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Prioritization of Research Vessel Lubricating Oil System Equipment for Maintenance Purpose Using Failure Mode Effect and Criticality Analysis (FMECA) Method. Study Case: RV. Baruna Jaya

Tris Handoyo[1)*)], Dhimas Widhi Handani[1)], Agus Sudaryanto[2)], Dimas Fajar Prasetyo[3)]

[1)]Department of Marine Engineering, Faculty of Marine Technology, Institut Teknologi Sepuluh Nopember, Surabaya 60111, Indonesia
[2)]National Research and Innovation Agency, Jakarta 10340, Indonesia, Indonesia
[3)]Research Center for Hydrodynamic Technology, National Research and Innovation Agency, Surabaya 60112, Indonesia, Indonesia
[*)]Corresponding Author: tris014@brin.go.id

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Abstract

Alongside the program, which requires research vessel operation, RV Baruna Jaya is needed to fill that requirement fully. RV Baruna Jaya reported many failures during the previous mission. Some failures need emergency maintenance. One of them is the problem with the lubricating oil system. The lubrication system of an engine supplies of lubricating oil to the various moving parts of the engine. Its main function is to form an oil film between moving parts, which reduces friction and wear. The lubricating oil is also used as a cleaner and, in some engines, as a coolant. During the survey Ina-TEWS in 2021, RV Baruna Jaya was ordered due high temperature of The Lubricating Oil System. The temperature exceeded the normal value, and due to safety considerations, the Engine had to be shut down. Because of this problem, the survey carried out by RV Baruna Jaya was delayed. So, it is important to maintain a lubricating oil system. In this analysis, to maintain the function and performance of the lubricating oil system, the FMECA (Failure Mode, Effect, and Criticality Analysis) is carried out. By prioritizing the lubricating oil system equipment using FMEA (Failure Mode and Effect Analysis) and Criticality Analysis, 6 pieces of equipment with 24 failure modes should be maintained. These equipment are lubricating oil cooler, lubricating oil pump, engine service oil tank, engine reserve oil tank, Engine lubricating oil standby pump, and lubricating oil transfer pump. The maintenance task is proposed to minimize the occurrence of failure mode, which could possibly happen in the equipment.

1. Introduction

Alongside the program, which requires research vessel operation, RV Baruna Jaya has already successfully finished her contribution to Indonesia' s marine survey operation in 2021. She will continue again in the next period. This survey operation was initiated not only by the government but also by Industries and academics. During the Cable Route Survey of Palapa Ring Timur and Indonesia Tsunami Early Warning System (Ina-TEWS), RV Baruna Jaya reported some ship machinery and survey equipment failure. This failure affected the survey operation, some of the effects were minor, and some of them were major. By the ages, RV Baruna Jaya has already been at the end of its lifetime period. As the marine survey operations will always be held on each year, the contribution of RV Baruna Jaya will always be waiting to support these operations.

A mechanical and electrical system supports RV Baruna Jaya. Like the other vessels, some of these mechanical systems are the ballast system, bilge system, oily water separator system, firefighting system, cooling system, fuel oil system, lubricating oil system, compressed air system, etc. The lubrication system of an engine supplies lubricating oil to the various moving parts of the engine. Its primary function is to enable the formation of a film of oil between the moving parts, which reduces friction and wear. The lubricating oil is also used as a cleaner and, in some engines, as a coolant. Lubricating oil for an engine is stored in the bottom of the crankcase, known as the sump, or in a drain tank located beneath the engine. It is then passed through a cooler before entering the engine and being distributed to the various branch pipes by the lubricating oil pump. The branch pipe for a particular cylinder may feed the main bearing, for instance. Some of this oil will pass along a drilled passage in the crankshaft to the bottom end bearing and then up a drilled passage in the connecting rod to the gudgeon pin or crosshead bearing. An alarm at the end of the distribution pipe ensures that adequate pressure is maintained by the pump. After use in the engine the lubricating oil drains back to the sump or drain tank for re-use [1].

These systems interact with each other and are very important in supporting the operation of the marine survey vessel. If one of these systems is interrupted, it could affect the main engine' s function. It is a crucial system for the passenger/cruise ships safety, and therefore needs to be meticulously analyzed in terms of safety, reliability, and availability [2]. For example, during the survey Ina-TEWS in 2021, RV Baruna Jaya reported a high temperature of The Lubricating Oil

System. This problem occurred because the contaminant blocked the lubricating oil and seawater heat exchanger. Because of this problem, the survey carried out by RV Baruna Jaya was delayed. And after hours of emergency maintenance, RV Baruna Jaya continued her mission. So, it is essential to keep this system available according to its standard performance during the survey by maintaining it properly. Because there is so much equipment, a plan is needed to prioritize it.

FMECA (Failure Mode, Effects, and Criticality Analysis) is a methodology that combines FMEA (Failure Mode and Effect Analysis) and Criticality Analysis. Failure Mode and Effects Analysis (FMEA) is a safety and reliability analysis tool that systematically identifies the consequences of component failure on systems and determines the significance of each failure mode regarding the system performance [3]. FMEA provides a formalized approach to identifying hazardous situations, addressing the gaps and interconnection variances, and improving safety, environmental performance, and operational downtime [4]. FMEA analysis focuses on the causes of damage and the mechanism of damage [5]. FMEA was applied by to find out the cause of failure on components in some fields, such as: in oil and gas industry [3], ships [6] [7], electrical power industries [8], textiles industries [9], etc. The FMEA methodology starts with Defining the system, Determination of failure mode, failure effects, classification of SOD (severity, occurrence, and detection), determination of RPN, and risk analysis [10]. Criticality Analysis is used to prioritize the equipment by its risk. The probability of failure and the consequence of equipment failure were converted into the level risk of High (H), Medium (M), and Low (L) using the risk matrix [11]. From each rating classification of the failure rate and the level of consequences, it will form a risk [12]. In this analysis failure rate will use the Occurrence (O) and the level of consequences will use the Severity from FMEA step. FMECA is implemented to identify potential forms of failure, determine their impact on production and identify actions that can be taken to reduce failures [13].

From the previous analysis, FMEA was carried out in fuel oil system on diesel engine of fishing vessel [10]. The analysis was done by determining the diagram block, potential failure mode, FMEA, risk assessment, and recommendation action. The results of this analysis were found that fuel storage tanks, transfer pumps, daily fuel tanks, separators, hand pumps, double stage filters high pressure fuel pumps, high pressure fuel line and injector are the most critical equipment. From the analysis on Distribution Transformer [8], the analysis was done by determining the failure modes, cause of failure, effects, classification of SOD (Severity, Occurrence, and Detection, and criticality analysis. The statistical analysis presented in that analysis indicates that the transformer failure rate is increasing every year and transformers are failing prematurely before completing its normal life. in the wind turbine, the analysis was carried out by determining the item of analysis, its function, failure mode, failure cause, likelihood, failure effects, β-Factor, consequence, and criticality. In this analysis A total of 337 individual failure modes have been identified and analyzed by a consortium representing more than 70% of the total offshore wind capacity installed in Europe [14]. In the main engine support system [7], the analysis was carried out using FMECA based on ABS classification and evaluation of FMECA using fuzzy logic simulation. In this analysis, 19 failure modes in the medium risk level and 56 failure modes in the low risk level. Fuzzy logic also used in ship propeller shaft [15], for evaluate 8 components and 13 failure modes. The criticality analysis in research vessel [12] has done by determining the hierarchy of the asset, probability rating, consequence rating, and risk prioritization. In this analysis was found that 23 (3%) of equipment in H (high), 138 (18%) in the M (medium) condition, and 605 (79%) in the L (low) condition. The criticality analysis was also carried out in gas central processing plant and found that 28 components had a critical level of H (high), 192 components had a critical level M (medium), and 454 components had L critical level (low) [11]. To prioritize the research vessel lubricating oil system equipment, the prioritization will be carried out using FMECA Methodology, starting with System Definition, determination of Block Diagram, FMEA, and Criticality Analysis.

2. Methods

To get the prioritization of RV Baruna Jaya Lubricating Oil System Equipment using FMECA, a flow chart methodology was developed first. This flow chart explains every step that will be taken to get the research results. Figure 1 shows the flow chart that will be used in this research.

From the flowchart, the first step to analyze the data is to collect all the data needed for the analysis. In this step, the Piping Instrument Diagram (PID), Equipment daily report, etc will be used. The second step is determining lubricating oil (LO) block diagram and asset register, A block diagram will help to understand how each equipment and components of the system interact. Asset register is used to determine how many equipment and components in the system and to ensure that every equipment or components has its own unique identification to avoid duplicate. The third step is FMEA which consist of some steps such as determination of equipment function, determination of functional failure, determination of failure mode, and determination of failure effects. The fourth step is determination of Occurrence (O), Severity (S), and Detection (D). In this step the scoring of O, S, and D will determine the Risk Priority Number (RPN). The fifth step is criticality analysis. In this step, the risk matrix will be used to plot each failure mode in to High (H), Medium (M), or Low (L) category. And the final step is determination of maintenance strategy for failure mode that has already prioritized in the previous step.

2.1. Data Collection

All data will be collected at the data collection step to determine the results. At Determination of Lubricating Oil System Block Diagram, the document that shows the process and equipment of lubricating oil system is needed. In this case, a Piping Instrument Diagram (PID) will be used to gather all the equipment and flow processes of the Lubricating Oil System. At the asset register step, the PID will also be used to register all the assets in the lubricating oil system. Figure 2 shows the example of PID and its equipment list. The main task of equipment contributing to the system and the equipment specification will be used in determining the equipment function. Equipment specification will be used as a standard performance of the equipment. To determine functional failure, the equipment standard performance will be used. This standard will define functional failure, such as equipment operating below standard performance, equipment not operating at all, etc. To determine failure mode, some reference and historical data will be used to define every failure mode that has already happened and potentially would happen. At the determination of the failure effects step, the block diagram and historical data will be used to predict the effect of equipment failure on safety, production, environment, and so on. Figure 3 shows the example of the main engine and supporting system daily report during the survey and will be used as a reference for historical data. At the determination of Severity, Occurrence, and Detection Indicator, the standard and some references will be used to get every description of the classification criteria. In this case, the S, O, and D indicator descriptions. At the determination of RPN, multiplication of severity, occurrence, and detection will give the result of RPN. The Pareto will eliminate which equipment and its failure mode will be prioritized to be maintained. At the Determination of the Risk matrix, the standard and some references of the risk matrix will be used to determine the criticality ranking. This criticality ranking will be considered to decide on the prioritization of equipment.

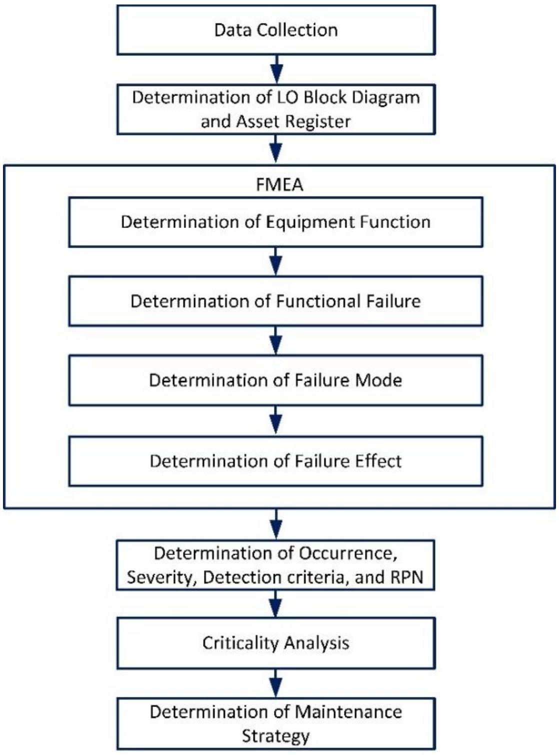


Figure 1. FMECA methodology flowchart

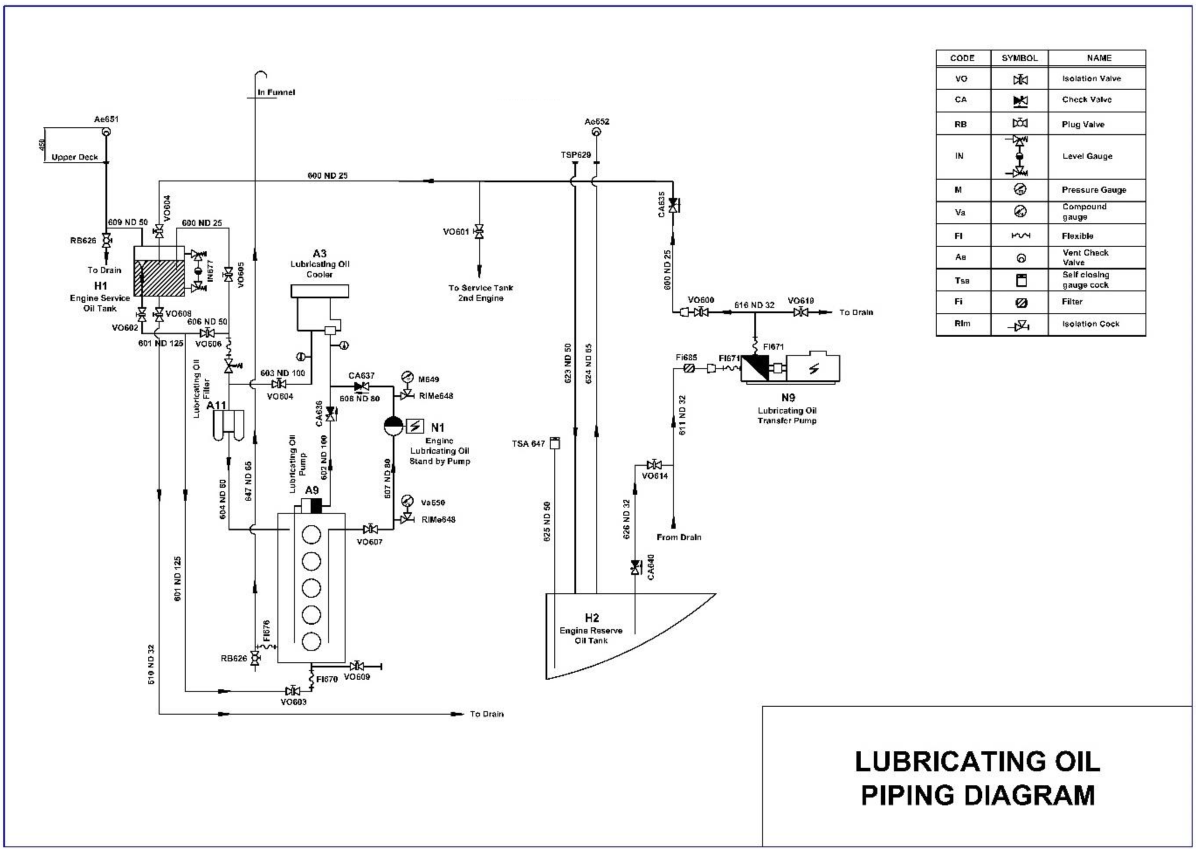
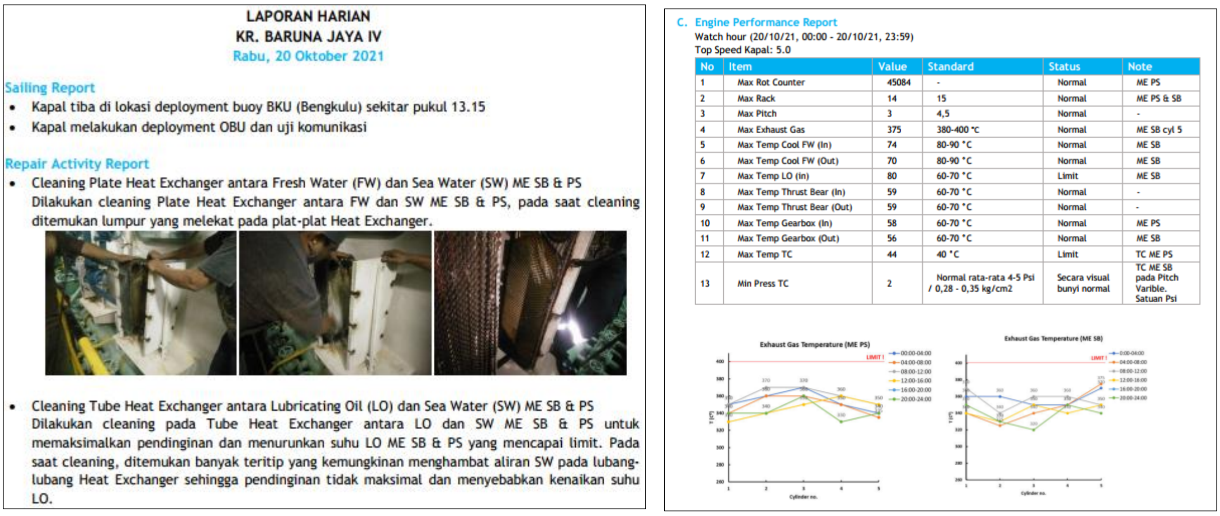


Figure 2. Piping Instrument Diagram (PID) and Equipment list



LAPORAN HARIAN
KR. BARUNA JAYA IV
Rabu, 20 Oktober 2021

Sailing Report
- Kapal tiba di lokasi deployment buoy BKU (Bengkulu) sekitar pukul 13.15
- Kapal melakukan deployment OBU dan uji komunikasi

Repair Activity Report
- Cleaning Plate Heat Exchanger antara Fresh Water (FW) dan Sea Water (SW) ME SB & PS
  Dilakukan cleaning Plate Heat Exchanger antara FW dan SW ME SB & PS, pada saat cleaning ditemukan lumpur yang melekat pada plat-plat Heat Exchanger.
- Cleaning Tube Heat Exchanger antara Lubricating Oil (LO) dan Sea Water (SW) ME SB & PS
  Dilakukan cleaning pada Tube Heat Exchanger antara LO dan SW ME SB & PS untuk memaksimalkan pendinginan dan menurunkan suhu LO ME SB & PS yang mencapai limit. Pada saat cleaning, ditemukan banyak teritip yang kemungkinan menghambat aliran SW pada lubang-lubang Heat Exchanger sehingga pendinginan tidak maksimal dan menyebabkan kenaikan suhu LO.

C. Engine Performance Report
Watch hour (20/10/21, 00:00 - 20/10/21, 23:59)
Top Speed Kapal: 5.0

No	Item	Value	Standard	Status	Note
1	Max Rot Counter	45084	-	Normal	ME PS
2	Max Rack	14	15	Normal	ME PS & SB
3	Max Pitch	3	4,5	Normal	-
4	Max Exhaust Gas	375	380-400 °C	Normal	ME SB cyl 5
5	Max Temp Cool FW (In)	74	80-90 °C	Normal	ME SB
6	Max Temp Cool FW (Out)	70	80-90 °C	Normal	ME SB
7	Max Temp LO (in)	80	60-70 °C	Limit	ME SB
8	Max Temp Thrust Bear (In)	59	60-70 °C	Normal	-
9	Max Temp Thrust Bear (Out)	59	60-70 °C	Normal	-
10	Max Temp Gearbox (In)	58	60-70 °C	Normal	ME PS
11	Max Temp Gearbox (Out)	56	60-70 °C	Normal	ME SB
12	Max Temp TC	44	40 °C	Limit	TC ME PS
13	Min Press TC	2	Normal rata-rata 4-5 Psi / 0,28 - 0,35 kg/cm2	Secara visual bunyi normal	TC ME SB pada Pitch Varible. Satuan Psi

Figure 3. Machinery Condition Daily Report

2.2. Determination of The Lubricating Oil System' s Block Diagram and Asset Register

A functional block diagram shows how the different parts of the system interact. They are powerful illustrative tools that aid in visualizing the interfaces and interdependencies between elements involved in system functionality [4]. The asset register is the step to register all the equipment and its information on the system. The system block diagram will be developed using the system PID reference. Figure 4 shows the block diagram, and Table 1 shows the asset register and its available information.

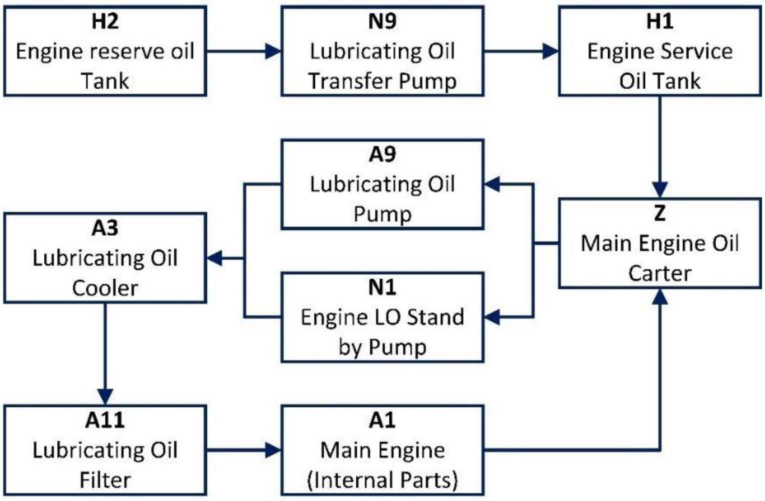


Figure 4. Lubricating Oil System Block Diagram

Table 1. The Asset Register of Lubricating System Equipment.

Tag	Item Name	Specification
H2	Engine Reserve Oil Tank	Volume: 3.95 m3
N9	Lubricating Oil Transfer Pump	-
H1	Engine Service Oil Tank	-
Z	Main Engine Oil Carter	-
A9	Lubricating Oil Pump	Normal Pressure: 5 - 6 kg/cm2 min allowable value (alarm): 5.3 kg/cm2 min limit (trip): 4.8 kg/cm2
N1	Engine Lubricating Oil Stand by Pump	Normal Pressure: 5 - 6 kg/cm2 min allowable value (alarm): 5.3 kg/cm2 min limit (trip): 4.8 kg/cm2
A3	Lubricating Oil Cooler	Normal Temperature: 60 - 70 C min allowable value (alarm): 75 C min limit (trip): 80 C
A11	Lubricating Oil Filter	-
A1	Main Engine (Internal Parts)	-

2.3. Failure Mode Effect Analysis

After the Block Diagram was determined, the next step was FMEA. In this part, every piece of equipment determined in the block diagram will be analyzed, starting from its functions, functional failures, Failure modes, and Effects. For example, the FMEA of Lubricating Oil Cooler (A3). The Lubricating Oil Cooler has the function of cooling down the temperature of lubricating oil by transferring heat from the lubricating oil to the seawater at normal temperature (60 - 70 C), as in Table 1 given. If the temperature cooldown is below standard, it will fail because it has already degraded from normal standard. At Table 1, the minimum allowable value (alarm) is at 75 C, and the limit (trip) is 80 C, and it would be stated as a failure when it cannot cool down the temperature of lubricating oil at all.

The maintenance record or logbook could be used as a reference to analyze the failure mode and effects that contribute to equipment failure. For example, during the deployment buoy of the Ina-TEWS program, many failures happened at RV Baruna Jaya. One of them was the high temperature of the lubricating oil system. The increasing temperature of the cooling system followed the Increasing temperature of lubricating oil in the system. If this continues without taking any action, the temperature will rise to 75 C and trigger the alarm to turn on. And if it reached 80 C, it would trip the Main Engine (ME). To prevent the ME from being shut down by the system and causing further damage, RV Baruna Jaya was ordered to stop and take emergency maintenance. The root cause of this case could be the lubricating system or the cooling system. This maintenance was taken to equipment that indicated to be the root cause of this problem. The main items prioritized to be maintained are the Plate Heat Exchanger (Central Cooler) for Fresh water and seawater, the Tube Heat Exchanger between the lubricating oil and seawater of ME, and the Tube Heat Exchanger between the Lubricating Oil and Sea Water of the gearbox. After the maintenance, it was found that these coolers were blocked by contaminants, which reduced the flow of water cooling. Figure 5 shows the cleaning process of the lubricating oil cooler. Figure 6 shows the contaminant (oysters) which blocked the cooling system' s seawater stream.

Figure 5. Cleaning process of lubricating oil cooler

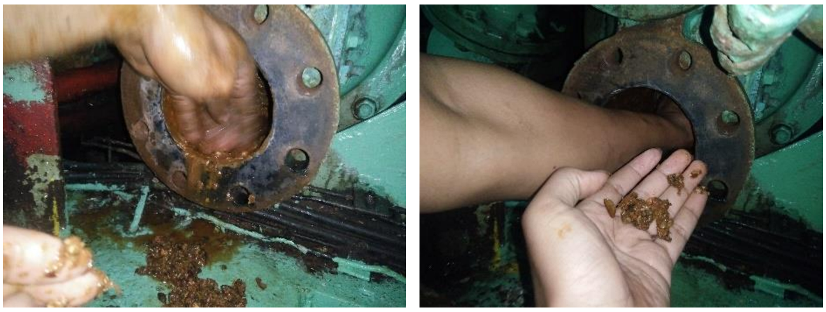


Figure 6. A contaminant that blocked the stream of seawater through the lubricating oil cooler

Watch hour (20/10/21, 00:00 - 20/10/21, 23:59)
Top Speed Kapal: 5.0

No	Item	Value	Standard	Status	Note
1	Max Rot Counter	45084	-	Normal	ME PS
2	Max Rack	14	15	Normal	ME PS & SB
3	Max Pitch	3	4,5	Normal	-
4	Max Exhaust Gas	375	380-400 °C	Normal	ME SB cyl 5
5	Max Temp Cool FW (In)	74	80-90 °C	Normal	ME SB
6	Max Temp Cool FW (Out)	70	80-90 °C	Normal	ME SB
7	Max Temp LO (in)	80	60-70 °C	Limit	ME SB
8	Max Temp Thrust Bear (In)	59	60-70 °C	Normal	-
9	Max Temp Thrust Bear (Out)	59	60-70 °C	Normal	-
10	Max Temp Gearbox (In)	58	60-70 °C	Normal	ME PS
11	Max Temp Gearbox (Out)	56	60-70 °C	Normal	ME SB
12	Max Temp TC	44	40 °C	Limit	TC ME PS
13	Min Press TC	2	Normal rata-rata 4-5 Psi / 0,28 - 0,35 kg/cm2	Secara visual bunyi normal	TC ME SB pada Pitch Varible. Satuan Psi

Figure 7. Daily Report of Main Engine and Supporting System Condition

Figure 7 shows the daily report of machinery condition during that watch hour. The value was taken from the maximum value that happened on that day. From that logbook, the lubricating oil temperature was recorded at 80 C, which has already reached its limitation area.

The maintenance report could be used as a reference for determining the FMEA, starting from the function, functional failure, failure mode, and effects. Table 2 shows the Example of Lubricating Oil Cooler FMEA that has already been written according to the worksheet. Some failure modes that have already happened or potentially could happen will be recorded and analyzed in the FMEA worksheet. After the FMEA is determined, the next step is determining the severity, occurrence, and detection indicator. This indicator will be used to score the FMEA result and get the risk priority number (RPN).

Table 2. Example of Main Engine Lubricating Oil Cooler FMEA

Item Tag	Item	Function	ID FF	Functional Failure	ID FM	Failure Mode	Failure Effects
A3	Main Engine Lubricating Oil Cooler	To cool down the temperature of lubricating oil by transferring heat from the lubricating oil to the seawater at standard temperature (60 - 70 C)	B	Cool down the temperature of lubricating oil below standard (> 60 - 70 C)	1	Main Engine Lubricating Oil Pump Cooler insufficient heat transfer due to leak on the tubes	Oil Cooler insufficient heat transfer due to a leak on the tube could create a cooling treatment that doesn' t work maximally. Increasing the temperature to 75 C could trigger the safety device to turn on the alarm, then the operator would shut down the ME. Temperature spikes until 80 C could shut down the ME (Trip). Increasing temperature due to insufficient heat transfer could damage the internal part of the ME. The seawater passing through the leaks on cooler tubes could flow with lubricating oil and damage/corrode the internal part of ME due to the high acidity of seawater. The lubricating oil that passes through a leak on cooler tubes could flow with seawater overboard. It could pollute the sea and its creatures.
					2	Main Engine Lubricating Oil Pump Cooler insufficient heat transfer due to contaminant buildup	Oil Cooler insufficient heat transfer due to contaminant blockage could create a cooling treatment that only works maximally. Increasing the temperature to 75 C could trigger the safety device to turn on the alarm, then the operator would shut down the ME. Temperature spikes until 80 C could shut down the ME (Trip). Increasing temperature due to insufficient heat transfer could damage the internal part of the ME and trigger the safety device to shut down the ME at a specific temperature.

2.4. Determination of Severity, Occurrence, Detection Indicator, and Risk Priority Number

The Severity, Occurrence, and Detection Indicators will define the RPN number. This analysis will refer to the criteria of Severity, Occurrence, and Detection [10]. From the Example of FMEA that has already been obtained in Table 2, the next step is scoring the Occurrence, Severity, and Detection using Tables 3, 4, and 5. The RPN will be obtained by multiplying the Occurrence, Severity, and Detection score. Table 6 shows the example of scoring by using FMEA from Table 2.

Table 3. Occurrence Criteria

Occurrence		
Ranking	Occurrence	Frequency
10	Very High	1 in 2
9		1 in 3
8	High	1 in 8
7		1 in 20
6	Moderate	1 in 80
5		1 in 400
4		1 in 2000
3	Low	1 in 15000
2		1 in 150.000
1	Remote	1 in 1.500.000

Table 4. Severity Criteria.

Severity		
Ranking	Severity	Criteria
10	Dangerously High	The failure effect is hazardous to customer/user safety
9	Extremely high	The same as above, only with a warning
8	Very high	The product is not operative High
7	High	High degradation of the product and customer dissatisfaction
6	Moderate	Partial malfunction of the product and customer dissatisfaction
5	Low	The product could be reworked, and some customer dissatisfaction
4	Very Low	The failure could be noticed by many customers
3	Minor	The failure could be noticed by a few customers
2	Very Minor	The failure is not apparent to the customer
1	None	No Effect

Table 5. Detection Criteria

Detection		
Tingkat	Detectability	Criteria
10	Absolute Incertainty	Impossible to detect the failure
9	Very remote	Very difficult to detect the failure
8	Remote	Difficult to detect the failure
7	Very low	Very low chance to detect failure
6	low	Low chance to detect failure
5	Moderate	Moderate chance to detect failure
4	Moderate High	Moderately High chance to detect failure
3	High	Probably the current Control Wills detect the failure
2	Very High	High probably the current Control Wills detect the failure
1	Almost certain	Surely the current Control Wills detect the failure

Table 6. RPN Example of Each Main Engine Lubricating Oil Cooler Failure Mode

Item Tag	ID FF	ID FM	O	Description	S	Description	D	Description	RPN
A3	B	1	4	1 in 2000	5	The product could be reworked, and some customer dissatisfaction	4	Moderately High chance to detect failure	80
		2	6	1 in 80	5	The product could be reworked, and some customer dissatisfaction	4	Moderately High chance to detect failure	120

2.5. Criticality Analysis

The criticality analysis aims to determine the risk ranking according to the risk [11]. In this step, the risk matrix will be used to convert from severity and occurrence into risk ranking H (High), M (Medium), and L (Low). in this analysis, the risk matrix will use a 10 x 10 risk matrix. Figure 8 shows the risk matrix that will be used in this analysis. Table 7 shows the criticality analysis from the Lubricating oil cooler.

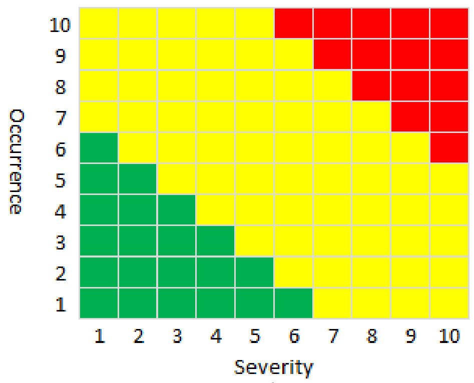


Figure 8. Risk Matrix

3. Results and Discussion

3.1. Failure Mode Effects and Criticality Analysis

After all examples of the process to determine the results until criticality analysis, the next step is to analyze all the already determined equipment. Table 8 shows the function and functional failure of the Lubricating Oil System equipment.

Table 9 shows the failure mode that has already been analyzed. Table 10 shows the example of failure effects on H2 and H9. Table 11 shows the FMEA worksheet of the lubricating oil pump. Table 12 shows the occurrence, severity, detection, RPN, and criticality analysis scoring.

Table 7. The Example of Main Engine Lubricating Oil Cooler Criticality Determination

Item Tag	ID FF	ID FM	failure Mode	O	S	CA
A3	B	1	Main Engine Lubricating Oil Pump Cooler insufficient heat transfer due to leak on the tubes	4	5	M
		2	Main Engine Lubricating Oil Pump Cooler insufficient heat transfer due to contaminant buildup	6	5	M

Table 8. The Function and Functional Failure of Lubricating Oil System Equipment

No	Item Tag	Item	Function		Functional Failure
1	H2	Engine reserve oil Tank	To store and provide 3.95 m3 lubricating oil for Lubricating oil system requirement	A	Unable to provide and retain lubricating oil in 3.95 m3
2	N9	Lubricating Oil Transfer Pump	To transfer Lubricating Oil from Engine Reserve Oil Tank (H2) to Engine Service Oil Tank (H1) at a specific rate	A	Unable to transfer lubricating oil from H2 to H1 at all
				B	transfer lubricating oil from H2 to H1 below certain rate
3	H1	Engine Service Oil Tank	To store clean lubricating oil and provide lubricating oil for the Main Engine Lubricating system	A	Unable to store clean lubricating oil and provide lubricating oil for the Main Engine Lubricating system
4	Z	Main Engine Carter	To receive and store lubricating oil after lubricating the internal part of the Main Engine	A	Unable to receive and store lubricating oil after lubricating the internal part of the Main Engine
5	A9	Lubricating Oil Pump	To transfer Lubricating Oil from ME Carter (Z) to Main Engine Internal Parts (A1), pass through Lubricating Oil Cooler (A3) and Lubricating Oil Filter (A11) at normal pressure (5-6 kg/cm2)	A	Unable to transfer lubricating oil at all
				B	Transfer Lubricating Oil below normal pressure (5-6 kg/cm2)
6	N1	Engine Lubricating Oil Stand by Pump	To backup Lubricating Oil Pump (A9) and transfer Lubricating Oil from ME Carter (Z) to Main Engine Internal Parts (A1), pass through Lubricating Oil Cooler (A3) and Lubricating Oil Filter (A11) at a specific rate and pressure	A	Unable to transfer lubricating oil at all
				B	Transfer Lubricating Oil below normal pressure (5-6 kg/cm2)
7	A3	Main Engine Lubricating Oil Pump Cooler	To cool down the temperature of lubricating oil by transferring heat from the lubricating oil to the seawater at standard temperature (60 - 70 C)	A	Unable to cool down the temperature of lubricating oil by transferring heat from lubricating oil t seawater
				B	Cooldown the temperature of lubricating oil below standard (> 60 - 70 C)
	A11	Lubricating Oil Filter	To clean and filter every contaminant contains in lubricating oil	A	Unable To clean and filter every contaminant that contains in lubricating oil at all
				B	Clean and filter every contaminant in lubricating oil at a specific point.

Note: A and B are ID for Functional Failure

The previous table has already obtained all the functions and functional failures. The functional failure was obtained to not fill its function at all and/or function below its standard performance. In this matter, the standard of the equipment was obtained from the specification of its equipment. After the function and functional failure were obtained, the next step is to define the failure mode. Table 9 shows the failure mode of the Main Engine Lubricating Oil System Equipment.

After collecting the maintenance record and reference to find the basic event that contributed to the equipment failure in the past and brainstorming to predict the possible basic event that could cause the equipment failure, there is 39 failure mode obtained from every piece of equipment. After the failure mode has already been obtained, the effects of this failure mode happened is analyzed. Table 10 shows the example of failure effect analysis of the Oil Lubricating Pump (A9).

Table 9. Failure Mode of Every Main Engine Lubricating Oil System Equipment

Item Tag	ID FF		Failure Mode
H2	A	1	Engine reserve oil tank structure deficiency due to rupture.
		2	Engine reserve oil tank structure deficiency due to corrosion.
N9	A	1	Lubricating Oil Transfer pump gear cracked due to fatigue.
		2	Lubricating Oil Transfer pump shaft cracked due to fatigue.
		3	Lubricating Oil Transfer pump overheats due to shaft misalignment.
		4	Lubricating Oil Transfer pump overheats due to the shaft bend.
		5	Lubricating Oil Transfer pump overheats due to the worn bearing.
	B	1	Lubricating Oil Transfer pump gear is corrosion due to time.
		2	Lubricating Oil Transfer pump shaft is corrosion due to time.
		3	The Lubricating Oil Transfer pump seal has worn out due to time.
		4	The Lubricating Oil Transfer pump vibrates due to shaft misalignment.
		5	The Lubricating Oil Transfer pump vibrates due to the shaft bend.
		6	The Lubricating Oil Transfer pump vibrates due to the worn bearing.
H1	A	1	Engine service oil tank structure deficiency due to rupture.
		2	Engine service oil tank structure deficiency due to corrosion.
Z	A	1	Main Engine carter structure deficiency due to corrosion.
A9	A	1	The lubricating oil pump gear cracked due to fatigue.
		2	The lubricating oil pump shaft cracked due to fatigue.
		3	The lubricating oil pump overheats due to shaft misalignment.
	B	1	The Lubricating oil pump gear is corrosion due to time.
		2	The Lubricating oil pump shaft is corrosion due to time.
		3	The lubricating oil pump seal has worn out due to time.
N1	A	1	Engine Lubricating Oil Stand by Pump gear cracked due to fatigue.
		2	Engine Lubricating Oil Stand by Pump shaft cracked due to fatigue.
		3	Engine Lubricating Oil Stand-by Pump overheats due to shaft misalignment.
		4	Engine Lubricating Oil Stand-by Pump overheats due to shaft bend.
		5	Engine Lubricating Oil Stand-by Pump overheats due to worn bearing.
	B	1	Engine Lubricating Oil Stand-by Pump gear is corrosion due to time.
		2	Engine Lubricating Oil Stand-by Pump shaft is corrosion due to time.
		3	Engine Lubricating Oil Stand-by Pump seal has worn out due to time.
		4	Engine Lubricating Oil Stand-by Pump vibrates due to shaft misalignment.
		5	Engine Lubricating Oil Stand-by Pump vibrates due to shaft bend.
		6	Engine Lubricating Oil Stand-by Pump vibrates due to the worn bearing.
A3	A	1	Main Engine Lubricating Oil Pump Cooler insufficient heat transfer due to tube rupture.
		2	Main Engine Lubricating Oil Pump Cooler insufficient heat transfer due to full contaminant blockage.
	B	1	Main Engine Lubricating Oil Pump Cooler has insufficient heat transfer due to a tube leak.
		2	Main Engine Lubricating Oil Pump Cooler insufficient heat transfer due to contaminant buildup.
A11	A	1	Lubricating Oil Filter chocked due to contaminant blockage.
	B	1	Lubricating Oil Filter pore diameters increase due to wear out.

Note: Number 1,2,3, and so on, shows the Failure Mode ID

The effects analysis results show that if the failure mode happened, it could affect the lubricating system, probably stop the system function, and potentially damage the equipment and other equipment. To analyze this failure mode and its effect, scoring is needed. In this analysis, the RPN number was used to prioritize it. The RPN will be determined using scoring of S, O, and D criteria in Table 3, 4, and 5. This scoring considers how frequently the failure would occur, the seriousness of the effect of the potential failure on the system, and the probability that the operating parameters monitoring system will detect a cause/mode of failure before the component/system is damaged and stopped. Table 11 shows the FMEA worksheet, which contains the item tag, item name, function, functional failure, and effects of the lubricating oil pump (A9).

Table 10. The example of failure effect analysis of the Oil Lubricating Pump (A9)

Item Tag	ID FF		Failure Mode	Failure Effects
A9	A	1	Lubrication oil pump gear crack due to fatigue	A Lubricating Oil pump gear crack due to fatigue could cause the lubricating oil transfer pump cannot to operate. lubricating oil doesn' t flow from ME Carter to ME internal part. It would make the operator turn on the lubricating oil stand-by pump.
		2	Lubrication oil pump shaft crack due to fatigue	The Lubricating Oil pump shaft crack due to fatigue could cause the lubricating oil transfer pump cannot to operate. lubricating oil doesn' t flow from ME Carter to ME internal part. It would make the operator turn on the lubricating oil stand-by pump.
		3	The lubrication oil pump overheats due to shaft misalignment	The Lubricating Oil pump overheating due to shaft misalignment could cause the lubricating oil transfer pump cannot to operate. lubricating oil doesn' t flow from ME Carter to ME internal part. It would make the operator turn on the lubricating oil stand-by pump.

Table 11. The Example of Lubricating Oil Pump (A9) FMEA worksheet

Item Tag	Item	Function		Functional Failure		Failure Mode	Failure Effects	O	S	D	RPN
A9	Lubricating Oil Pump	To transfer Lubricating Oil from ME Carter (Z) to Main Engine Internal Parts (A1) pass through Lubricating Oil Cooler (A3) and Lubricating Oil Filter (A11) at normal pressure (5-6 kg/cm2)	A	Unable to transfer Lubricating Oil at all	1	Lubrication oil pump gear crack due to fatigue	A Lubricating Oil pump gear crack due to fatigue could cause the lubricating oil transfer pump not to operate. Lubricating oil doesn' t flow from ME Carter to the ME internal part. It would make the operator turn on the lubricating oil standby pump.	3	8	8	192
					2	Lubrication oil pump shaft crack due to fatigue	A Lubricating Oil pump shaft crack due to fatigue could cause the lubricating oil transfer pump not to operate. Lubricating oil doesn' t flow from ME Carter to the ME internal part. It would make the operator turn on the lubricating oil standby pump.	4	8	8	256
					3	The lubrication oil pump overheats due to shaft misalignment	The Lubricating Oil pump overheating due to shaft misalignment could cause the lubricating oil transfer pump not to operate. Lubricating oil doesn' t flow from ME Carter to the ME internal part. It would make the operator turn on the lubricating oil standby pump.	2	7	9	126

Table 12. The RPN and Criticality Ranking

Item Tag	ID FF	ID FM	failure Mode	O	S	D	RPN	CA
A9	A	2	The lubricating oil pump shaft cracked due to fatigue.	4	8	8	256	M
N1	B	2	Engine Lubricating Oil Stand by Pump shaft is corrosion due to time.	6	7	6	252	M
N1	B	1	Engine Lubricating Oil Stand by Pump gear is corrosion due to time.	5	7	7	245	M
N9	A	2	The Lubricating Oil Transfer pump shaft cracked due to fatigue.	4	8	7	224	M
N9	B	5	The Lubricating Oil Transfer pump vibrates due to the shaft bend.	7	4	8	224	M
N1	A	2	Engine Lubricating Oil Stand by Pump shaft cracked due to fatigue.	4	8	7	224	M
N1	A	3	Engine Lubricating Oil Stand by Pump overheats due to shaft misalignment.	5	8	5	200	M
N9	B	4	The Lubricating Oil Transfer pump vibrates due to shaft misalignment.	7	4	7	196	M
A9	A	1	The Lubricating oil pump gear cracked due to fatigue.	3	8	8	192	M
A9	B	1	The Lubricating oil pump gear is corrosion due to time.	5	4	9	180	M
N1	B	6	Engine Lubricating Oil Stand by Pump vibrates due to worn bearing.	6	6	5	180	M
N9	A	1	The Lubricating Oil Transfer pump gear cracked due to fatigue.	3	7	7	147	M
N9	B	1	The Lubricating Oil Transfer pump gear is corrosion due to time.	7	3	7	147	M
N1	A	1	Engine Lubricating Oil Stand by Pump gear cracked due to fatigue.	3	7	7	147	M
A3	A	2	Main Engine Lubricating Oil Pump Cooler insufficient heat transfer due to full contaminant blockage.	3	7	7	147	M
H2	A	1	Engine reserve oil tank structure deficiency due to rupture.	3	9	5	135	M
H1	A	1	Engine service oil tank structure deficiency due to rupture.	3	9	5	135	M
A9	A	3	The lubricating oil pump overheats due to shaft misalignment.	2	7	9	126	M
N1	A	4	Engine Lubricating Oil Stand-by Pump overheats due to shaft bend.	3	7	6	126	M
A9	B	2	The Lubricating oil pump shaft is corrosion due to time.	6	4	5	120	M
N1	B	5	Engine Lubricating Oil Stand by Pump vibrates due to shaft bend.	4	6	5	120	M
A3	B	2	Main Engine Lubricating Oil Pump Cooler insufficient heat transfer due to contaminant buildup.	6	5	4	120	M
N1	A	5	Engine Lubricating Oil Stand-by Pump overheats due to worn bearing.	6	6	3	108	M
N9	A	4	The Lubricating Oil Transfer pump overheat due to the shaft bend.	3	7	5	105	M
N1	B	4	Engine Lubricating Oil Stand by Pump vibrates due to shaft misalignment.	4	5	5	100	M
A3	A	1	Main Engine Lubricating Oil Pump Cooler insufficient heat transfer due to tube rupture.	2	7	7	98	M
N9	A	3	The Lubricating Oil Transfer pump overheats due to shaft misalignment.	3	8	4	96	M
Z	A	1	Main Engine carter structure deficiency due to corrosion.	5	6	3	90	M
A11	B	1	The Lubricating Oil Filter pore diameters increase due to wear out.	6	5	3	90	M
N9	B	2	The Lubricating Oil Transfer pump shaft is corrosion due to time.	7	4	3	84	M
A3	B	1	Main Engine Lubricating Oil Pump Cooler insufficient heat transfer due to leak on the tubes	4	5	4	80	M
N9	A	5	The Lubricating Oil Transfer pump overheats due to worn bearing	3	6	4	72	M
N9	B	6	The Lubricating Oil Transfer pump vibrates due to worn bearing	7	3	3	63	M
H2	A	2	Engine reserve oil tank structure deficiency due to corrosion	5	4	3	60	M
H1	A	2	Engine service oil tank structure deficiency due to corrosion	5	4	3	60	M
N1	B	3	Engine Lubricating Oil Stand-by Pump seal worn out due to time	6	3	3	54	M
A11	A	1	The Lubricating Oil Filter chocked due to contaminant blockage	3	5	3	45	L
N9	B	3	The Lubricating Oil Transfer pump seal worn out due to time	7	3	2	42	M
A9	B	3	The Lubricating oil pump seal worn out due to time	6	3	2	36	M

The FMEA of the Lubricating oil system shows that the highest RPN is shaft crack due to fatigue, followed by gear crack and shaft misalignment. The highest occurrence is shaft crack, the highest severity is gear crack and shaft crack, and the highest detection is shaft misalignment. Table 12 shows the Occurrence (O), Severity (S), Detection (D), Risk Priority Number (RPN), and Criticality (CA) from every failure mode of lubricating oil system equipment that has been obtained before.

From the RPN results, the highest RPN is 256, lubricating oil pump (A9) shaft cracked due to fatigue. This was obtained from the four scores of occurrence, eight of Severity, and eight of Detection. Pareto is used to prioritize which failure mode will be prioritized to be maintained first. Figure 9 shows the Pareto graph of every failure mode RPN. And from the graph, it is shown that the failure mode of the lubricating oil pump is shaft crack due to fatigue until the failure mode of the lubricating oil transfer pump, which is overheating due to shaft bend, will be prioritized first. The Criticality based risk was obtained mostly on the medium area except for the failure mode of the lubricating Oil Filter, which choked due to contaminant blockage. Figure 10 shows the risk matrix plot for equipment prioritized in the first stage using Pareto. In this plot, all the equipment has a medium risk ranking. Table 13 shows the list of equipment and its failure mode that will be maintained first.

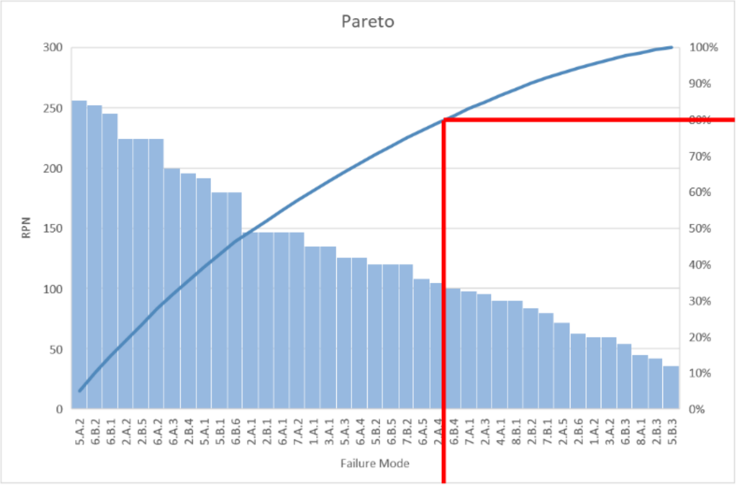


Figure 9. Pareto graph

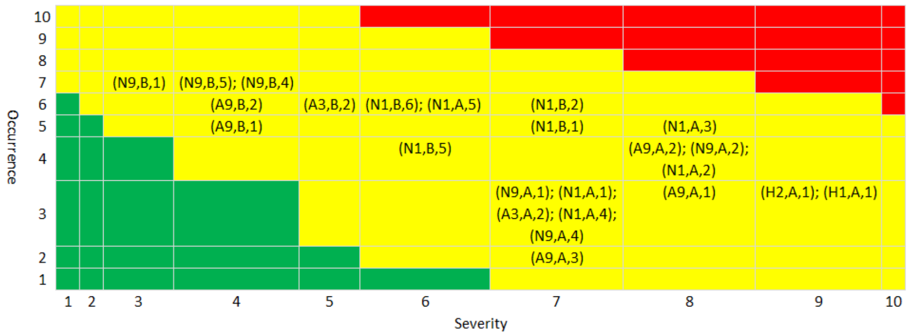


Figure 10. Risk Matrix Plot

Table 13. Equipment and its failure mode that will be prioritized to be maintained.

Item Tag	ID FF	ID FM	failure Mode	O	S	D	CA	RPN
A9	A	2	The Lubricating oil pump shaft cracked due to fatigue.	4	8	8	M	256
N1	B	2	Engine Lubricating Oil Stand by Pump shaft is corrosion due to time.	6	7	6	M	252
N1	B	1	Engine Lubricating Oil Stand by Pump gear is corrosion due to time.	5	7	7	M	245
N9	A	2	The Lubricating Oil Transfer pump shaft cracked due to fatigue.	4	8	7	M	224
N9	B	5	The Lubricating Oil Transfer pump vibrates due to the shaft bend.	7	4	8	M	224
N1	A	2	Engine Lubricating Oil Stand by Pump shaft cracked due to fatigue.	4	8	7	M	224
N1	A	3	Engine Lubricating Oil Stand-by Pump overheats due to shaft misalignment.	5	8	5	M	200
N9	B	4	The Lubricating Oil Transfer pump vibrates due to shaft misalignment.	7	4	7	M	196
A9	A	1	The lubricating oil pump gear cracked due to fatigue.	3	8	8	M	192
A9	B	1	The Lubricating oil pump gear is corrosion due to time.	5	4	9	M	180
N1	B	6	Engine Lubricating Oil Stand by Pump vibrates due to worn bearing.	6	6	5	M	180
N9	A	1	Lubricating Oil Transfer pump gear cracked due to fatigue.	3	7	7	M	147
N9	B	1	Lubricating Oil Transfer pump gear is corrosion due to time.	7	3	7	M	147
N1	A	1	Engine Lubricating Oil Stand by Pump gear cracked due to fatigue.	3	7	7	M	147
A3	A	2	Main Engine Lubricating Oil Pump Cooler insufficient heat transfer due to full contaminant blockage.	3	7	7	M	147
H2	A	1	Engine reserve oil tank structure deficiency due to rupture.	3	9	5	M	135
H1	A	1	Engine service oil tank structure deficiency due to rupture.	3	9	5	M	135
A9	A	3	The lubricating oil pump overheats due to shaft misalignment.	2	7	9	M	126
N1	A	4	Engine Lubricating Oil Stand-by Pump overheats due to shaft bend.	3	7	6	M	126
A9	B	2	Lubrication oil pump shaft is corrosion due to time.	6	4	5	M	120
N1	B	5	Engine Lubricating Oil Stand by Pump vibrates due to shaft bend	4	6	5	M	120
A3	B	2	Main Engine Lubricating Oil Pump Cooler insufficient heat transfer due to contaminant buildup	6	5	4	M	120
N1	A	5	Engine Lubricating Oil Stand-by Pump overheats due to worn bearing	6	6	3	M	108
N9	A	4	Lubricating Oil Transfer pump overheat due to the shaft bend	3	7	5	M	105

3.2. Recommendation for maintenance strategy

After the maintenance object was determined using FMECA, the next step is to determine the maintenance activity or maintenance task to minimize the occurrence of failure mode. In this analysis, some of the maintenance tasks from the reference is used. Table 14 shows the maintenance task of the RV Baruna Jaya lubricating oil system maintenance object.

Table 14. Maintenance Task.

Item Tag	Item Name	ID FF	ID FM	Maintenance Task	Reference
A3	Lubricating Oil Cooler	A B	2 2	1. The heat transfer surfaces of heat exchangers should be kept reasonably clean to assure satisfactory performance. Convenient means for cleaning should be made available. Heat exchangers may be cleaned either online or offline by chemical or mechanical methods.	[16]
A9	Lubricating Oil Pump	A A A B B	1 2 3 1 2	1. Vibration trends should be reviewed. If the pump is trending toward unacceptable vibration levels 2. When coupling halves are disconnected for an alignment check, the vertical shaft movement of a pump with sleeve (journal) bearings should be checked at both ends with packing or seals removed. Any movement exceeding 150% of the original design clearance should be investigated to determine the cause. 3. All instruments and flow-metering devices should be recalibrated whenever feasible, and—whenever possible—the pump should be tested to determine whether proper performance is being obtained. If internal repairs are made, the pump should again be tested after the completion of the repairs.	[17]
H1	Engine Service Oil Tank	A	1	The primary tank should be inspected monthly for the presence of water. Inspection should take place at the lowest possible points inside the primary tank. Remove any water found. Water and sediment can cause the plugging of filters. Also, bacterial growth originating from the fuel can cause filters to plug and the corrosion of tanks and lines.	[18]
H2	Engine Reserve Oil Tank	A	1	The primary tank should be inspected monthly for the presence of water. Inspection should take place at the lowest possible points inside the primary tank. Remove any water found. Water and sediment can cause the plugging of filters. Also, bacterial growth originating from the fuel can cause filters to plug and the corrosion of tanks and lines.	[18]
N1	Engine Lubricating Oil Stand by Pump	A A A A A B B B B	1 2 3 4 5 1 2 5 6	1. Vibration trends should be reviewed. If the pump is trending toward unacceptable vibration levels 2. When coupling halves are disconnected for an alignment check, the vertical shaft movement of a pump with sleeve (journal) bearings should be checked at both ends with packing or seals removed. Any movement exceeding 150% of the original design clearance should be investigated to determine the cause. 3. All instruments and flow-metering devices should be recalibrated, whenever feasible, and—whenever possible—the pump should be tested to determine whether proper performance is being obtained. If internal repairs are made, the pump should again be tested after the completion of the repairs.	[17]
N9	Lubricating Oil Transfer Pump	A A A B B B	1 2 4 1 4 5	1. Vibration trends should be reviewed. If the pump is trending toward unacceptable vibration levels 2. For pumps equipped with shaft packing, the packing should be removed and the shaft sleeves or shaft, if no sleeves are used—should be examined for wear. 3. For pumps equipped with mechanical seals, if the seals were indicating signs of leaking, they should be removed and returned to the seal manufacturer for inspection, possible bench testing, and refurbishment. 4. When coupling halves are disconnected for an alignment check, the vertical shaft movement of a pump with sleeve (journal) bearings should be checked at both ends with packing or seals removed. Any movement exceeding 150% of the original design clearance should be investigated to determine the cause. 5. All instruments and flow-metering devices should be recalibrated, whenever feasible, and—whenever possible—the pump should be tested to determine whether proper performance is being obtained. If internal repairs are made, the pump should again be tested after completion of the repairs.	[17]

4. Conclusion

The lubricating oil system is crucial to the main engine function, it is essential to maintain the lubricating oil system performance. With the large amount of equipment in the system, it is vital to prioritize which equipment should be maintained first. The FMECA has already carried out to prioritized the lubricating oil system equipment. The results have been obtained by determining the block diagram and asset register of the system, equipment function, functional equipment failure, equipment failure mode effects, and its criticality. The results show 9 pieces of equipment in the lubricating oil system and 39 failure modes. By prioritizing it using FMEA and Criticality Analysis, there are six types of equipment with 24 failure modes that should be maintained. These types of equipment are a lubricating oil cooler, lubricating oil pump, engine service oil tank, engine reserve oil tank, Engine lubricating oil standby pump, and lubricating oil transfer pump. The maintenance task is proposed to minimize the occurrence of failure mode, which could happen in the equipment.

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