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IMPLEMENTATION OF RCM IN MAINTENANCE STRATEGY OF FO SYSTEM, LO SYSTEM, AND COOLING SYSTEM MAIN ENGINE

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ABSTRACT

The performance of a ship's main engine largely depends on the reliability of its three primary subsystems: fuel, lubricating, and cooling. These systems must operate optimally to ensure efficiency and safety under varying operational conditions. This study evaluates the reliability of the KM. The Lawit main engine subsystems use the Reliability Centered Maintenance (RCM) approach. Four analytical methods were applied: Failure Mode and Effect Analysis (FMEA) to identify critical components, Fault Tree Analysis (FTA) to trace root causes of failures, Reliability Block Diagram (RBD) to model interrelationships, and Monte Carlo simulation to estimate system reliability probabilistically. The analysis was based on operational and maintenance data from 2023–2024. FMEA identified the duplex filter in the fuel system (RPN = 288), the lubricating oil filter (RPN = 280), and the expansion tank in the cooling system (RPN = 140) as the most critical components requiring priority maintenance. Monte Carlo simulation over hours showed the cooling system achieved the highest reliability, with a Mean Time to Failure (MTTF) of 1,022.21 hours and a Mean Time Between Failures (MTBF) of 7,587.47 hours. Across all systems, availability levels exceeded 99%, indicating strong reliability and minimal risk of operational failure. These findings highlight the effectiveness of integrating FMEA, FTA, RBD, and Monte Carlo simulation within the RCM framework. The results emphasize the need for preventive maintenance strategies to sustain the long-term operational stability and safety of the main engine.

Keywords: Failure mode and effect analysis, fault tree analysis, Monte Carlo, reliability block diagram

Introduction

Sea transportation plays a crucial role in facilitating both passenger mobility and large-scale goods distribution, especially in connecting archipelagic regions [1]. In Indonesia, where thousands of islands are separated by vast stretches of sea, maritime transportation becomes indispensable [2]. One of the most essential maritime transport services is the operation of passenger ships, which are the backbone of inter-island connectivity. These ships enable seamless access to services, markets, and essential goods, contributing to regional integration and national development [3].

PT Pelayaran Nasional Indonesia (Pelni), a state-owned enterprise, plays a strategic role in national

development through its maritime transport services [4]. By connecting various islands across the archipelago, Pelni not only functions as a transport provider but also as a development agent that stimulates regional economic growth [5]. Pelni's diverse fleet ensures the accessibility of essential commodities and services, directly impacting the quality of life of the Indonesian people [6]. This connectivity promotes equitable development and reduces regional disparities.

Among Pelni's fleet is the KM. Lawit is a vessel dedicated to community service and regional connectivity. KM. Lawit's operational reliability heavily depends on its main engine, which is powered by a complex network of subsystems, including the fuel oil system, lubricating oil system,

and cooling system [7]. These three systems are interdependent and vital to ensuring the engine's performance, efficiency, and operational safety [8].

In the research on reliability-based maintenance analysis of the fuel system on the main engine of the KM. Kelimutu ship, it shows from the simulation, an availability value of 0.993 and a *Mean Time to Failure* (MTTF) of 317.99 hours were obtained [9]. Another study on the reliability analysis of the ship's main engine lubricating system showed in a simulation for 5,000 hours that the initial MTTF value of 711.54 hours increased to 831.62 hours. In addition, the Mean Time Between Failures (MTBF) has increased from 975.89 hours to 1,355.65 hours after adding a redundancy system to the LO Filter Duplex and LO Cooler [10]. Other research on the reliability analysis of the KM. Pangrango ship's main engine cooler. MTTF value on pipe components is every 399 hours [11].

An effective strategy to address these risks is to adopt a risk-based maintenance framework, such as Reliability-Centered Maintenance [12]. RCM systematically identifies system functions and potential failures, enabling the development of preventive measures that focus on critical components [13]. By emphasizing functionality and the consequences of failures, RCM establishes structured and standardized maintenance policies [14]. It is also recognized for its ability to reduce maintenance costs by eliminating unnecessary procedures while maintaining critical system functions [15].

Even when a maintenance program is already in place, RCM analysis is often used to evaluate and optimize it by eliminating inefficient or redundant maintenance steps [16]. While most previous studies focused on evaluating a single engine subsystem, this research presents an integrated analysis of the fuel system, lubricating system, and cooling system [17].

To model and analyze system reliability, this study applies a combination of advanced techniques: FMEA to identify failure modes and critical components [18], FTA to trace root causes of failures [19]. The best fit distribution is determined to ensure that the reliability input of each component in the RBD matches its actual failure pattern [20], and RBD to visualize the interdependence between components [21]. Additionally, Monte Carlo simulation is used to predict system reliability through probabilistic modeling [22]. These methodologies provide

complementary perspectives that enhance the reliability assessment process [23].

The integration of these four methods in a single framework is rare in maritime engineering literature, yet highly effective for analyzing complex systems under uncertainty [24]. A study applying Monte Carlo simulation in maintenance strategy development demonstrated the importance of such probabilistic techniques in estimating MTTF and MTBF under real operating conditions [25]. Furthermore, the use of software tools such as *Relyence* enables more accurate modeling and validation of reliability assessments.

This research builds upon previous methodologies to develop a maintenance recommendation system for KM. Lawit, ensuring that maintenance actions are guided by critical reliability metrics and system behavior over time. Ultimately, this integrated approach supports optimal operational performance, system availability, and improved preventive maintenance planning.

Methodology

The object of this research is KM. Lawit, a passenger vessel operated by PT PELNI (Persero). Data collection was conducted while the vessel was berthed at Tanjung Emas Port, Semarang, Central Java. The principal dimensions of KM. Lawit are as follows: length overall (LOA) 99.80 m, length between perpendiculars (LBP) 90.5 m, breadth (B) 18.00 m, depth (H) 9.40 m, and draft (T) 4.20 m. The vessel has a service speed of 14 knots and an IMO number of 8502353. The methodology employed in this research comprises several analytical stages, which are described in the following sections.

a. Failure Mode and Effect Analysis (FMEA)

Failure Mode and Effect Analysis (FMEA) is an analysis method used to find potential failures in a system and evaluate their impact and cause. As a basis for handling priorities [26]. FMEA is widely used in the engineering industry, including ship machinery systems, to prevent failures and design risk-based maintenance strategies [27]. In this study, it starts by separating the three systems, then identifying what components are contained in the diagram of each system to determine the potential failure, the effects caused, and the main cause of failure.

The next stage is to assess each component failure based on the severity parameter (Severity), the level of probability of failure occurring

(Occurrence), and the level of how the failure can be detected (Detection) [28]. The three values will later be used to calculate the Risk Priority Number (RPN) with the formula, $RPN = S \times O \times D$ [29]. Components with the highest RPN value need to be prioritized in maintenance, because they have a high risk of causing overall system disruption.

b. Compilation of Fault Tree Analysis (FTA)

The stages of compiling FTA begin with determining the main failure (top event) of each system [30]. Then, look for the causes of failure, which are arranged in stages using logic gates. OR gates are used if one of several events can cause failure, while AND gates are used if the connected events must occur simultaneously.

Each cause is then further broken down until it reaches the basic event. Through this failure tree, researchers can determine the cut set or combination of failures that can trigger the top event [30].

c. Determine the Best Fit Distribution

The purpose of determining the best fit distribution is to determine the best probability distribution that interprets the failure time data of a component of a system, in choosing the distribution to model failure patterns based on historical data [24]. From determining this best-fit distribution, researchers can calculate MTTF, Reliability $R(t)$, and failure rate [31].

Failure time data is obtained from damage and maintenance data KM. Lawit period 2023-2024. Researchers used Relyance Free Trial Software to

determine the distribution of each system component.

d. Preparation of Reliability Block Diagram (RBD)

A reliability block diagram (RBD) is a deductive method used to analyze the reliability of a system. In RBD, complex systems can be repaired and evaluated through drawings or diagrams that show the logical relationships between components [33]. This diagram illustrates how each component, subsystem, or reliability event is connected to the others in a certain arrangement. There are various types of arrangements, such as series configurations, parallel configurations, and mixed configurations, which are used to assess the reliability of these systems [20].

The initial step in preparing the RBD is to identify the system workflow according to the system diagram.

e. Monte Carlo Simulation

Monte Carlo simulation is a statistical method that uses a randomized approach to predict the reliability of complex and uncertain systems. In its application to ship mother engines, this method is used to estimate MTTF, MTBF, and availability values by running thousands of component failure simulations based on a predetermined probability distribution of damage [32].

This simulation aims to model system reliability randomly based on the predetermined failure distribution of each component. The simulation produces reliability estimates of MTTF, MTBF, MTTF, *Availability*, and *Reliability*.

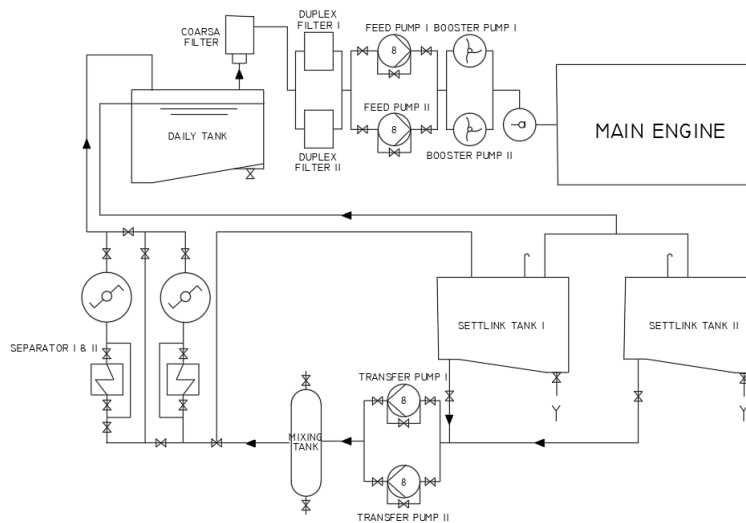


Figure 1. Diagram of Fuel System

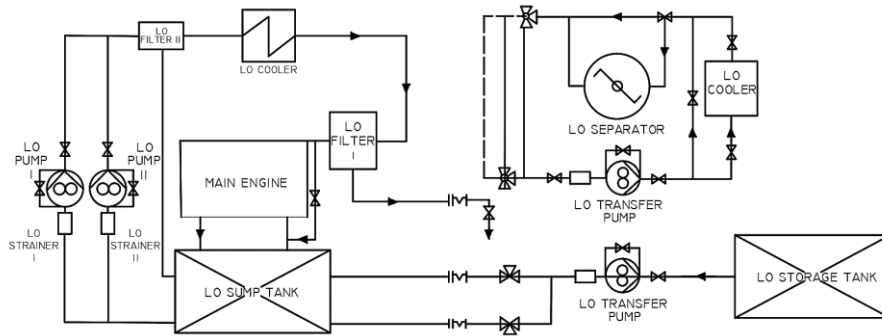


Figure 2. Diagram of Lubricating Oil System

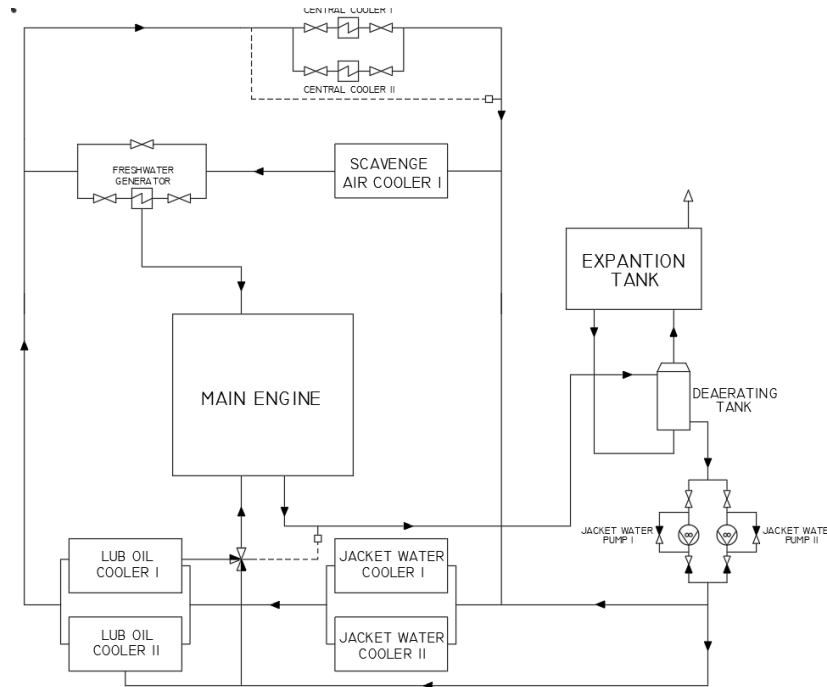


Figure 3. Diagram of Cooling System

Result and Discussion

The following section presents the results and discussion of the research conducted using the RCM approach. The analysis was carried out through four main methods: FMEA, FTA, RBD, and Monte Carlo Simulation. These methods complement each other in identifying failure modes, determining risk

levels, analyzing inter-component relationships, and estimating system reliability probabilistically.

a. FMEA Analysis Results

After completing the determination of the FMEA critical components of each system, the results of the Risk Priority Number (RPN) value are obtained, and these results are visualized in Figure 4.

Table 1. FMEA of Fuel Oil System

Component FO	Failure Mode	Failure Mode Effect	Cause of Failure Mode	Severity	Occurance	Detection	RPN
Settling Tank	Uneven mixing	Disrupted fuel flow	Valve blockage	6	6	4	144
Transfer Pump	Leakage	Fuel not entering daily tank	Corrosion	5	6	5	150

Mixing Tank	Fuel contamination	Fuel quality degrades	Leakage in the tank	2	5	3	30
Separator	Separation of impurities is not maximized	Dirty fuel	Sludge buildup	5	7	6	210
Daily Tank	Tank Leakage	Fire Risk	Corrosion on the tank wall	4	7	3	84
Coarse Filter	Leakage	Obstructed fuel flow	Dirty fuel	7	5	3	105
Duplex Filter	Filter blockage	Obstructed fuel distribution	Filter wear	9	8	4	288
Feed Pump	Pump Stuck	Fuel flow is stopped	Motor damage	5	8	5	200
Booster Pump	Pump pressure decreased	Fuel too thick	The temperature sensor is not running	8	5	4	160
Injection Pump	Weak injection pressure	Fuel is not thoroughly	Spring damage	6	9	5	270

Based on the calculations in Table 1, the duplex filter has the highest RPN of 288 due to filter wear that hinders fuel flow. This is followed by the injection pump with an RPN of 270 due to spring

damage that weakens injection pressure. Other components, such as the separator and feed pump, also have high RPNs of 210 and 200, respectively, indicating a significant risk of failure.

Table 2. FMEA of Lubricating Oil System

Component LO	Failure Mode	Failure Mode Effect	Cause of Failure Mode	Severity	Occurance	Detection	RPN
LO Storage Tank	Tank leakage	Lubricating oil wasted	Corrosion of the tank	3	5	3	45
LO Sump Tank	Excessive sludge deposition	Filter quickly clogs	Dirty oil	3	6	3	54
LO Transfer Pump	Pump stuck	Oil not supplied	Imperller wear	7	6	5	210
LO Pump	Pump not running	Oil is not circulated throughout the system	Dirty buildup	5	9	5	225
Oil Mist Detector	Sensor not working	Cannot detect overheating	Electrical malfunction	6	6	6	216
LO Filter	Clogging	Oil flow is blocked	Dirty buildup	8	7	5	280
LO Strainer	Damaged strainer	Impurities enter the pump	Excessive pressure	4	6	3	72

LO Separator	Overflow	Lubricating oil quality decreases	Dirty buildup	4	6	4	96
LO Cooler	Heat exchanger failure	Oil not cooled enough	Over pressurization	2	8	5	80
LO Storage Tank	Tank leakage	Lubricating oil wasted	Corrosion of the tank	3	5	3	45

Based on the results of the FMEA calculation of the lubrication system in Table 2, it is known that the LO filter is the component with the highest RPN value of 280. This failure is caused by blockages due to dirt buildup, which hinders the flow of lubricating oil. Another component with a high risk is the LO pump with an RPN value of 225, followed

by the oil mist detector with an RPN value of 216. The component with the lowest RPN value is the LO storage tank with an RPN of 45, indicating the lowest risk level. The next step is to analyze the FMEA for the cooling system, with the analysis results shown in Table 3.

Table 3. FMEA of Cooling System

Component	Failure Mode	Failure Mode Effect	Cause of Failure Mode	Severity	Occurance	Detection	RPN
Expansion Tank	Leakage	Overheat	Overpressure	4	7	5	140
Deaerating Tank	System unable to exhaust air	Flow is interrupted	Blockage occurs	3	6	4	72
Jacket Water Pump	Pump stuck	Engine overheating	Engine Shutdown	5	9	3	135
Jacket Water Cooler	Low efficiency	Engine overheating	Fouling	4	8	3	96
Lub Oil Cooler	Decrease d cooling	Oil temperature to high	Fouling	4	8	4	128
Central Cooler	Cooling efficiency decreased	Risk of overheating	Scale	5	9	3	135
Scavage Air Cooler	Clogged fin	Scavage temperature increases	Imperfect filtration	5	5	5	125
Freshwater Generator	Fresh water decreases	Freshwater demand is not met	Pump malfunction	3	6	4	72

Based on the cooling system calculations in Table 3, it is known that the expansion tank is the component with the highest RPN value of 140. Failure of this component poses a direct risk of causing the engine to overheat, which could potentially disrupt the overall operational performance of the ship.

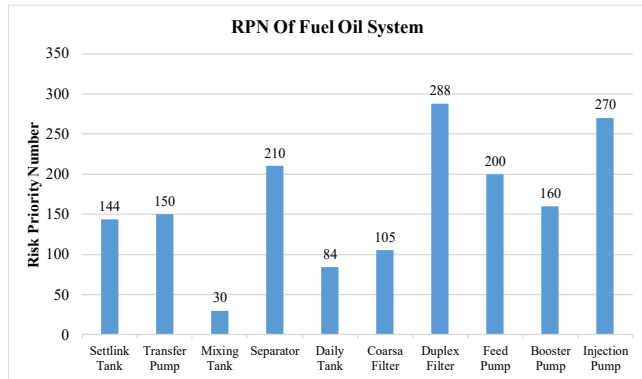


Figure 4. RPN of Fuel Oil System

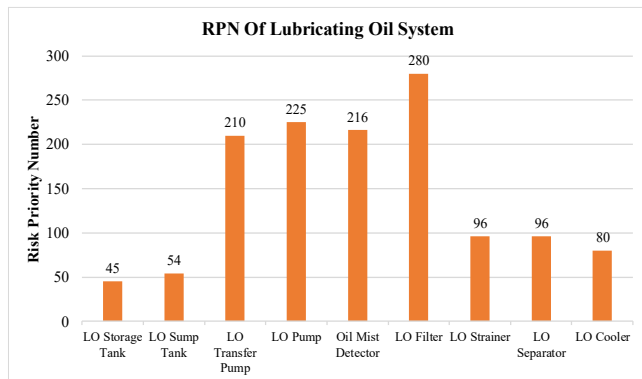


Figure 5. RPN of Lubricating Oil System

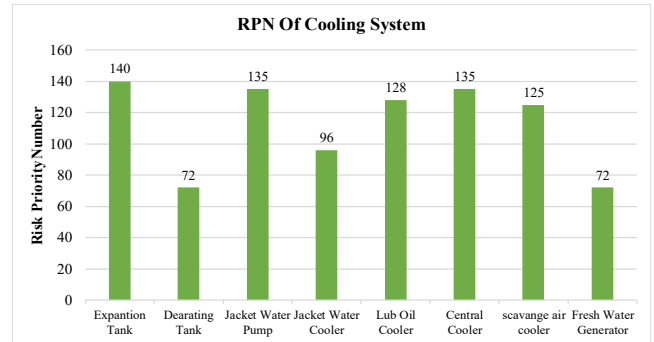


Figure 6. RPN of Cooling System

b. FTA Analysis Result

Fault Tree Analysis (FTA) is a risk analysis method with a top-down approach used to identify various combinations of failures that can trigger an overall system failure. This process starts from the main failure (top event), then traces to a more detailed level according to the needs of analysis, data availability, and allocation of time and resources.

The result of the FTA is a fault tree diagram that visually depicts the cause-and-effect relationship. This diagram is also used to develop cut sets and minimum cut sets, which are collections of components that, if they fail, can cause the system to fail completely. Based on minimum cut set analysis of the fuel system, the results are as follows: Figure 7, Figure 8, Figure 9, and Table 4, Table 5, Table 6.

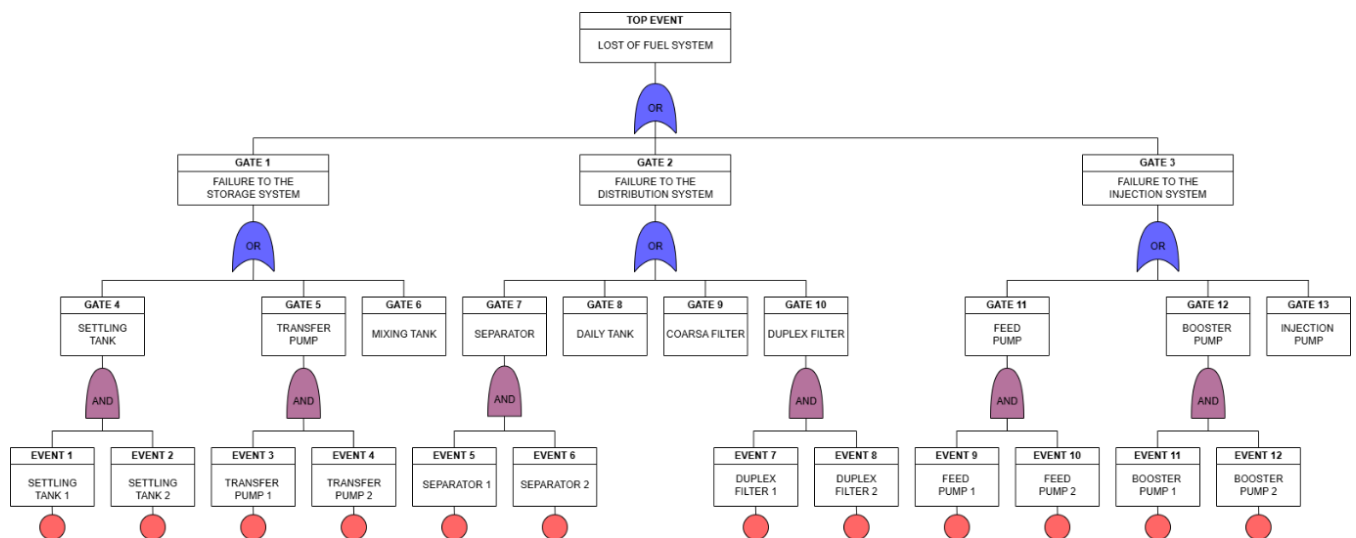


Figure 7. FTA of Fuel Oil System

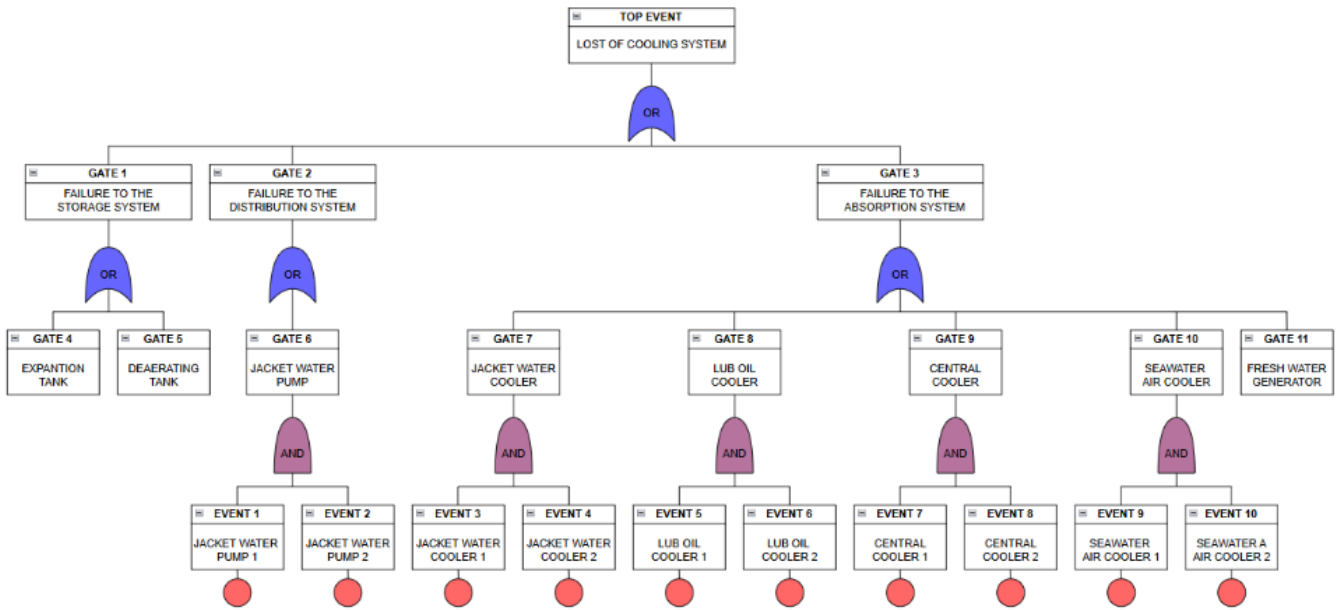


Figure 8. FTA of Lubricating Oil System

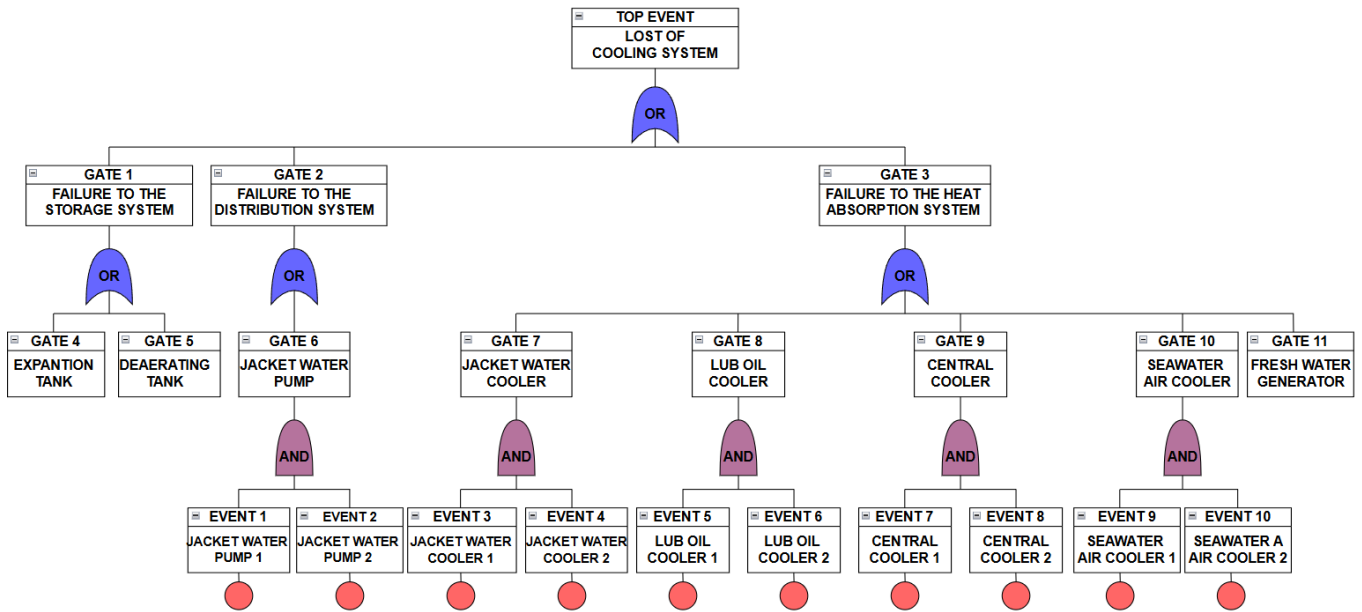


Figure 9. FTA of Cooling System

Table 4. Minimal Cut Set of Fuel Oil System

Minimal Cut Set	Order	Components
{1,2}	Second	Transfer Pump 1, Transfer Pump 2
{3,4}	First	Feed Pump 1, Feed Pump 2
{5,6}	First	Booster Pump 1, Booster Pump 2
{7,8}	First	Duplex Filter 1, Duplex Filter 2
{9}	First	Separator

{10}	First	Daily Tank
{11}	First	Coarse Filter
{12}	Third	Injection Pump 1
{13}	Third	Injection Pump 2

Based on the fuel system fault tree shown in Figure 5, the results of the minimum cut set identification for the fuel system are presented in Table 4 as follows:

1. Transfer pump 1 and transfer pump 2 components are included in the second order {1,

- 2}, meaning that the system can still run if one of them is still functioning.
2. Components such as the feed pump, booster pump, and duplex filter are included in the first-order {3, 4}, {5, 6}, and {7, 8}, indicating that the failure of both will immediately cause the system to stop.
 3. The separator, daily tank, and coarse filter components are also in the first order, indicating a high level of criticality because a single component is sufficient to trigger failure.
 4. The injection pump 1 and injection pump 2 components are in the third-order cut set {12} and {13}, meaning that their contribution to system failure is smaller but still needs to be monitored.

Table 5. Minimal Cut Set of Lubricating Oil System

Minimal Cut Set	Order	Components
{1,2}	Second	LO Transfer Pump 1, LO Transfer Pump 2
{3,4}	First	LO Pump 1, LO Pump 2
{5,6}	First	LO Filter 1, LO Filter 2
{7,8}	First	LO Strainer 1, LO Strainer 2
{9,10}	First	LO Separator 1, LO Separator 2
{11,12}	First	LO Cooler 1, LO Cooler 2
{13}	First	Oil Mist Detector

Based on the lubrication system fault tree shown in Figure 6, the results of the minimum cut set identification for the lubrication system are presented in Table 5 as follows:

1. The LO transfer pump 1 and LO transfer pump 2 components are included in the second order {1, 2}, meaning that the system can still operate if one of the pumps is still functioning.
2. The components LO pump, LO filter, LO strainer, LO separator, and LO cooler are included in the first order {3, 4}, {5, 6}, {7, 8}, {9, 10}, and {11, 12}, indicating that the simultaneous failure of both will immediately cause the system to malfunction.
3. The oil mist detector component is in the first order {13}, indicating that a single failure of this component is sufficient to cause the system to fail, thus requiring special attention.

Table 6. Minimal Cut Set of Cooling System

Minimal Cut Set	Order	Components
{1}	First	Expansion Tank
{2}	First	Deaerating Tank
{3,4}	First	Jacket Water Pump 1, Jacket Water Pump 2
{5,6}	First	Jacket Water Cooler 1, Jacket Water Cooler 2
{7,8}	First	LO Cooler 1, LO Cooler 2
{9,10}	First	Central Cooler 1, Central Cooler 2

Based on the cooling system fault tree shown in Figure 7, the results of the minimum cut set identification for the fuel system are presented in Table 6 as follows:

1. The expansion tank and deaeration tank are included in cut sets {1} and {2}, meaning that a single failure of either of these components is sufficient to cause the cooling system to malfunction.
2. The jacket water pump 1 and jacket water pump 2 are in cut sets {3, 4}, indicating that the system will fail if both pumps fail simultaneously.
3. The jacket water cooler, lubricating oil cooler, and central cooler are also included in first-order cut sets {5, 6}, {7, 8}, and {9, 10}, indicating that the failure of both units in each pair will cause serious disruption to the system's ability to absorb heat.

c. Determine Best Fit Distribution

Determination of the best fit distribution of each system component was determined based on the daily report data of the KM. Lawit engine room period 2023-2024. In the process, researchers used reliability-free trial software. The results of this best-fit distribution will be used for the preparation of the reliability diagram block. The purpose of determining the best fit distribution is to determine the best probability distribution that interprets the failure time data of a component or system, in choosing the appropriate distribution to model failure patterns based on historical data. From determining this best-fit distribution, researchers can calculate Mean Time to Failure (MTTF), reliability, and failure rate. The best fit distribution can saw at Table 7.

Table 7. Best Fit Distribution

System	Component	Best Fit Distribution	Parameter
Fuel Oil System	Settling Tank	Exponential	$\eta = 2606,0858$ $\lambda = 3,83717$
	Transfer Pump	Weibull 2p	$\eta = 8129,9930$ $\beta = 0,828254$
	Mixing Tank	Rayleigh 1p	$\eta = 2269,7982$ $\beta = 2,0000$
	Separator	Lognormal	$\mu = 7,930854$ $\sigma = 1,766137$
	Daily Tank	Exponential	$\eta = 4097,4183$ $\lambda = 2,440561$
	Coarse Filter	Weibull 2p	$\eta = 4014,2784$ $\beta = 0,296837$
	Duplex Filter	Weibull 2p	$\eta = 5201,0983$ $\beta = 0,820396$
	Feed Pump	Weibull 2p	$\eta = 6317,0090$ $\beta = 2,749826$
	Booster Pump	Weibull 2p	$\eta = 8949,0938$ $\beta = 0,825077$
	Injection Pump	Weibull 2p	$\eta = 4094,2528$ $\beta = 0,778029$
Lubricating Oil System	LO Storage Tank	Exponential	$\eta = 6514,9822$ $\lambda = 1,53492$
	LO Sump Tank	Exponential	$\eta = 2778,5089$ $\lambda = 3,599053$
	LO Transfer Pump	Weibull 2p	$\eta = 2910,5345$ $\beta = 2910,5345$
	LO Pump	Weibull 2p	$\eta = 2736,5890$ $\beta = 0,534660$
	Oil Mist Detector	Weibull 2p	$\eta = 6849,5488$ $\beta = 0,891756$
	LO Filter	Weibull 2p	$\eta = 3783,3508$ $\beta = 1,260283$
	LO Strainer	Weibull 2p	$\eta = 6312,9543$ $\beta = 1,417231$
	LO Separator	Weibull 2p	$\eta = 307,3268$ $\beta = 1,046844$
Cooling System	Expansion Tank	Exponential	$\eta = 5473,4371$ $\lambda = 1,82706$
	Deaerating Tank	Exponential	$\eta = 4871,9150$ $\lambda = 2,052581$
	Jacket Water Pump	Weibull 2p	$\eta = 3928,3445$ $\beta = 0,497760$
	Jacket Water Cooler	Weibull 2p	$\eta = 2463,0170$ $\beta = 0,855139$
	Lub Oil Cooler	Weibull 2p	$\eta = 3289,1931$ $\beta = 0,967183$
	Central Cooler	Weibull 2p	$\eta = 2651,9887$ $\beta = 0,507268$
	Seawater Air Cooler	Weibull 2p	$\eta = 3707,6683$ $\beta = 0,587309$

Fresh Water Generator	Weibull 2p	$\eta = 7994,5738$ $\beta = 0,806823$
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The data obtained during the sampling period was analyzed using Relyence Free Trial software to determine the best-fit distribution. This distribution was then used in the simulation process in the preparation of the RBD diagram.

d. Result of Reliability Block Diagram

Scribe the level of reliability of the workflow of each system. The preparation of this diagram used relyence free trial, with redundancy configurations such as parallel and cold standby also determined based on real conditions on the ship.

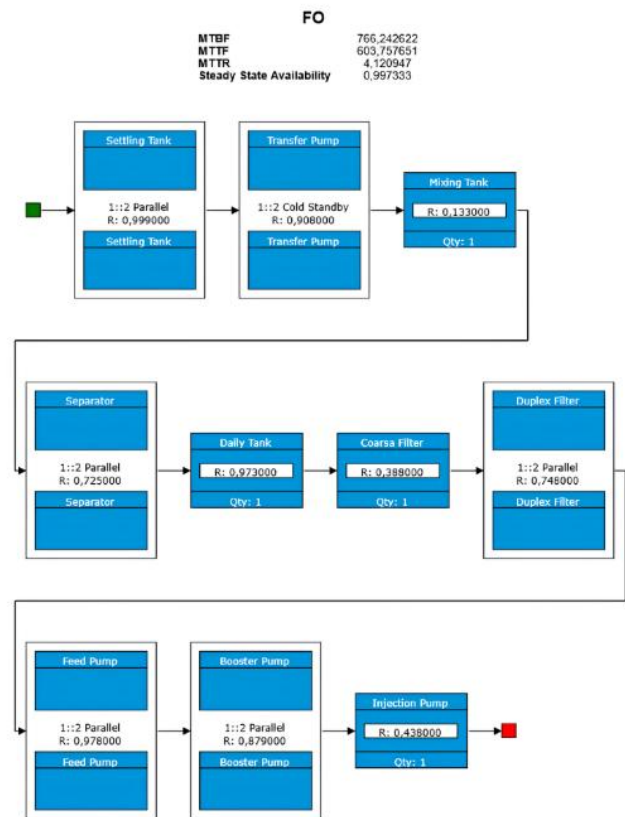


Figure 10. RBD of Fuel Oil System

Hot Standby describes a condition in which the backup unit is always active and ready to immediately replace the main unit in the event of a failure, without any delay. Meanwhile, a 1:2 Parallel configuration means that two components work simultaneously, but only one is required for the system to continue functioning. Both schemes aim to improve system reliability by providing a backup that ensures the system continues to run even if a component fails.

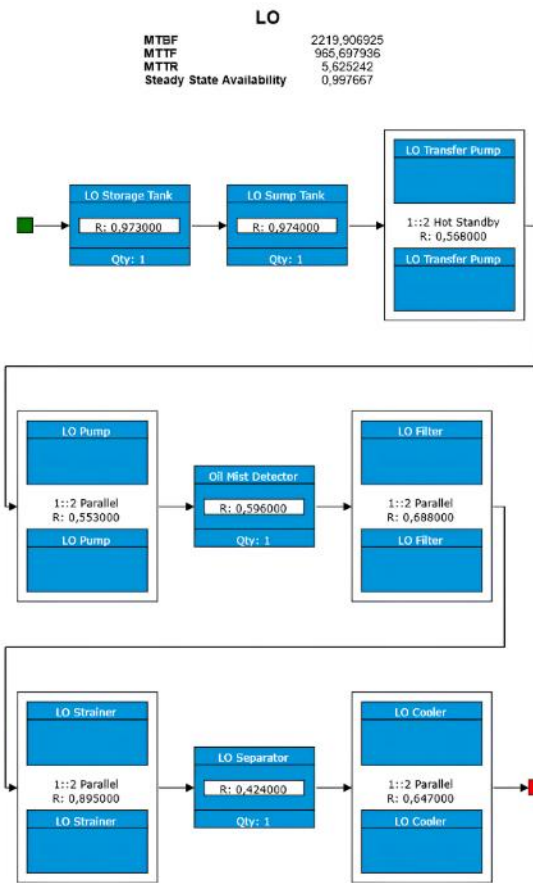


Figure 11. RBD of Lubricating Oil System

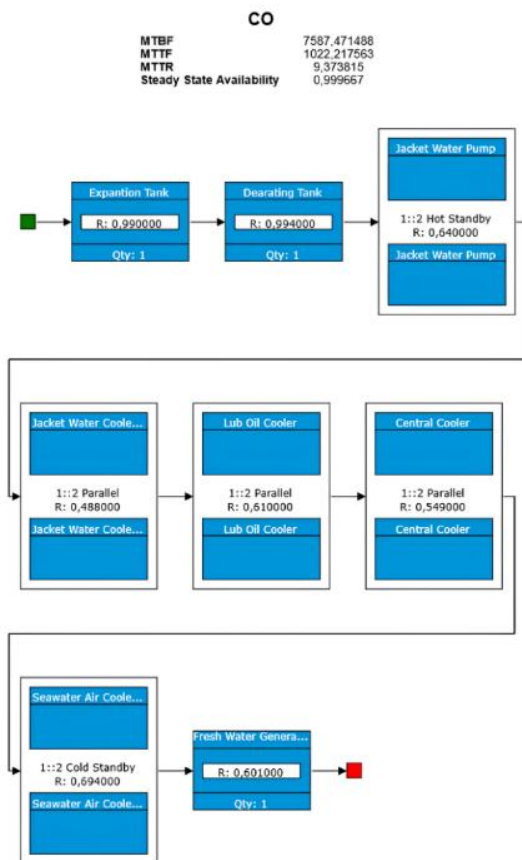


Figure 12. RBD of Cooling System

The resulting RBD model effectively visualizes the logical structure of the fuel oil, lubricating oil, and cooling systems, enabling quantitative assessment of their reliability performance. It also provides a clear representation of critical paths within each system, which can be used as a reference for maintenance prioritization and optimization of redundancy strategies on board KM Lawit.

e. Monte Carlo Simulation

After completing the preparation of the RBD and the parameters of each component have been filled in, the simulation process can be run, and the simulation results for each system are as follows: Figure 11.

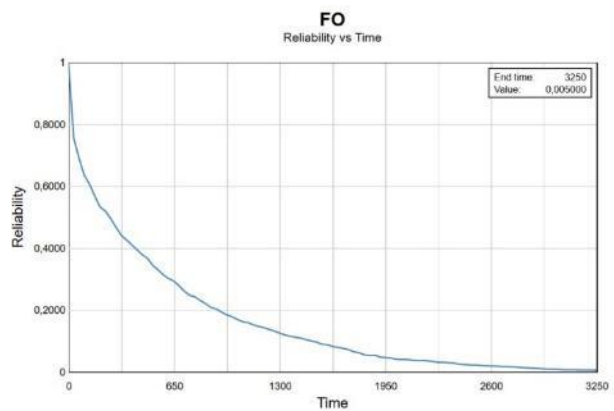


Figure 11. Result reliability vs time fuel oil system based on Monte Carlo Simulation

Table 8. Summary: Simulation of Fuel Oil System

Simulation Summary FO					
Number of Simulations		1000			
Number of End Time		3250 hour			
MTTF		603,75			
MTBF		766,24			
MTRR		4,12			
Time	Reliability	Availability	Unavailability	Failure Rate	Total Downtime
0	1,0000	1,0000	0,0000	12739,9	0,0000
325	0,4980	0,9960	0,0040	1826,2	1,6837
650	0,3480	0,9930	0,0070	1398,6	3,0009
975	0,2420	0,9960	0,0040	1008,8	4,4559
1300	0,1600	0,9970	0,0030	1143,1	5,8225
1625	0,0970	0,9930	0,0070	1255,9	7,5726
1950	0,0630	0,9930	0,0070	969,1	9,2462

2275	0,0380	0,9930	0,0070	1598,4	11,1935
2600	0,0230	0,9930	0,0070	1544,8	12,9344
2925	0,0130	0,9970	0,0030	1755,5	14,8484
3250	0,0060	0,9920	0,0080	2379,0	16,4775

Based on Monte Carlo simulations of the fuel system, the results of the relationship between reliability and time are shown in Figure 11, with the conclusions summarized in Table 8 as follows:

1. The simulation was conducted up to 3250 hours.
2. As the system approaches its end time, the reliability of the fuel system drops to 0.005000 or 0.5%
3. When the system first starts, reliability is very high, exceeding 90%, but the reliability of the fuel system continues to decline over time
4. After approximately 3000 hours, the likelihood of the system still functioning properly is very low.

The next step is to analyze the reliability of the lubrication system using the same method.

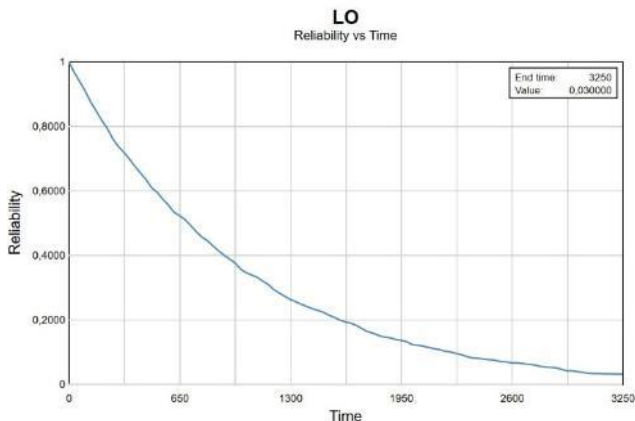


Figure 12. Result reliability vs time lubricating oil system based on Monte Carlo Simulation

Table 9. Summary Simulation of the LO System

Simulation Summary LO					
Number of Simulations		1000			
Number of End Time		3250 hours			
MTTF		965.69			
MTBF		2219.90			
MTRR		5.62			
Time	Reliability	Availability	Unavailability	Failure Rate	Total Downtime
0	1.0000	1.0000	0.0000	992.5	0.0000
325	0.7070	0.9970	0.0030	950.0	0.7792

650	0.5020	0.9990	0.0010	609.9	1.6125
975	0.3650	0.9990	0.0010	1169.0	2.4701
1300	0.2640	0.9990	0.0010	1610.4	3.2268
1625	0.1970	0.9940	0.0060	1236.9	4.0485
1950	0.1280	0.9990	0.0010	954.1	4.8834
2275	0.0094	0.9990	0.0010	1295.5	5.6344
2600	0.0710	0.9970	0.0030	863.4	6.3929
2925	0.0500	0.9980	0.0020	1218.6	7.0400
3250	0.0400	0.9930	0.0070	3002.4	7.8900

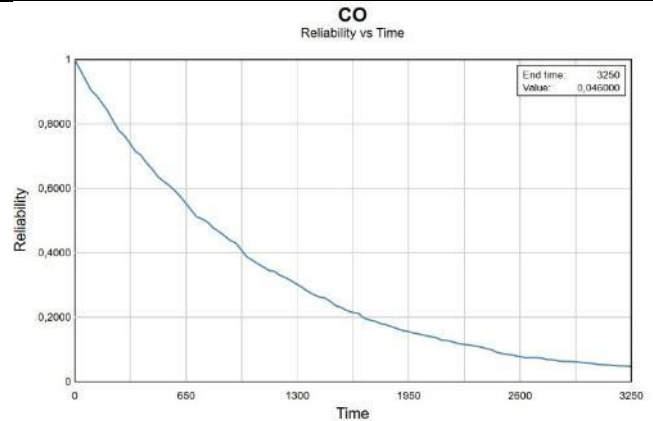


Figure 13. Result reliability vs time cooling system based on Monte Carlo Simulation

Table 10. Summary Simulation of Cooling System

Simulation Summary CO					
Number of Simulations		1000			
Number of End Time		3250 hours			
MTTF		1022.21			
MTBF		7587.47			
MTRR		9.3			
Time	Reliability	Availability	Unavailability	Failure Rate	Total Downtime
0	1.0000	1.0000	0.0000	618.4	0.0000
325	0.7180	0.9980	0.0020	935.6	0.8238
650	0.4970	0.9990	0.0010	493.2	1.4905
975	0.3900	1.0000	0.0000	627.9	2.2115
1300	0.2980	0.9970	0.0030	820.5	2.7694
1625	0.2325	0.9950	0.0050	790.6	3.2624
1950	0.1550	1.0000	0.0000	117.6	3.7165
2275	0.0990	0.9970	0.0030	618.4	4.2568
2600	0.0710	0.9980	0.0020	1022.8	4.8250

2925	0.0550	0.9980	0.0020	785.6	5.2789
3250	0.0420	0.9960	0.0040	829.7	5.7338

Based on Monte Carlo simulations of the cooling system, the results of the relationship between reliability and time are shown in Figure 13, with the conclusions summarized in Table 10 as follows:

1. The simulation was conducted for 3,250 hours.
2. As the end time approached, the reliability value of the cooling system was only 0.046000, or 4.6%.
3. When the system first started operating, reliability was very high, approaching 1 (100%). However, the reliability of the lubrication system continued to decline over time.
4. After approximately 3000 hours, reliability decreases sharply, indicating that the likelihood of the system continuing to function properly becomes very small.

Simulations were conducted 1,000 times, with a duration of 3,250 hours for each system. A total of 1,000 simulations in the Monte Carlo analysis were selected to obtain consistent results that statistically represent actual conditions. Increasing the number of iterations will reduce the level of variation or deviation from the expected value. From the simulation results, the cooling system shows the highest MTBF value of 7,587.47 hours, followed by the lubricating system of 2,219.90 hours, and the fuel system of 766.24 hours.

The highest Mean Time to Failure (MTTF) value is also owned by the cooling system, which is 1,022.21 hours, indicating that this system is more reliable and stable. In addition, the availability values of the three systems range from 0,9920 to 1,0000, indicating that the systems generally

function well and only experience minor interruptions. These results serve as a reference in evaluating the condition of the system as well as devising a more appropriate maintenance strategy to keep the performance of the main engine optimized.

The analysis results indicate that the fuel oil, lubricating oil, and cooling systems of the KM Lawit main engine exhibit high levels of reliability and availability, each exceeding 99%. The reliability curves show that the system’s reliability gradually decreases over time. Overall, the integration of qualitative analyses (FMEA and FTA) with quantitative methods (RBD and Monte Carlo simulation) provides a comprehensive understanding of the system’s reliability behavior. This discussion emphasizes that component reliability analysis cannot be separated from the interdependence among subsystems that collectively influence the overall performance of the main engine. Therefore, the application of the RCM approach has proven effective as a decision-making framework for determining maintenance priorities and optimizing ship resource management.

f. Maintenance Recommendation

Based on the results of FMEA, FTA, RBD, and Monte Carlo simulation analyses of the fuel, lubricant, and cooling systems of the KM Lawit main engine, a number of components with a high risk of failure were identified. Therefore, maintenance recommendations are provided for the most critical components to enhance the operational reliability of the vessel, reduce the risk of failure, and maintain the efficiency and safety of the main engine. The details of the maintenance recommendations are presented in Table 11.

Table 11. Maintenance Recommendation

System	Component	Maintenance Recommendation
Fuel Oil System	Duplex Filter	Inspect and replace filter elements regularly every 250–500 operating hours, and avoid operating with a single filter for too long.
	Injection Pump	Test injection pressure every 500 operating hours and use fuel with the appropriate viscosity.
	Separator	Clean sludge and perform separator performance testing every 1000 operating hours.
Lubricating Oil System	LO Filter	Clean the filter every 300 hours and install a differential pressure gauge to monitor pressure.
	LO Pump	Perform system flushing, check the pump for oil contamination and impeller wear every 720 operating hours.

	Oil Mist Detector	Test sensor function weekly, replace cables and sensors every 1 year.
Cooling System	Expansion Tank	Inspect the condition of the Expansion Tank and monitor pressure regularly every 2000 operating hours.
	Jacket Water Pump	Schedule inspection and cleaning of the impeller every 1000 operating hours.
	Central Cooler	Clean the heat exchanger surface using chemical cleaning every 1000-1500 operating hours.

Conclusion

This study successfully applied a Reliability Centered Maintenance (RCM) approach to evaluate the reliability of the KM. The main engine's fuel, lubricating, and cooling systems using FMEA, FTA, RBD, and Monte Carlo simulation. FMEA was used to identify failure modes and critical components, FTA to analyze failure paths, RBD to model component reliability connections, and Monte Carlo simulation to statistically project system performance.

FMEA identified the most critical components: duplex filter (RPN = 288), LO filter (RPN = 280), and expansion tank (RPN = 140), which require maintenance priority to avoid overall system disruption. Monte Carlo results showed all systems had availability above 99%, with the cooling system achieving the highest MTTF (1,022.2 hours) and MTBF (7,587.5 hours), followed by the lubricating and fuel systems.

This research provides a structured and data-driven maintenance framework to improve operational efficiency, reduce the risk of failure, and support safer, more reliable, and sustainable vessel operations. This indicates that a reliability-based integrated approach is effective in producing accurate and relevant evaluations to guide maintenance priorities in ship engine systems.

For future research, it is recommended to conduct a more comprehensive maintenance cost analysis that includes other systems, such as the power transmission and control systems, to obtain a more holistic understanding of overall reliability. In addition, the use of fully licensed software is suggested to ensure that the simulation and modeling results are more accurate and not limited by trial version features. Future studies are also encouraged to consider longer time frames for component failure data based on engine room daily reports, in order to achieve more precise and representative results.

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