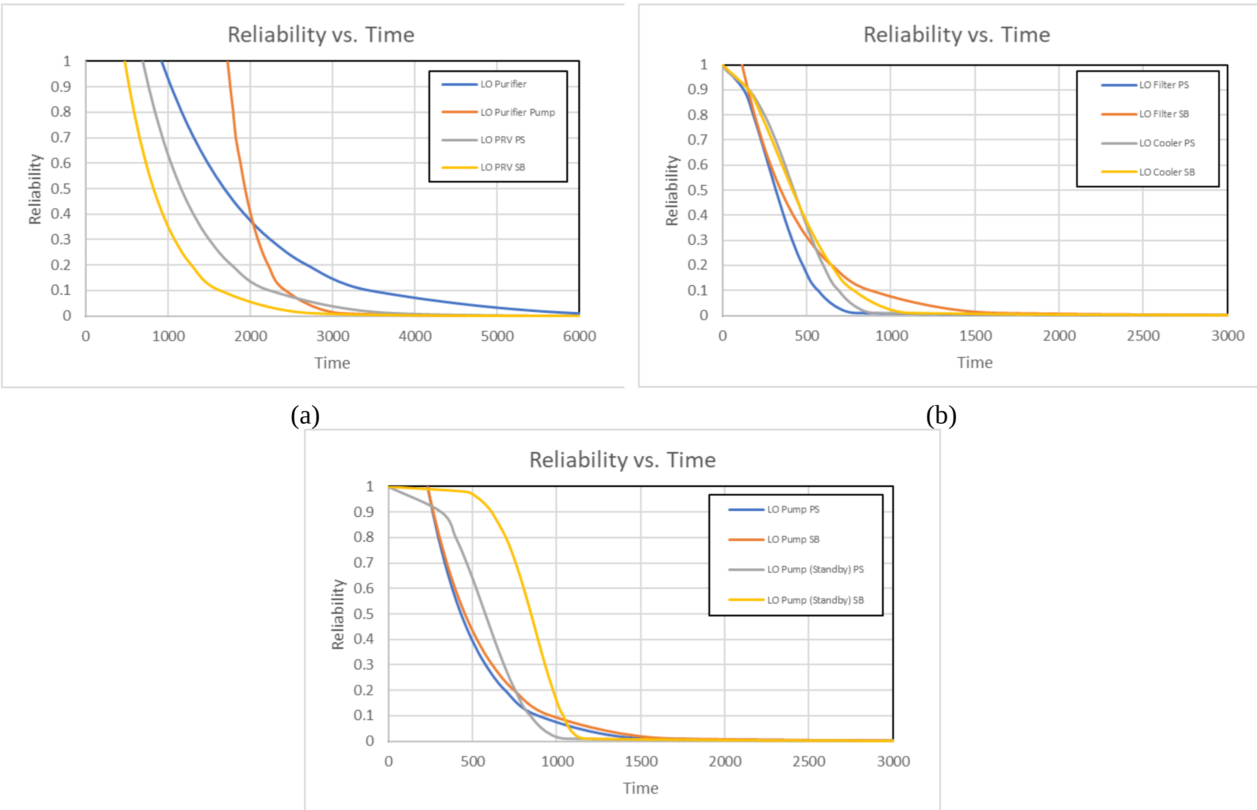

Figure. 4. Reliability vs. Time

5) Reliability Value Calculation

Reliability value was obtained based on determined distribution. Calculation was done for each component with the supporting Relyence software.

As shown in Figure 4 (a), the curve for the components of LO Purifier, LO Purifier Pump, LO Pressure Regulating Valve PS, and SB showed lowering reliability values with the increasing of time intervals. Reliability value starts to decrease on the 926th hour for LO Purifier, 1719th hour for LO Purifier Pump, 689th hour for LO PRV PS, and the 473rd hour for LO PRV SB.

In figure 4 (b), we know that in the LO Filter PS, the reliability value starts to decrease on the 127th hour, 114th hour for the LO Filter SB component, 135th hour for the LO Cooler PS, and 155th hour for the LO Cooler SB.

The decrease in the reliability value was also found in Figure 4 (c). Components of LO Pump PS and SB were declining on the 231st hour, for LO Pump (Standby) PS on the 316th hour, and LO Pump (Standby) SB on the 464th hour. The difference in reliability functions to time on each component was caused by the difference in damage speed (λ).

TABLE 6.

COMPONENT PERIODIC MAINTENANCE SCHEDULE

No	Parts	MTTF (hour)	Interval (hour)	R(t)
1	Lubricating Oil purifier	2025	2000	0.37
2	LO Pump (Standby) PS	580.447	550	0.55
3	LO Pump (Standby) SB	837.5	830	0.545
4	LO Filter PS	336.517	330	0.47
5	LO Filter SB	446.18	400	0.422
6	LO Pump PS	517.6	500	0.39
7	LO Pump SB	550.91	550	0.368
8	LO Cooler PS	425.44	400	0.54
9	LO Cooler SB	448.64	400	0.52
10	LO PRV PS	1360.5	1300	0.402
11	LO PRV SB	976.325	950	0.38
12	LO Purifier Pump	2025.66	2000	0.4

6) Periodic Maintenance Preparation

The purpose of periodic maintenance preparation is to keep the system's condition to be always available and can operate optimally. Avoiding sudden damages to components in order to not gain loss in ships operational. The maintenance schedule was made based on MTTF with consideration of the reliability value of each component.

IV. Conclusion

Based on the KT Batavia III main engine lubrication system analysis, there are 3 lost types that could cause failures: low pressure on oil, oil overheating, and the presence of a pollutant in oil. It has identified critical components, namely LO Filter and LO Pump (standby), with RPN values of 120 and 105. The failure mode is a clogged filter, filter damage due to lifetime, and low pump pressure.

To prevent failures in the lubrication system which can result in downtime during ship operations—recommended periodic maintenance before passing the MTTF value on each component by performing preventive maintenance regularly, such as periodic inspection and cleaning of all lubrication system components preventing components from being severely damaged. Also, do corrective maintenance for several components in repair and replacement. Given that the system has a probability of 0.45 to experience moderate damage and 0.55 to experience severe damage at its steady state.

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