Kapal: Jurnal Ilmu Pengetahuan dan Teknologi Kelautan
(Kapal: Journal of Marine Science and Technology)
journal homepage : http://ejournal.undip.ac.id/index.php/kapal
2301-9069 (e)
1829-8370 (p)

Reliability-Based Analysis of Main Propulsion Fuel Oil System Maintenance for Tugboats with Qualitative and Quantitative Methods

Imam Pujo Mulyatno[1], Keyza Taqi Wafi[1], Sarjito Joko Sisworo[1] , Tuswan Tuswan[1*]

[1]) Department of Naval Architecture, Faculty of Engineering, Diponegoro University, Jl. Prof. Soedarto, SH, Undip Tembalang Campus, Semarang, Indonesia 50275
*) Corresponding Author : tuswan@lecturer.undip.ac.id

Article Info

Keywords:
Main Engine FO System;
FMEA;
FTA;
OEE;
MDP;
Reliability;

Article history:
Received: 02/10/2022
Last revised: 05/02/2023
Accepted: 06/02/2023
Available online: 06/02/2023
Published: 08/02/2023

DOI:
https://doi.org/10.14710/kapal.v20i1.49335

Abstract

This study aims to analyze the maintenance of the main propulsion fuel oil system for tugboats using both qualitative and quantitative methods. The focus is on evaluating the reliability of the system and identifying potential areas for improvement. The research employs a combination of expert interviews, industry standards, and statistical analysis to provide a comprehensive overview of the maintenance practices in place. The goal is to enhance the overall performance and longevity of the main propulsion fuel oil system in tugboats. The study uses data on the operational time, failure time and frequency, the number of vessels served, and fuel system diagrams to analyze the system's reliability. Qualitative methods such as Failure Mode and Effect Analysis (FMEA) and Fault Tree Analysis (FTA) were used, as well as quantitative methods such as Overall Equipment Effectiveness (OEE), Markovian Decision Process (MDP), and reliability methods. The study found that the FO Purifier component was the critical component with a Risk Priority Number (RPN) of 294. The average value of OEE was 47%, lower than the standard of 85%. The MDP analysis showed a probability of 0.08 for mild damage and 0.46 for moderate to severe damage under steady-state conditions. The FO Purifier component had the lowest Mean Time to Failure (MTTF) value of 1658.50 hours. The study provides a graph of the reliability function against time, and recommends maintenance actions based on the MTTF and MDP.

1. Introduction

Ships are complex machines that require a high degree of reliability to operate safely and efficiently. One of the most critical systems on a ship is the propulsion system, which is responsible for providing the power necessary to move the ship through the water. The reliability of this system is essential for ensuring the safety of the crew and passengers and minimizing the risk of costly downtime and repairs. One approach to improving the reliability of ship systems is through reliability analysis. This is the process of evaluating the performance of a system and identifying ways to improve its reliability. In the case of ship propulsion systems, reliability analysis can help identify potential failure modes and recommend maintenance strategies that can reduce the risk of failure.

Reliability analysis is an essential tool for improving the performance and safety of ship systems. By identifying potential failure modes and recommending maintenance strategies, reliability analysis can help reduce the risk of failure and improve the system's overall reliability. Several cutting-edge methods have been developed to assess ship reliability, including Fault Tree Analysis (FTA), Failure Mode and Effects Analysis (FMEA), Reliability Block Diagram (RBD), Reliability-Centered Maintenance (RCM), Monte-Carlo Simulation (MCS), Markov Analysis (MA), and Bayesian Networks (BN) [1,2,3].

There are several methods used in the reliability analysis of ship systems, including Fault Tree Analysis (FTA): This is a top-down approach that starts with the system failure and works backward to identify the root causes of the failure. Event Tree Analysis (ETA): This method starts with an initiating event and works forward to identify the possible consequences of the event. Reliability Block Diagram (RBD): This method uses the graphical representation to analyze the reliability of the system by breaking it down into smaller, simpler components. Failure Modes, Effects and Criticality Analysis (FMECA): This method involves identifying all possible failure modes, assessing their effects on the system, and determining their criticality.

As one of the fundamental principles in the operation of a diesel engine, which serves as the primary propulsion source for ships, fuel is distributed through a system referred to as the fuel oil system. This system typically encompasses the supply of fuel oil, its purification, and storage in fuel oil tanks [4]. These components must function optimally to ensure smooth and efficient distribution of fuel, as the engine's operation is integral to the overall utility and success of the ship.

A tugboat, a ship designed for pulling and pushing other ships belonging to a company providing ship towing services in Indonesia, may result in losses if it is not operating at full capacity [5]. The performance of the fuel oil system is crucial for the tugboat's utility and the company's profitability. Therefore, it is important to ensure that the fuel system's components are always in optimal condition. KM Kelimutu researched the fuel oil system, using Failure Modes and Effects Analysis (FMEA) and Fault Tree Analysis (FTA) as qualitative methods to identify the critical components and Monte Carlo simulation for quantitative reliability calculations. The results showed that the fuel system is expected to fail after 317.998 hours of operation, with an end time of 5000 hours [6]. Monte Carlo simulation provides accurate results, with 99% similarity to those obtained using Reliability Block Diagram [7]. The comparison between the Monte Carlo simulation and a subset simulation using a random failure system for the failure of carbon dioxide storage showed that the coefficient variation obtained through Monte Carlo was 10% higher, indicating that the Monte Carlo simulation is more effective for cases with a low probability of failure [8]. In addition to Monte Carlo simulation, the condition of an object or system can also be analyzed through the Markov Decision Process method. This method has been applied in research on multi-state systems to prevent failures and has resulted in the proposal of predictive maintenance actions, leading to average savings of 26.3% of the original maintenance cost [9].

Recently, it has been shown that using the FTA and FMEA procedures in tandem or sequentially is beneficial, efficient, and growing in popularity. An integrated FTA-FMEA strategy can provide a full review of system safety risks when used methodically [10]. FMEA provides the precise manner in which these faults occur and their direct consequences on the top event, whereas FTA produces a thorough breakdown of faults leading to the undesirable top event, making the combination suitable for safety and reliability evaluations. Although many experts contend benefits vary depending on the particular application, the backward integration of both tools appears to offer stronger advantages. To investigate and identify the many reasons of failures in a gas leak detection system, Khaiyum and Kumaraswamy [11] consecutively performed FMEA after doing FTA in parallel. However, the particular techniques' limitations weren't looked into. A significant improvement over the conventional FMEA was made by Bluvband et al. [12] in their unified bouncing approach, which took interaction matrices into account for multiple point failures. As the methodologies interact more intricately, it becomes necessary to have a thorough understanding of the instruments and, in particular, the system being researched. According to [13], the most notable solutions for addressing FMEA limitations are Artificial Intelligence (AI), fuzzy rule-based systems, Grey theory, and Multi-Criteria Decision Analysis (MCDA) models such as Analytic Hierarchy Process (AHP) and Analytic Network Process (ANP). Furthermore, Gilchrist's [14] cost-based FMEA models have gained traction.

The above-mentioned review provides valuable insights into the use of reliability analysis in improving the performance and safety of ship systems. Reliability analysis can play a critical role in ensuring ships' safe and efficient operation by analyzing the potential failure modes and recommending maintenance strategies. The fuel oil system plays a critical role in the safe and efficient operation of ships. Ensuring the reliability of this system is essential for maintaining the safety of the ship and its crew and minimizing the risk of costly downtime and repairs. However, the complexity of these systems and the harsh marine environment in which they operate can make maintenance challenging. This study presents a reliability-based analysis of fuel oil system maintenance for ships. Our goal is to provide ship operators and maintenance personnel with a comprehensive understanding of the various maintenance strategies available and to evaluate their effectiveness in terms of reliability and cost. We begin by introducing the various components of a fuel oil system and the standard failure modes that can occur. We then present a variety of maintenance strategies, including planned maintenance, condition-based maintenance, and reliability-centered maintenance. Using a combination of theoretical analysis and real-world data, we evaluate the performance of these strategies and provide recommendations for selecting the most appropriate maintenance plan for a given fuel oil system. We conclude by discussing the potential impact of our findings on the overall reliability and cost-effectiveness of fuel oil systems on ships.

Therefore, the authors are interested in finding out the critical components of the fuel oil system for the main propulsion engine of the tugboat and proposing maintenance and scheduling actions through qualitative analysis with the FMEA and FTA method or quantitative analysis with OEE, MDP, and reliability. The goal is to identify the critical components of the tugboat's fuel oil system, suggest maintenance actions on these components, and schedule these maintenance actions so that the company can minimize losses and ensure that the system's performance value is not below 85%, which is the minimum standard value [15].

2. Methods

In this study, the fuel oil system of one of the 3200 hp Tugboats fueled by marine diesel oil for the January 2020 - December 2020 period belongs to a ship towing company in Indonesia which is the object of the research. In operation according to the diagrams in Figures 1-3 obtained from the company, the object of this research has components consisting of a FO tank, FO transfer pump, FO transfer pump (stand by hand pump), FO purifier pump, FO purifier, daily tank, sedimentation tank, FO feed pump (stand by), FO feed pump. This study uses supporting data from the fuel oil system for the period 2017 – 2021, which has been operating for 24 years, to review the result of reliability value where the fuel oil system is analyzed using system dynamics modeling with Weibull distribution that obtains the condition of the FO tank at starboard (S) & portside (P), sedimentation tank, and daily tank (S&P), when used 5070 hours, has a reliability value of 0.5 and 3458 hours has a reliability value of 0.85. When used for 458 hours, the FO purifier has a reliability value of 0.5, and for 378 hours has a reliability value of 0.85. FO transfer pump, when used for 5157 hours, has a reliability value of 0.5, and 3652 hours has a reliability value of 0.85. FO feed pump (S&P), when using 4870 hours, has a reliability value of 0.5 and 3458 hours has a reliability value of 0.85 [16].

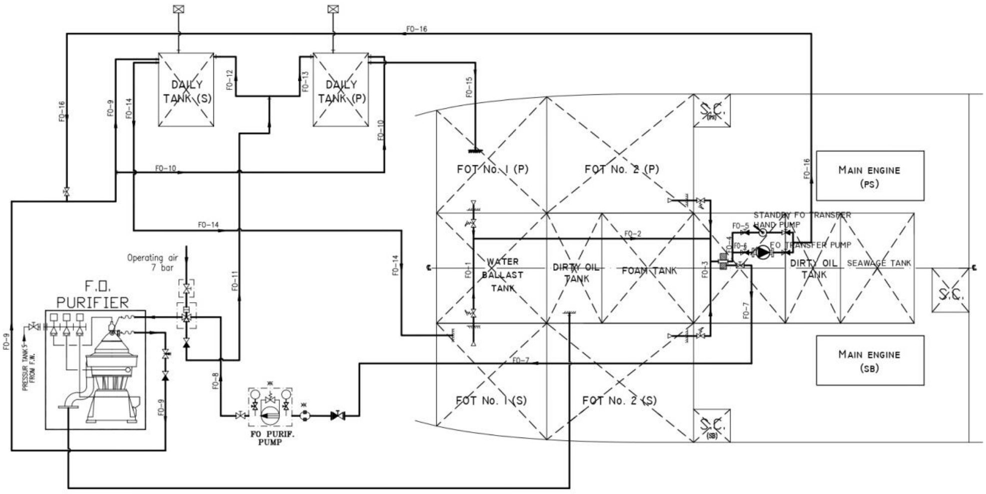

Figure 1. Diagram transfer line of the 3200 hp tugboat fuel oil system.

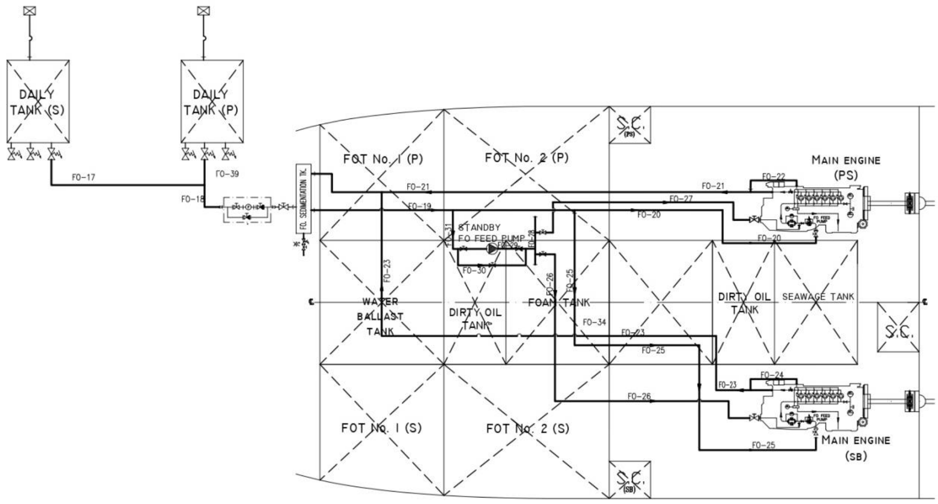

Figure 2. Diagram service line of the 3200 hp fuel oil system.

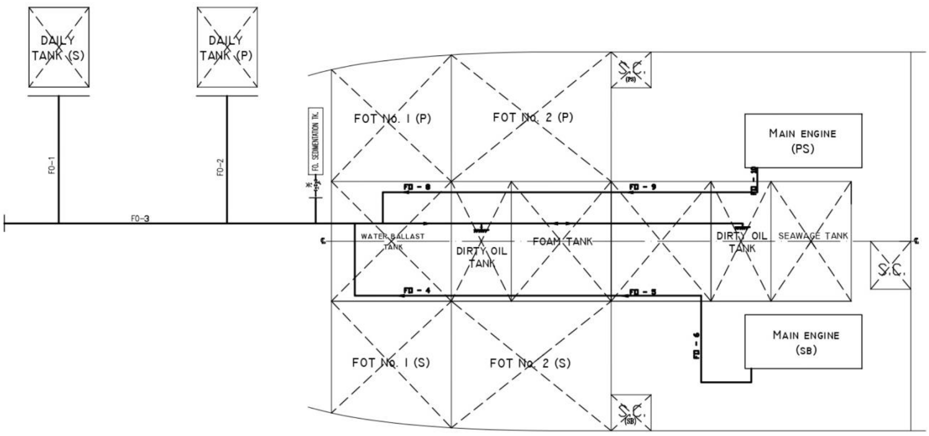

Figure 3. Diagram of drain line of the 3200 hp fuel oil system.

2.1. Qualitative Assessment

Reliability analysis of the fuel oil system using qualitative assessment involves evaluating the various components of the fuel oil system to determine their ability to perform as required. This type of analysis involves the use of expert judgment and subjective assessments to evaluate the quality and performance of the fuel oil system. Qualitative assessment can take the form of observation, expert consultation, interviews, or surveys. The objective of qualitative reliability analysis is to identify the key factors that affect the reliability of the fuel oil system and to prioritize maintenance actions based on the importance of these factors. The analysis may also consider the operating environment of the fuel oil system, including factors such as temperature, humidity, vibration, and corrosive conditions, to determine their impact on reliability.

Qualitative reliability analysis can be an effective tool for identifying potential reliability problems in the fuel oil system and for making informed decisions about maintenance and upgrades. This type of analysis can also be used to develop a maintenance strategy for the fuel oil system, considering the impact of different maintenance actions on system reliability. The results of qualitative reliability analysis can provide valuable information for decision-makers, allowing them to make informed decisions about maintenance, upgrades, and system design to ensure optimal performance and reliability of the fuel oil system. This information can also be used to prioritize maintenance activities, improve operational efficiency, and reduce the risk of system failure. Data analysis is based on facts found in the field in the form of frequency, interval, and duration of downtime, which can be seen in Table 1. This study conducted a qualitative analysis of the fuel system to determine the critical components and their underlying causes using FMEA and FTA.

Table 1. Downtime of 3200 hp tug fuel oil system components.

No.	Component	Frequency of downtime	Interval of downtime (hours)	Duration of downtime (hours)
1	Fuel Oil Tank (S & P)	0	-	-
2	Fuel Oil Transfer Pump	1	8016	>24
3	Fuel Oil Transfer Pump (Stand By Hand Pump)	0	-	-
4	Fuel Oil Purifier Pump	1	8016	>24
5	Fuel Oil Purifier	13	528 504 1104 240 624 360 864 336 696 600 984 720 456	4 4,5 4 5,5 4 5 5 4,5 5 3 5,5 6 >24
6	Daily Tank (S & P)	0	-	-
7	Sedimentation Tank	0	-	-
8	Fuel Oil Feed Pump (Stand By)	0	-	-
9	Fuel Oil Feed Pump (S & P)	1	8016	>24

Failure Modes and Effects Analysis (FMEA) is a structured method for identifying and evaluating the potential failure modes of a system or component and the effects of these failures on the system or component's performance. It is used to identify potential problems early in the design process so that appropriate design changes can be made to prevent or mitigate these problems. The fundamental idea guiding the weighting of failure modes and risk factors to produce RPNs has received a great deal of criticism [17]. The process of FMEA involves creating a list of potential failure modes, evaluating the impact of each failure mode on the system, and determining the likelihood of each failure mode occurring. The results of the FMEA are used to prioritize the risk of each failure mode and to develop strategies for mitigating or eliminating the risk. FMEA is a structured methodology to identify/analyze failures/errors that may occur, generating an RPN for each component [18]. The RPN value is obtained using the equation as shown in Equation 1.

$$RPN = Severity\ x\ Occurrence\ x\ Detection \tag{1}$$

With a scale of 1 – 10, the longer the downtime, the greater the value of the severity, the shorter the time interval between downtimes, the greater the occurrence value, and the more difficult the signs of the cause of downtime to be detected will be greater detection value.

Fault Tree Analysis (FTA) is a systematic, quantitative method for identifying and analyzing potential failure modes in complex systems. It is used to identify the root causes of failures and the interactions between different components in a system and to determine the probability of system failures. FTA is a logical method for determining, assessing, and modeling the interrelationships between the events that result in failure or an undesirable state [19]. The process of FTA involves creating a graphical representation of the system and its components, identifying potential failures and their causes, and quantifying the likelihood of these failures. The resulting fault tree diagram visually represents the system's potential failure modes and their relationships. FTA is commonly used in safety-critical industries such as aviation, nuclear power, and transportation to identify potential hazards and reduce the risk of accidents. FTA is an analysis method where an undesired event occurs in the system, and the system is then analyzed with the existing environmental and operational conditions to find all possible ways that lead to the undesired event [20]. The system is analyzed to find the possibility of failure in the form of a cut set as a basic event that results in a top event.

2.2. Quantitative Assessment

Quantitative reliability analysis can be performed using various methods, such as reliability block diagrams, fault tree analysis, Markov analysis, and life data analysis. Compared to qualitative assessment, these methods can provide a more objective and accurate assessment of the fuel oil system's reliability. Reliability block diagrams provide a graphical representation of the fuel oil system, showing the interdependencies between its components and the impact of failures on system performance. Fault tree analysis is used to identify the potential causes of system failures and to evaluate the probability of these failures occurring. Markov analysis is used to model the state transitions of the fuel oil system and to predict future performance. Life data analysis is used to estimate the reliability of the fuel oil system based on historical data. The results of quantitative reliability analysis can be used to make informed decisions about maintenance, upgrades, and system design. The analysis can also provide valuable information for decision-makers, such as the mean time between failures (MTBF) and the probability of failure, to prioritize maintenance activities, improve operational efficiency, and reduce the risk of system failure.

Quantitative reliability analysis provides a more comprehensive and accurate assessment of the fuel oil system's reliability compared to qualitative assessment. This type of analysis can be especially useful for critical systems, where even small failures can have significant consequences. By providing a more objective assessment of the fuel oil system's reliability, quantitative analysis can help to ensure that maintenance and upgrade decisions are based on sound data and analysis. Data analysis is based on facts in the field using data recorded by the company in the form of operational time, failure time and frequency, and the number of ships served, as shown in Table 2.

Table 2. 3200 hp tugboat operation

Month	Number of Vessels Served	Possible Time (hours)	Planned		Actual		Tugboat Availability (hours)	Utilities (hours)	Tugboat Downtime (hours)
			System Downtime (hours)	System Availability (hours)	System Downtime (hours)	System Availability (hours)			
Jan	323	744	5	739	4.41	739.59	720.67	485.67	23.33
Feb	261	696	5	691	6	690	654.08	407.75	41.92
Mar	318	744	6	738	4	740	725.08	475.08	18.92
Apr	269	720	5	715	6	714	680.08	407.80	39.92
May	197	744	5	739	14	730	614.83	302.33	129.17
Jun	267	720	18.5	701.5	5.5	714.5	691.08	377 ,92	28.92
Jul	289	744	5	739	5	739	721.25	407.33	22.75
Aug	304	744	5	739	8	736	729.00	414.08	15.00
Sept	262	720	6	714	3.3	716.7	706, 33	366.25	13.67
Oct	225	744	5	739	7	737	714.50	326.17	29.50
Nov	55	720	5	715	9	711	225.33	80.92	494.67
Dec					Docking				

In this study, a quantitative analysis of the fuel oil system was performed with the aim of determining the appropriate maintenance actions based on the current state of the fuel oil system. The analysis was conducted using data collected over a sample period, which was used to evaluate the maintenance schedule for the fuel oil system components. The focus of the analysis was to assess the relationship between the age of the fuel oil system components and the efficiency of the fuel oil system. The study utilized three key metrics, including Overall Equipment Effectiveness (OEE), Maintenance Decision Point (MDP), and reliability, to analyze the performance of the fuel oil system. The results of the analysis were then used to make recommendations for maintenance actions that would improve the efficiency and reliability of the fuel oil system and ensure that the system continues to perform optimally.

Overall Equipment Effectiveness (OEE) is a metric used to measure the productivity and performance of a machine [21]. It provides an overall score that reflects the efficiency of a machine and its ability to meet production goals. The OEE metric is calculated by considering three key factors: availability, performance, and quality. Availability refers to the proportion of time a machine is available for production, performance refers to the speed at which a machine operates compared to its maximum speed. Quality refers to the proportion of good products produced compared to the total number of products produced. By combining these three factors, OEE provides a comprehensive picture of machine productivity and performance, allowing for continuous improvement and optimization. OEE has been obtained by using Equation. 2.

$$OEE \ = \ Availability \ x \ Performance \ x \ Rate \ of \ Quality \ Product \tag{2}$$

The availability ratio (A) is the ratio of available time utilization with system operation, as shown in Equation 3.

$$A = \frac{operation\ time}{loading\ time} \tag{3}$$

Since the fuel oil system operates only when the tugboat is in use, and the tugboat operates only when performing services, the operation time of the fuel oil system is equivalent to the utilization time of the tugboat. The loading time is the time available for operation, and the average tugboat is available for 70% of the time. Tugboats are only used for 70% of the time because the average tugboat performs 13-14 services per day, with each service taking 1.25 hours. This results in a 70% available time for operation within 24 hours. Therefore, the equation that will be used is shown in Equation 4.

$$A_T = \frac{utility}{70\%\ of\ tugboat\ availability} \tag{4}$$

Performance efficiency (P) is the ratio of the efficiency or ability of the system performance, as shown in Equation 5.

$$P = \frac{processed\ amount\ x\ ideal\ cycle\ time}{operation\ time} \tag{5}$$

The processed amount is the amount that is successfully processed by the system, on tugboats it is the same as the number of services performed because the fuel oil system operates only when the tugboat is in use. The ideal cycle time is the time that is expected to be used for a process, on tugboats it is their ideal time per service. Thus, the equation that will be used is shown in Equation 6.

$$P_T = \frac{number\ of\ services\ x\ ideal\ time\ per-service}{utility} \tag{6}$$

Quality product (Q) is the ratio of the system's ability to produce according to the standard/target as shows as Equation 7.

$$Q = \frac{processed\ amount - defect\ amount}{processed\ amount} \tag{7}$$

In this context, "processed amount" refers to the amount that is successfully processed by the system, which on tugboats, is equivalent to the number of services performed. The "defect amount" is calculated as the difference between the expected amount in a process and the actual amount. On tugboats, the process is the service, and the amount is the time. Therefore, the equation used to calculate the defect amount is shown in Equation 8. The "utility time" of the tugboat is equivalent to the operating time of the fuel oil system. The utility value of the plan is 70% of the plan system's availability, with the assumption that other systems are functional, allowing the tugboats to perform services. This is because tugboats have an ideal 70% availability for operation within 24 hours.

$$Q_T = \frac{utility}{plan\ utility} \tag{8}$$

Markovian Decision Process (MDP) is a mathematical method that is widely used for modeling various systems and predicting future changes based on past changes. This technique utilizes descriptive analysis to determine the status of a system and identify all possible conditions of the system [22]. The process of MDP involves collecting data on past system changes and using that information to model future changes. This allows for a more proactive approach to system maintenance and management, enabling decision-makers to anticipate and address potential problems before they occur. MDP is widely recognized and utilized in various industries, including transportation, energy production, and manufacturing, where it improves the efficiency, reliability, and safety of systems and components. The method is based on Markovian processes and mathematical models describing how systems change over time based on past conditions and events. The determination of system status in the MDP calculation can be seen in Table 3.

Table 3. Assessment criteria for system

Status	OEE (%)	Condition
1	85.01 to 100	Perfect (good)
2	60.01 to 85	World Class (light damage)
3	40.01 to 60	Fair (moderate damage)
4	0 to 40	Low (severe damage)

Next, the system status transition data is calculated by determining the change in system status from one condition to another. The number of state transitions is calculated to determine the number of system transitions in each state, and the state probability is calculated to determine the probability of a system state. First, the magnitude of the transition probability is determined, which can be calculated from the sum of each state of the system. After obtaining the probability of each system state, the initial probability matrix of the system is formed. Then, the probability of switching the state of the system (P_{xnnn}) is sought to get a transition matrix to n (B_n). The calculation of the transition probability matrix ends when the matrix value remains constant at a certain n, referred to as the steady state, which is the probability matrix of the long-term system status. This calculation can be done using the QM application for Windows V5 or by using Equation 9.

$$B_n = B^{n-1}.B^1 \tag{9}$$

The long-term system probability matrix result is used to calculate the transition probability, which then refers to the proposed system maintenance action as preventive maintenance. The sum of the probability must equal 1, as referenced in Equation 10.

$$x_1 + x_2 + x_3 = 1 \quad (10)$$

Decisions in determining proposed maintenance actions can be classified as shown in Table. 4.

Table 4. Classification of determination of treatment actions

Decisions	Conditions
1	No maintenance action is carried out
2	Preventive maintenance (system returns to the previous status)
3	Corrective maintenance (system returns to state 1)

Reliability is defined as the probability that a component or system will perform as intended over a specified period of time under certain operating conditions [23]. This theory can be used to predict when a component will fail, so that maintenance, replacement, or resupply can be scheduled. To determine the time between failures, the number of time intervals between each consecutive failure is calculated. The best fit distribution for each component is determined using the Relyence application or by finding the highest correlation value from Equation 11. This equation is applied to each distribution, using the values of x_i and y_i.

$$r = \frac{n \sum x_i y_i - (\sum x_i . \sum y_i)}{\sqrt{[(n \sum x_i{}^2) - (\sum x_i)^2][(n \sum y_1{}^2) - (\sum y_i)^2]}} \quad (11)$$

Several types of distributions can be used in calculations. The component age distributions include normal, exponential, lognormal, and Weibull. The normal distribution is a continuous random variable with a symmetrical curve [24]. It is commonly misunderstood and assumed to be a normal distribution. The exponential distribution is a model of the failure time interval for components or systems in reliability engineering [25]. It is commonly used for components with a constant failure rate. The lognormal distribution has two parameters representing the mean failure time, and its shape can vary similarly to the Weibull distribution. Thus, data that is approximated by the Weibull distribution can also be approximated by the lognormal distribution. The Weibull distribution has many parameters and can model various data, such as component damage data with an unpredictable damage rate. Several parameters are needed to test a dataset of failure and repair times for a component. This test can be performed using the ranked regression, which can be done using the free trial of the Relyence application or using Equations 12 and 13.

$$\sum_{i=1}^{N} (\hat{a} + \hat{b} x_i + y_i)^2 = \min \sum_{i=1}^{N} (a + b x_i + y_i)^2 \quad (12)$$

$$\sum_{i=1}^{N} (\hat{a} + \hat{b} y_i + x_i)^2 = \min \sum_{i=1}^{N} (a + b y_i + x_i)^2 \quad (13)$$

Then, to determine the time until just before failure for the system, Equation 14 can be used for normal distribution, Equation 15 for exponential distribution, Equation 16 for lognormal distribution, and Equation 17 for Weibull 3-parameter distribution.

$$MTTF = \mu \quad (14)$$

$$MTTF = \frac{1}{\lambda} \quad (15)$$

$$MTTF = t_{med} \cdot e^{\frac{s^2}{2}} \quad (16)$$

$$MTTF = \gamma + \eta \ . \ \Gamma \ \left(1 + \frac{1}{\beta}\right) \quad (17)$$

3. Results and Discussion

3.1. Result of Failure Mode Effect Analysis (FMEA)

The duration, time interval, and failure detection methods of fuel oil system components on tugboats were obtained through FMEA analysis as severity (S), occurrence (O), detection (D) value as shown in Table 5 which its the FMEA worksheet that also contain the component function, potential failure, potential cause failure, potential effect, control failure detection. According to the FMEA worksheet in Table 5, the fuel oil purifier has the highest RPN value of 294 due to its relatively high failure intensity, making it a critical component in the 3200 hp tug fuel system.

Table 5. Worksheet FMEA of 3200 hp tugboat fuel oil system

No.	Component	Function Component	Potential Failure	Potential Cause Failure	Potential Effect	Control Failure Detection	S	O	D	RPN
1	Fuel Oil Tank (S & P)	A place to store ship fuel	Corrosion of fuel tank walls	High humidity levels cause metal oxidation in the fuel tank.	The walls of the fuel tank are thin so they can leak	Visual direct observation	10	1	4	40
2	Fuel Oil Transfer Pump	Transfers fuel from the fuel oil tank to the daily tank	Leaky seals, worn shafts, damaged electromotors and capacitors	Component fatigue and overload	Decreased flow pressure fuel so that engine performance decreases	Checking fuel flow pressure	7	3	6	126
3	Fuel Oil Transfer Pump (Stand By Hand Pump)	Replaces the work of the fuel oil transfer pump when it fails	Seal leaks	Component fatigue and overload	Decreases fuel flow pressure resulting in decreased engine performance	Checking fuel flow pressure	7	3	6	126
4	Fuel Oil Purifier Pump	Transferring fuel from the fuel oil tank to the fuel oil purifier	Leaking seal, worn shaft, damaged electromotor and capacitor	Component fatigue and overload	Decreased fuel flow pressure resulting in decreased engine performance	Pressure check fuel flow	7	3	6	126
5	Fuel Oil Pu rifier	Separates fuel from unneeded fine particles	Fuel system clogged and dirty	filter due to the presence of foreign micro particles with high intensity carried along with	fuel Dirty fuel so that it can hinder engine work	Checking by disassemblin g component parts regularly	7	6	7	294
6	Daily Tank (S & P)	To store ship fuel for daily use	Corrosion of daily tank walls	High humidity levels cause metal oxidation in daily tanks	walls become thin so they can leak	Direct visual observation	10	1	4	40
7	Sedimentatio n Tank	For deposition of particles that are not needed in the combustion process	Corrosion of the walls of the sedimentatio n tank	High humidity levels and the presence of microbes that cause corrosion cause metal oxidation in the sedimentatio n tank	The walls of the sedimentation tank become thin so they can leak	Direct visual observation	10	1	4	40
8	Fuel Oil Feed Pump (Stand By)	Replaces the work of the fuel oil feed pump when it fails	Leaky seal, worn shaft, damaged electromotor and capacitors	Fatigue components and overload	Low fuel flow pressure resulting in decreased engine performance	Pressure check fuel flow	7	3	6	126
9	Fuel Feed Pump (S & P)	Changes fuel pressure so that it can flow to the engine	Leaky seal, worn shaft, damaged electromotor and capacitors	Fatigue components and overload	Low fuel flow pressure resulting in decreased engine performance	Pressure check fuel flow	7	3	6	126

3.2. Result of Fault Tree Analysis (FTA)

Based on the analysis of the diagram and downtime of the fuel oil system components of 3200 hp tugboat using the free trial of the DPL 9 Fault Tree application, an FTA diagram is obtained in Figure 4. Based on the FTA diagram, there are three failures in the fuel oil system. Failure 1 is corrosion on the tank wall in the fuel oil tank, daily tank, and sedimentation tank as the cut sets with a cut set order of 1, which means that the system will immediately fail if that cut set fails. Failures

2 and 3 are a lack of fuel flow pressure because of pump failure with cut sets order of 2 and 3 respectively, which means that the system will not immediately fail if one of these cut sets fails, but will only fail if at least one of them fails as the failure of the minimum cut set. The minimum cut set for system failure can be seen in Table 6.

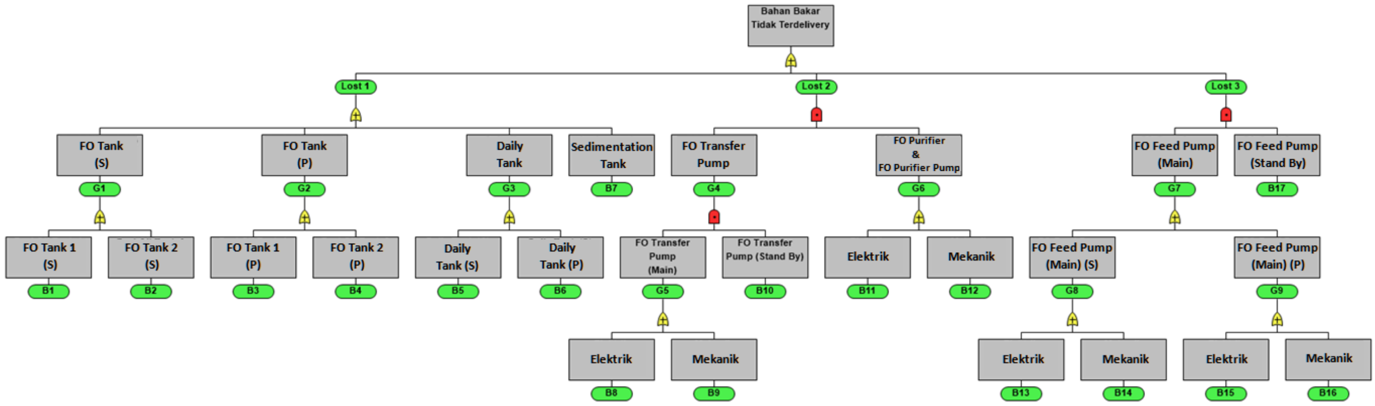

Figure 4. FTA diagram of 3200 hp tugboat fuel oil system.

Table 6. Minimum cut set for system failure.

Code	Minimal Cut Set	Order
B1	FO *Tank* 1 (S)	1
B2	FO *Tank* 2 (S)	1
B3	FO *Tank* 1 (P)	1
B4	FO *Tank* 2 (P)	1
B5	*Daily Tank* (S)	1
B6	*Daily Tank* (P)	1
B7	*Sedimentation Tank*	1
{B8 or B9, B10, B11 or B12}	FO *Transfer Pump* Electric or FO *Transfer Pump* Mechanical, FO *Transfer Pump Stand By*, FO *Purifier* & FO *Purifier Pump* Electric or, FO *Purifier* & FO *Purifier Pump* Mechanical	3
{B13 or B14 or B15 or B16, B17}	FO *Feed Pump* (S) Electric or FO *Feed Pump* (S) Mechanical or FO *Feed Pump* (P) Electric or FO *Feed Pump* (P) Mechanical, FO *Feed Pump Stand By*	2

3.3. Result of Overall Equipment Effectiveness (OEE)

Based on the data recorded by the company to obtain the OEE value by using the availability that obtained from tugboat utility and availability using Equation 2, performance that obtained from number of service, ideal time per-ship service, and tugboat utility using Equation 4, and product quality that obtained from tugboat utility and tugboat utility plan using Equation 6, these values are generated, which can be seen in Table 7.

Table 7. Calculation of availability, performance, and product quality of 3200 HP tugboat fuel oil system.

Month	Utility Plan (Hours)	Utility (Hours)	Tugboat Availability (Hours)	Number of Services	Ideal Time per-Ship Service (Hours)	Availability	Performance	Quality Product
January	517.30	485.67	720.67	323	1.25	96%	83%	94%
February	483.70	407.75	654.08	261	1.25	89%	80%	84%
March	516.60	475.08	725.08	318	1.25	94%	84%	92%
April	500.50	407.80	680.08	269	1.25	86%	82%	81%
May	517.30	302.33	614.83	197	1.25	70%	81%	58%
June	491.05	377.92	691.08	267	1.25	78%	88%	77%
July	517.30	407.33	721.25	289	1.25	81%	89%	79%
August	517.30	414.08	729.00	304	1.25	81%	92%	80%
September	499.80	366.25	706.33	262	1.25	74%	89%	73%
October	517.30	326.17	714.50	225	1.25	65%	86%	63%
November	500.50	80.92	225.33	55	1.25	51%	85%	16%
December	0.00	0.00	0.00	0	0.00	0%	0%	0%

Based on availability, performance, and quality product obtained in Table 7, then calculated using the Equation 8 to have the OEE value of the tugboat fuel oil system each months in 2020 obtained are as shown as Table 8. The average value of OEE was 47%, lower than the standard of 85%. OEE value tends to be small when the tugboat's utility is small, which means that the level of system productivity is small because the tugboat is not operating.

Table 8. Results of calculation of OEE fuel oil system

Month	OEE
January	75%
February	60%
March	72%
April	58%
May	33%
June	53%
July	56%
August	60%
September	49%
October	35%
November	7%
December	0%

3.4. Result of Markov Decision Process (MDP)

Based on the OEE value obtained in Table 8, the fuel oil system's condition and status for the tugboat's main propulsion engine for the period January 2020 – December 2020 according the criteria in Table 3 can be seen in Table 9. Then, based on the status in Table 9, it is necessary to calculate the change from light damage to light damage, light damage to moderate damage and vice versa, light damage to severe damage and vice versa, moderate damage to moderate damage, and severe damage to severe damage as shown as Table 10.

Table 9. Fuel oil system status.

Month	Condition	State
January	Light Damaged	2
February	Moderate Damaged	3
March	Light Damaged	2
April	Moderate Damaged	3
May	Severe Damaged	4
June	Moderate Damaged	3
July	Moderate Damaged	3
August	Moderate Damaged	3
Septembe r	Moderate Damaged	3
October	Severe Damaged	4
November	Severe Damaged	4
December	Severe Damaged	4

Table 10. The status transition of the fuel oil system.

System Status	Status to System Status		
	Light Damage (LD)	Moderate Damage (MD)	Severe Damage (SD)
Light Damage (LD)	0	2	0
Moderate Damage (MD)	1	3	2
Severe Damage (SD)	0	1	2

After calculating the transition of each state to another, it is necessary to calculate the number of transitions to each state as shown as Table 11. Then find the probability that will be a reference for determining the steady state condition by dividing each transition status by the total number of transitions. The results obtained as shown as Table 12 which means if the system has 0.55 as the probability value in the steady state condition it means the system has moderate damage condition.

Table 11. Number of transitions of fuel oil system status

Number of Transitions to Status			Amount
Light Damage (LD)	Moderate Damage (MD)	Severely Damaged (SD)	
1	6	4	11

Table 12. Probability of fuel system transition.

Probability			Amount
Light Damage (LD)	Moderate Damage (MD)	Severely Damaged (SD)	
0.09	0.55	0.36	1.00

To find the long-term probability, first have to calculate the initial probability by dividing the transition to the state by the number of transitions from the original state obtained from Table 10; thus, the initial probability matrix of the system will be formed. With Equation 9 calculate the transition probability matrix until the matrix value remains at a certain n (steady state) which is the probability matrix of the long-term system status.

$$B^1 = \begin{bmatrix} LD\ to\ LD & LD\ to\ MD & LD\ to\ SD \\ MD\ to\ LD & MD\ to\ MD & MD\ to\ SD \\ SD\ to\ LD & SD\ to\ MD & SD\ to\ SD \end{bmatrix}$$

$$B^1 = \begin{bmatrix} 0.00 & 1.00 & 0.00 \\ 0.17 & 0.50 & 0.33 \\ 0.00 & 0.33 & 0.67 \end{bmatrix}$$

$$B^2 = \begin{bmatrix} 0.17 & 0.50 & 0.33 \\ 0.09 & 0.53 & 0.39 \\ 0.06 & 0.39 & 0.56 \end{bmatrix}$$

$$B^3 = \begin{bmatrix} 0.09 & 0.53 & 0.39 \\ 0.09 & 0.48 & 0.43 \\ 0.07 & 0.43 & 0.50 \end{bmatrix}$$

$$B^4 = \begin{bmatrix} 0.09 & 0.48 & 0.43 \\ 0.08 & 0.47 & 0.45 \\ 0.07 & 0.45 & 0.48 \end{bmatrix}$$

$$B^5 = \begin{bmatrix} 0.08 & 0.47 & 0.45 \\ 0.08 & 0.46 & 0.46 \\ 0.08 & 0.46 & 0.47 \end{bmatrix}$$

$$B^6 = \begin{bmatrix} 0.08 & 0.46 & 0.46 \\ 0.08 & 0.46 & 0.46 \\ 0.08 & 0.46 & 0.46 \end{bmatrix}$$

The calculation stops at the value of n = 6 because the matrix values at n = 6 and n = 7 are the same, which means the system is in a steady state. With QM for Windows V5 application, the long-term probability found by steady state matrix are obtained as shown in Table 13.

Table 13. Probability steady state of fuel oil system by QM for Windows V5 application.

	State 1	State 2	State 3
State 1	0.0801	0.4644	0.4554
State 2	0.079	0.4626	0.4584
State 3	0.0774	0.4584	0.4642
Steady State Probability	0.0783	0.4609	0.4609

With reference to the transition probability in Table 12, the status of the steady state probability of fuel oil system show in Table 14 by rounding up the matrix elements. The probability in this steady state shows that in the next period the fuel oil system of 3200 hp tugboat has a light damage condition and moderate to severe damage condition.

Table 14. Fuel oil system status of steady state probability.

	Probability	Condition	State
X_1	0.08	LD	2
X_2	0.46	MD to SD	3

	Probability	Condition	State
X_3	0.46	MD to SD	3

Proposed maintenance actions that can be taken based on the classification in Table 4 are preventive maintenance including periodic checks and cleaning before components fail and corrective maintenance in the form of cleaning and repair if needed so that the system can return to condition 1 (one).

3.5. Result of Reliability Test

Based on the data of time interval for damage to the fuel oil system components of 3200 hp tugboat for the period January 2020 - December 2020 obtained from company data in Table 1, the failure time interval values for each component of the 3200 hp tugboat's fuel oil system are sorted from the shortest to the longest intervals in Table 15 which are then used in the free trial Relyence application to get the best fit distribution. The best fit distribution is obtained based on the highest correlation value (r). Table 16 shows the correlation value of each distribution from the highest to the lowest.

Table 15. Time interval of 3200 hp tugboat components fuel oil system damage from the smallest.

Component	Failure Time
Fuel Oil Purifier	240
	336
	360
	456
	504
	528
	600
	624
	696
	720
	864
	984
	1104
Fuel Oil Transfer Pump, Fuel Oil Purifier Pump, Fuel Oil Feed Pump (S & P)	8016
Fuel Oil Tank (S & P), Daily Tank (S & P), Sedimentation Tank	0

Table 16. Best fit distribution of fuel oil purifier in 3200 hp tugboat from free trial Rlyence application.

Rank	Distribution	r
1	Weibull	0,9964
2	Lognormal	0,992
3	Normal	0,9876
4	Eksponensial	0,9732

The distribution of each component varies based on the time interval between failures and the frequency of failures. Components with unpredictable time intervals are likely to have unstable values, and the Weibull distribution is suitable for modeling such components. On the other hand, components that have only one failure interval do not need distribution. Table 17 presents the Weibull distribution parameters obtained from the free trial Relyence application, that will be used in this analysis.

Table 17. The parameters of component best fit distribution.

Component	Best Fit Distribution	Parameter
Fuel Oil Purifier	Weibull 3	γ (estimation parameter) = 108.81 η (scale parameter) = 580.41 β (shape parameter) = 1.97
Fuel Oil Transfer Pump, Fuel Oil Purifier Pump, Fuel Oil Feed Pump (S & P)	None, because the damage data is only once during the sample period	-
Fuel Oil Tank (S & P), Daily Tank (S & P), Sedimentation Tank	None, because no damage occurred during the sample period	-

To find the failure time for each components based on the best fit distribution of each components and parameters found using Equation 17.

$$MTTF = \gamma + \eta \; . (1 + \frac{1}{\beta})$$
$$= 108.81 + 580.41 \; . (1 + \frac{1}{1.97})$$

In the gamma function the value of $(1 + \frac{1}{1.97}) = 2.67$

$$= 108.81 + (580.41 \; . \; 2.67)$$
$$= 1658.50 \text{ hours}$$

With an MTTF value of 1658,50 hours, the fuel oil purifier has a reliability value of 0.01 according to the graph which can be seen in Figure 5.

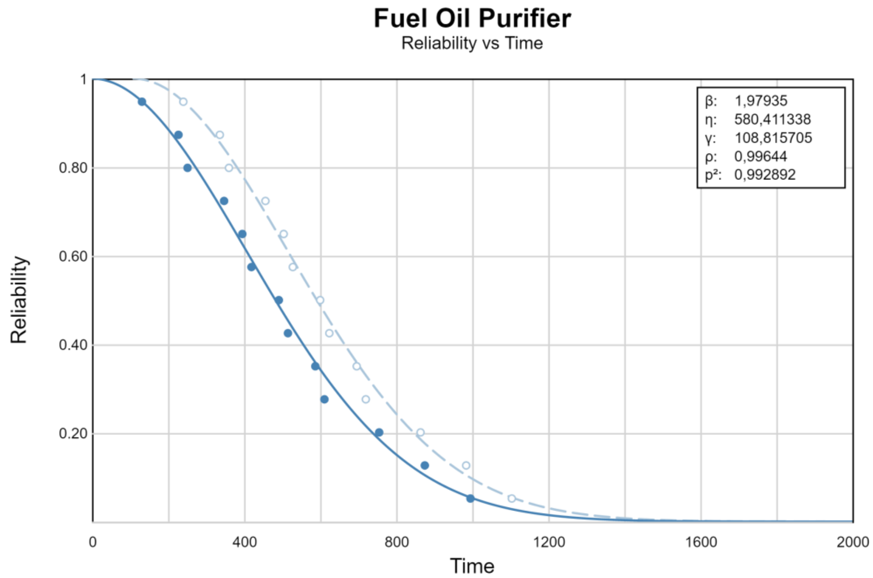

Figure 5. Reliability vs. time-based on the best fit distribution of fuel oil purifier

The fuel oil transfer pump, fuel oil purifier pump, and fuel oil feed pump (S & P) have no distribution, as the damage only occurred once during the sample period. As a result, the MTTF is the same as the damage interval in the sample period, which was 8016 hours with a reliability value of 0. The fuel oil tank (S & P), daily tank (S & P), and sedimentation tank do not have a distribution, as there was no damage during the sample period, so the MTTF cannot be determined. Based on the quantitative analysis of OEE, MDP, and reliability, the recommended time for preventive and corrective maintenance on the fuel system components of the tugboat is presented in Table 18.

Table 18. Proposed scheduling and action for 3200 hp tugboat fuel oil system components.

Components	Type of Maintenance	Schedule	Conditions
Fuel Oil Purifier	Preventive Maintenance (Periodic Checks and Cleaning if necessary)	After operating for 340 hours or the equivalent of having served approximately 272 ships.	Has a probability of failure of 15% or a reliability value of 85% and less than the component's MTTF value.
	Preventive & Corrective Maintenance (Periodic Checking, Cleaning, and Repairing if necessary)	After operating for 590 hours or the equivalent of having served approximately 472 ships.	Has a probability of failure of 50% or a reliability value of 50% and less than the component's MTTF value.
Fuel Oil Transfer Pump, Fuel Oil Purifier Pump, Fuel Oil Feed Pump (S & P)	Preventive & Corrective Maintenance (Periodic Checking, Cleaning, and Repairing if necessary)	After operating for 8016 hours or the equivalent of having served approximately 6412 ships.	Has a probability of failure of 100% or a reliability value of 0%, equal to the component's MTTF value.
Fuel Oil Tank (S & P), Daily Tank (S & P), Sedimentation Tank	Preventive Maintenance (Periodic Checks and Cleaning if necessary)	After operating for 8016 hours or the equivalent of having served approximately 6412 ships.	-

This research reviewed the reliability analysis results of fuel system components that have operated for 24 years, with a sample period of 5 years. The components did not experience more than one failure during this time. This shows that the component life, as determined by the Weibull distribution with a sample period of 1 year using qualitative and quantitative methods, is not less than the age of the components in the research, which have a sample period of up to 5 years and are all subjected to distribution.

4. Conclusion

The findings of the study on the 3200 hp tugboat fuel oil system, which provided services to 2770 ships during the period of January 2020 to December 2020, have been obtained through a combination of qualitative and quantitative analysis.

1. The FMEA method revealed that the 3200 hp tugboat has a critical component, the FO Purifier, with an RPN value of 294. This component was further analyzed using the FTA method, which showed that it is one of the cut sets causing system failure of order 3.
2. The condition of the 3200 hp tugboat's fuel oil system was then analyzed using the MDP method, which produced values of 0.08 and 0.46. These values suggest that in the next year, the fuel system is predicted to experience light damage and moderate to severe damage, respectively. Based on these classifications, it is recommended that the maintenance performed on the components be preventive in nature, in the form of periodic inspections and cleaning as needed, and corrective, in the form of repairs if necessary, to meet the standards of the Japan Institute of Plant Maintenance.
3. The proposed maintenance schedule for each component is based on its reliability value, and it should be performed before the MTTF. For example, the proposed preventive maintenance for the FO Purifier is carried out before 340 hours of use with a reliability value of 85% and before 590 hours of use with a reliability value of 50%. Corrective maintenance is performed when the component reliability is 50%. The proposed preventive and corrective maintenance actions for the FO transfer pump and FO feed pump (S&P) should be carried out before 8016 hours, and the proposed preventive maintenance actions for the FO tanks (S&P), sedimentation tanks, and daily tanks (S&P) should be carried out before 8016 hours.

In conclusion, the analysis of the fuel oil system of the 3200 HP tugboat has provided valuable insights into the condition of the system and the components that require maintenance. The proposed preventive and corrective maintenance actions, when implemented, will ensure the system meets the standards of the Japan Institute of Plant Maintenance and continues to provide safe and reliable service to the 2770 ships served within one year in the period January 2020 - December 2020.

Acknowledgment
The authors would like to express their gratitude to the Laboratory of Ship Construction at Diponegoro University, Indonesia, for providing research facilities and assistance.

References

[1] J. Moubray, *Reliability-Centered Maintenance*, 2nd ed.; Butterworth-Heinemann: Oxford, UK, 1999.
[2] S. Chen, Z. Qi, D. Chen, L. Guo, and W. Peng, " Investigation of Bayesian network for reliability analysis and fault diagnosis of complex systems with real case applications," *Advances in Mechanical Engineering*, vol. 9, no. 10, p. 168781401772885, 2017, doi: 10.1177/1687814017728853.
[3] M. Shafiee, I. Animah, B. Alkali, and D. Baglee, " Decision support methods and applications in the upstream oil and gas sector," *Journal of Petroleum Science and Engineering*, vol. 173, pp. 1173– 1186, 2019, doi: 10.1016/j.petrol.2018.10.050.
[4] A.K. Samlawi, *Teori Dasar Motor Diesel*. 2015.
[5] H. Henk, *Tug use in port: a practical guide*, Nautical Institute, 2003.
[6] C.F. Prasetyo, H. Yudo, A.F. Zakki, A.H. Muhammad, " Analisa Perawatan Berbasis Keandalan Sistem Bahan Bakar pada Main Engine di Kapal KM. Kelimutu," *Jurnal Penelitian Enjiniring*, vol. 25, no. 2, pp. 132-140, 2021, doi: 10.25042/jpe.112021.08
[7] M. Jirgl, Z. Bradac, K. Stibor, and M. Havlikova, " Reliability analysis of systems with a complex structure using Monte Carlo approach," *IFAC Proc. Vol.*, vol. 46, no. 28, pp. 461– 466, 2013, doi: 10.3182/20130925-3-CZ-3023.00031.
[8] S. Xiao, S. Oladyshkin, and W. Nowak, " Reliability sensitivity analysis with subset simulation: application to a carbon dioxide storage problem," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 615, no. 1, p. 012051, Oct. 2019, doi: 10.1088/1757-899X/615/1/012051.
[9] C. Guo and Z. Liang, " A predictive Markov decision process for optimizing inspection and maintenance strategies of partially observable multi-state systems," *Reliability Engineering and System Safety*, vol. 226, p. 108683, Oct. 2022, doi: 10.1016/j.ress.2022.108683.
[10] M. Whiteley, S. Dunnett, and L. Jackson, " Failure Mode and Effect Analysis, and Fault Tree Analysis of Polymer Electrolyte Membrane Fuel Cells," *International Journal of Hydrogen Energy*, vol. 41, no. 2, pp. 1187– 1202, Jan. 2016, doi: 10.1016/j.ijhydene.2015.11.007.
[11] S. Khaiyum and Y. S. Kumaraswamy, " An Effective Method for the Identification of Potential Failure Modes of a System by Integrating FTA and FMEA," 2014, pp. 679– 686. doi: 10.1007/978-3-319-03107-1_74.

[12] Z. Bluvband, R. Polak, and P. Grabov, " Bouncing failure analysis (BFA): the unified FTA-FMEA methodology," in *Annual Reliability and Maintainability Symposium, 2005. Proceedings.*, pp. 463– 467. doi: 10.1109/RAMS.2005.1408406.
[13] H.-C. Liu, L. Liu, and N. Liu, " Risk evaluation approaches in failure mode and effects analysis: A literature review," *Expert Syst. Appl.*, vol. 40, no. 2, pp. 828– 838, Feb. 2013, doi: 10.1016/j.eswa.2012.08.010.
[14] W. Gilchrist, " Modelling Failure Modes and Effects Analysis," *International Journal of Quality & Reliability Management*, vol. 10, no. 5, May 1993, doi: 10.1108/02656719310040105.
[15] S. Nakajima, " Introduction to TPM: total productive maintenance," Productivity Press, Inc., 1988, 129.
[16] M.F. Gaffar, " Analisa keandalan sistem bahan bakar pada kapal KM Pangrango dengan pemodelan dinamika sistem=Analysis of the reliability of the fuel system on the ship KM Pangrango with system dynamics modeling, Undergraduate thesis, Universitas Hasanuddin, 2022.
[17] F. Dinmohammadi and M. Shafiee, " A Fuzzy-FMEA Risk Assessment Approach for Offshore Wind Turbines," *International Journal of Prognostics and Health Management*, vol. 4, no. 3, Nov. 2020, doi: 10.36001/ijphm.2013.v4i3.2143.
[18] D. Press, " Guidelines for failure mode and effects analysis (FMEA), for automotive, aerospace, and general manufacturing industries" , CRC Press, 2003.
[19] X. Han and J. Zhang, " A combined analysis method of FMEA and FTA for improving the safety analysis quality of safety-critical software," in *2013 IEEE International Conference on Granular Computing (GrC)*, Dec. 2013, pp. 353–356. doi: 10.1109/GrC.2013.6740435.
[20] S. Kristiansen, " Maritime transportation: safety management and risk analysis" , Routledge, 2013.
[21] C.E. Ebeling, " An introduction to reliability and maintainability engineering" , Waveland Press, 2019.
[22] Oliver, " Markov processes for stochastic modeling" , Newnes, 2013.
[23] D. Kececioglu, " Realiability Engineering Handbook , vol. 2" , Destech Publications, inc, Lancaster, Pennsylvania 17601, U.S.A, 2002.
[24] R.E. Walpole, H.M. Raymond, " Ilmu Probabilitas dan Statistik untuk Insinyur dan Ilmuan" , Bandung: ITB; 1995.
[25] D.C. Montgomery, " Introduction to statistical quality control" , John Wiley & Sons, 2020.