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TABLE OF CONTENTS

ARTICLE

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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 × O × 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.*

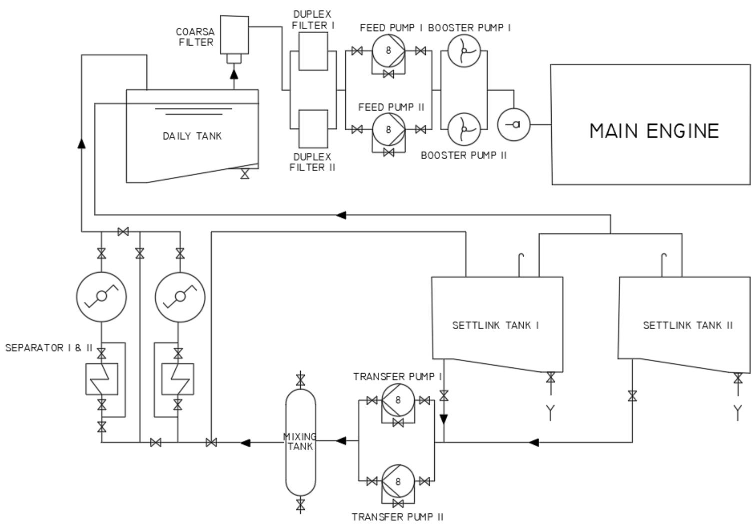

Figure 1. Diagram of Fuel System

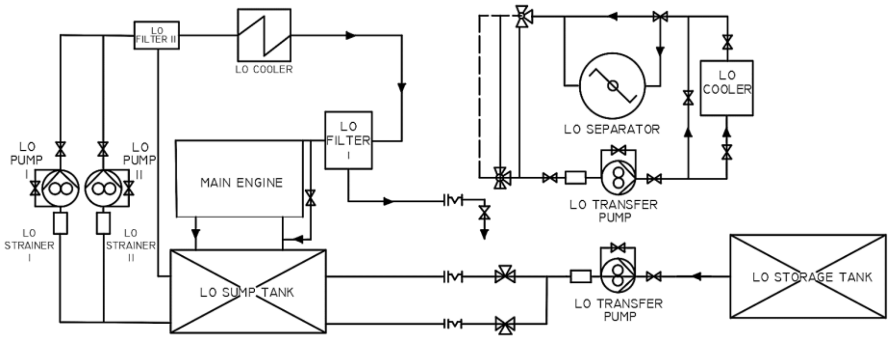

Figure 2. Diagram of Lubricating Oil System

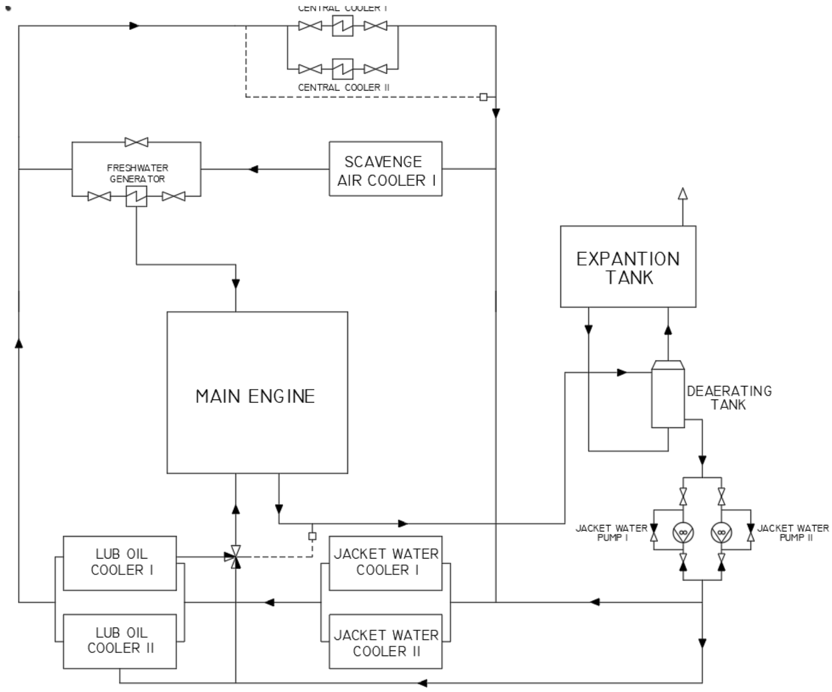

Figure 3. Diagram of Cooling System

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 CO	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
Scavange Air Cooler	Clogged fin	Scavenge 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.

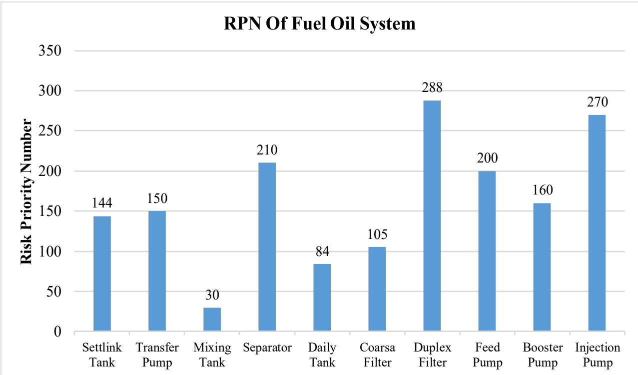

Figure 4. RPN of Fuel Oil System

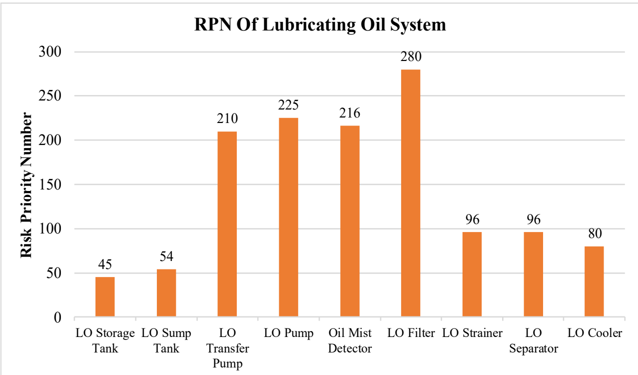

Figure 5. RPN of Lubricating Oil System

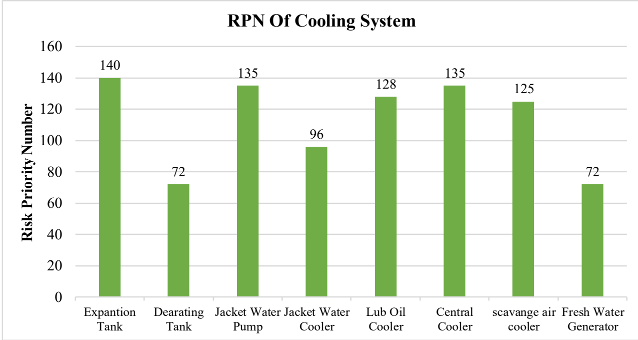

Figure 6. RPN of Cooling System

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.

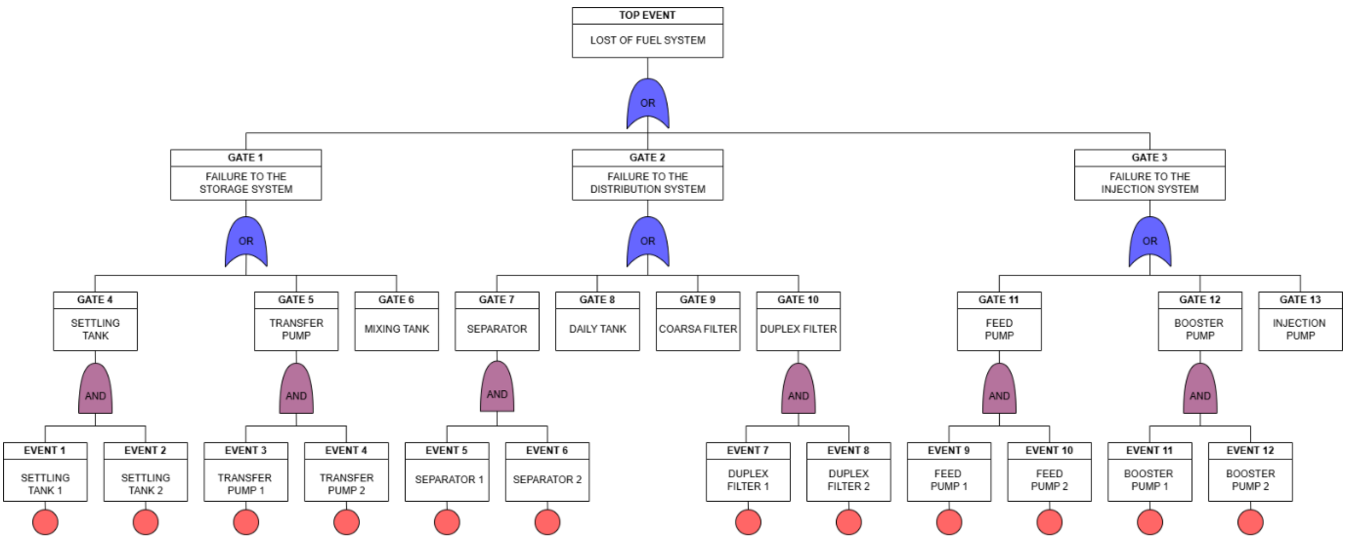

Figure 7. FTA of Fuel Oil System

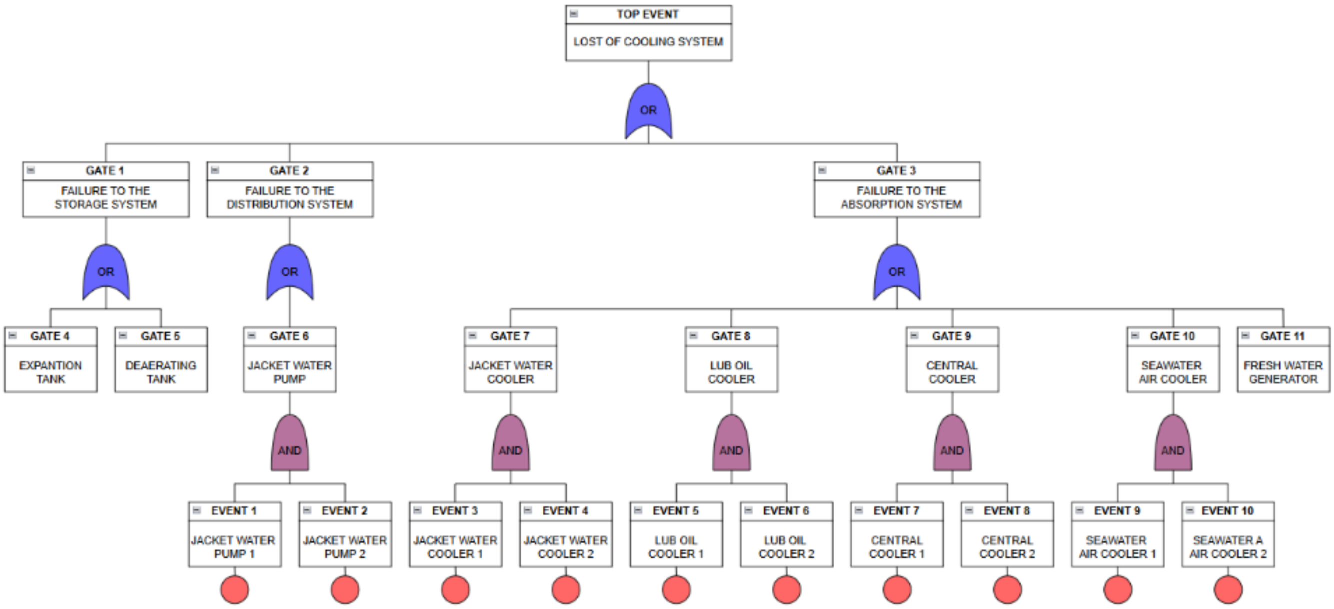

Figure 8. FTA of Lubricating Oil System

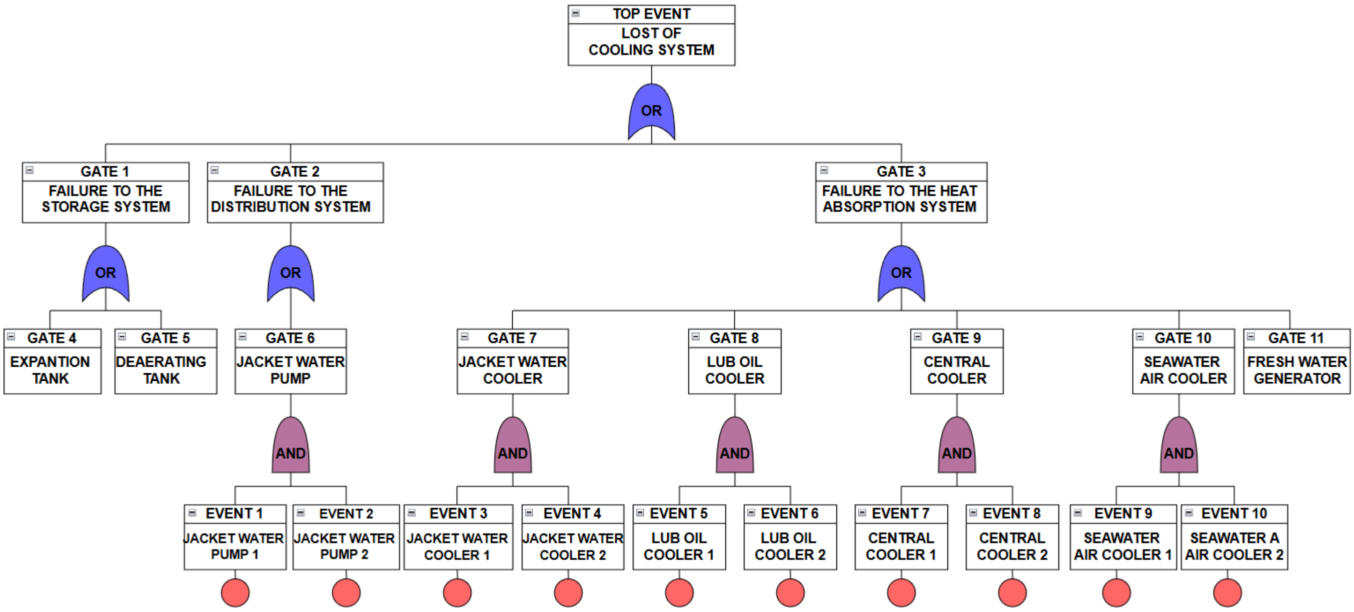

Figure 9. FTA of Cooling System

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	Compo-nent	Best Fit Distribution	Parameter
Fuel Oil System	Settling Tank	Exponential	η = 2606,0858 λ = 3,83717
	Transfer Pump	Weibull 2p	η = 8129,9930 β = 0,828254
	Mixing Tank	Rayleight 1p	η = 2269,7982 β = 2,0000
	Separator	Lognormal	μ = 7,930854 σ = 1,766137
	Daily Tank	Exponential	η = 4097,4183 λ = 2,440561
	Coarse Filter	Weibull 2p	η = 4014,2784 β = 0,296837
	Duplex Filter	Weibull 2p	η = 5201,0983 β = 0,820396
	Feed Pump	Weibull 2p	η = 6317,0090 β = 2,749826
	Booster Pump	Weibull 2p	η = 8949,0938 β = 0,825077
	Injection Pump	Weibull 2p	η = 4094,2528 β = 0,778029
Lubricating Oil System	LO Storage Tank	Exponential	η = 6514,9822 λ = 1,53492
	LO Sump Tank	Exponential	η = 2778,5089 λ = 3,599053
	LO Transfer Pump	Weibull 2p	η = 2910,5345 β = 2910,5345
	LO Pump	Weibull 2p	η = 2736,5890 β = 0,534660
	Oil Mist Detector	Weibull 2p	η = 6849,5488 β = 0,891756
	LO Filter	Weibull 2p	η = 3783,3508 β = 1,260283
	LO Strainer	Weibull 2p	η = 6312,9543 β = 1,417231
	LO Separator	Weibull 2p	η = 307,3268 β = 1,046844
	LO Cooler	Weibull 2p	η = 3833,5997 β = 3833,5997
Cooling System	Expansion Tank	Exponential	η = 5473,4371 λ = 1,82706
	Dearating Tank	Exponential	η = 4871,9150 λ = 2,052581
	Jacket Water Pump	Weibull 2p	η = 3928,3445 β = 0,497760
	Jacket Water Cooler	Weibull 2p	η = 2463,0170 β = 0,855139
	Lub Oil Cooler	Weibull 2p	η = 3289,1931 β = 0,967183
	Central Cooler	Weibull 2p	η = 2651,9887 β = 0,507268
	Seawater Air Cooler	Weibull 2p	η = 3707,6683 β = 0,587309
	Fresh Water Generator	Weibull 2p	η = 7994,5738 β = 0,806823

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.

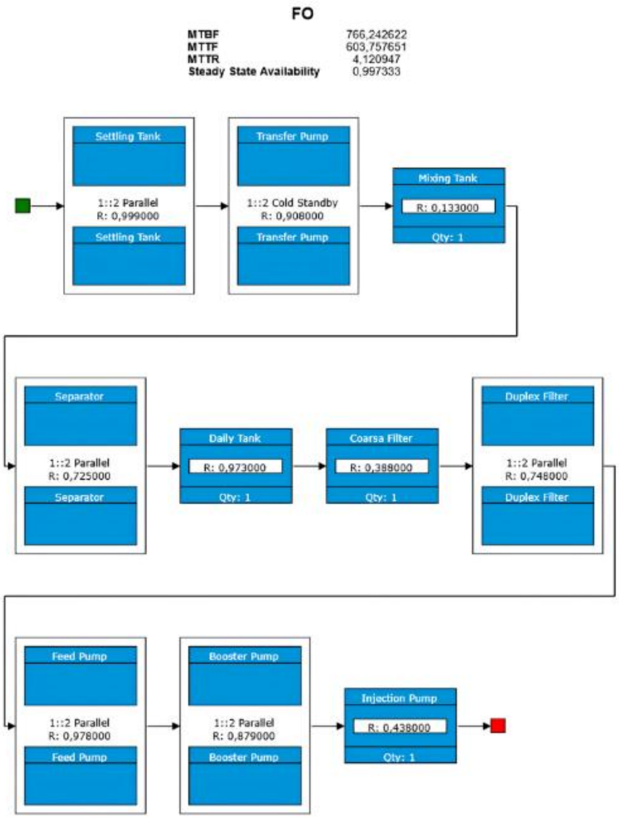

Figure 10. RBD of Fuel Oil System

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.

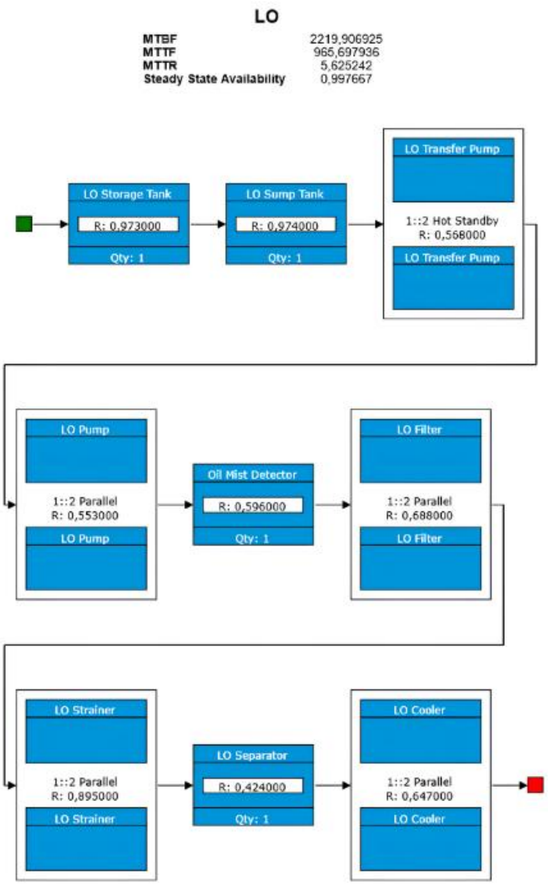

Figure 11. RBD of Lubricating Oil System

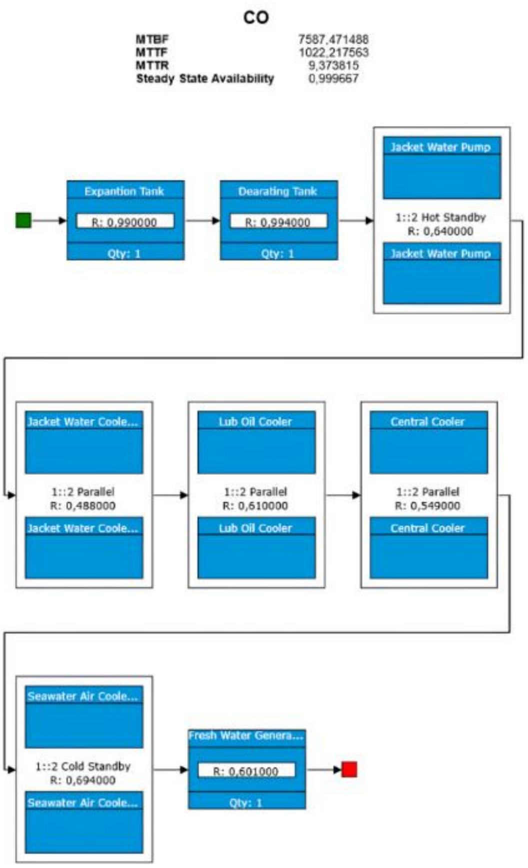

Figure 12. RBD of Cooling System

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.

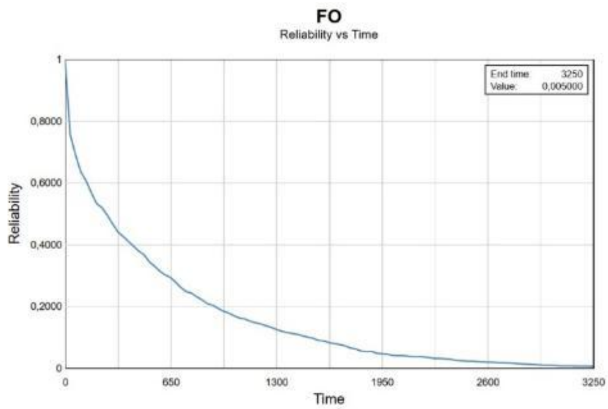

Figure 11. Result reliability vs time fuel oil system based on Monte Carlo Simulation

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.

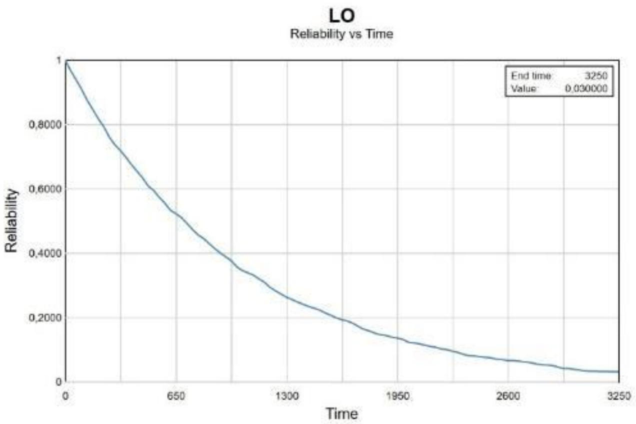

Figure 12. Result reliability vs time lubricating oil system based on Monte Carlo Simulation

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

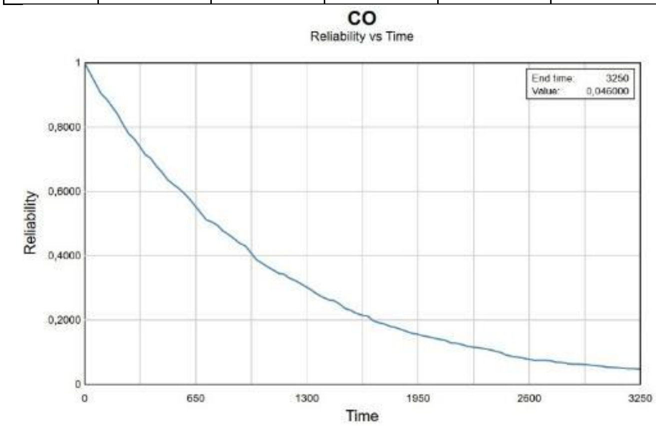

Figure 13. Result reliability vs time cooling system based on Monte Carlo Simulation

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.

Acknowledgments

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ANALYSIS FOR A SAILING SAFETY INFORMATION SYSTEM IN KARANGHARJO VILLAGE, KRAGAN SUBDISTRICT, REMBANG REGENCY

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ABSTRACT

Karangharjo Village, located in Kragan Subdistrict, Rembang Regency, is a community where the majority of residents work as small-scale fishermen using vessels under 5 GT. These fishermen face a high risk of maritime accidents due to a limited understanding of and access to sailing safety technology. Based on a social mapping survey conducted in 2024, the village has 25 fishing groups with a total of 250 fishermen. Every year, maritime accidents occur, resulting in physical disabilities, fatalities, and an increasing number of orphans. Advanced satellite-based safety mitigation and navigation technologies, which are commonly used by larger vessels, are difficult for these small-scale fishermen to access due to informational and economic constraints. The Marine Affairs and Fisheries Agency of Rembang Regency states that 30% of maritime accidents are caused by a lack of information and inadequate navigation devices, a situation worsened by the fishermen's highly fluctuating income. The problems are formulated as follows: how can sailing safety technology be implemented for small-scale fishing groups, and how can an information system workflow be designed for maritime emergencies? The problem-solving approach for this research involves a needs analysis of small-scale fishermen and the development of an information block model for emergency response. Based on these issues, the objectives of this study are to reduce the rate of maritime accidents in Karangharjo Village and to accelerate the handling of emergency situations. This study uses a mixed-methods approach, combining quantitative and qualitative techniques with the Sustainable Livelihood Approach (SLA). The expected outputs of this research are a publication in an accredited international journal and a copyright, falling under the category of Key Performance Indicator (IKU) 5, as research results that are utilized by the community.

Keywords: Fishermen, information system, sailing safety, needs analysis

Introduction

Karangharjo Village, located in Kragan Subdistrict, Rembang Regency, is a coastal area where the majority of residents work as small-scale fishermen, operating vessels with engine capacities of less than 5 GT. Based on the results of a social mapping survey in 2024, there are 25 groups with a total of 250 small-scale fishermen in this village [1]. However, sailing safety has not yet become a primary concern, even though fishing is a high-risk occupation with a significant potential for accidents [2-5]. Interviews with the Head of Karangharjo Village (2024) revealed that maritime accidents occur every year, leading to physical disabilities, fatalities, and social impacts, including 73 families who have been left orphaned.

Various safety technologies have been widely adopted by larger vessels, such as satellite systems, emergency calls, and modern navigation tools. However, such technologies remain inaccessible to small-scale fishermen due to financial constraints and limited access to information. The Marine Affairs and Fisheries Agency of Rembang Regency reported that around 30% of maritime accidents are caused by a lack of safety information and navigation equipment. Moreover, fishermen's incomes fluctuate significantly, from around 90 kg of fish per day during peak harvest seasons to only 10 kg during the west wind season [6]. This condition forces fishermen to prioritize basic needs over investment in safety equipment [7].

Previous studies have emphasized the importance of technology in supporting maritime safety, such as GPS-based monitoring systems [8], maritime weather prediction applications [9], and emergency communication systems based on mobile applications [10-13]. In addition, smartphone applications have been developed to improve maritime safety [14], including Internet of Things (IoT)-based vessel tracking systems [15]. Nevertheless, most of these innovations are not fully relevant to the context of Indonesian small-scale fishermen. Therefore, this study proposes a more contextual approach that adapts to the local conditions of Karangharjo fishermen. A relevant example can be seen in coastal community empowerment in the Kenjeran Area, where training in the use of GPS for sailing safety was conducted [16].

The main problems of this research are how to map the needs of small-scale fishermen to implement a sailing safety information system that aligns with their socio-economic conditions, and how an information system workflow can be designed to support emergency response at sea. The approach used includes a needs analysis of Karangharjo's small-scale fishermen for a safety system that is adaptive to resource limitations, followed by the development of an information block model in the form of an emergency response workflow diagram. The goal of this research is expected to reduce the rate of maritime accidents and accelerate response during emergency conditions.

Methodology

The research location is Karangharjo Village, Kragan Subdistrict, Rembang Regency. The study was conducted from July to August 2025 using a mixed-methods approach, combining quantitative and qualitative methods to obtain comprehensive data [17].

The data used consisted of both primary and secondary sources. Primary data were collected through observations, questionnaire surveys, interviews, and Focus Group Discussions (FGDs) with the Village Government, the Marine and Fisheries Agency of Rembang Regency, and fishermen groups. Secondary data were obtained from literature reviews and official documents from various institutions. Informants were selected using purposive sampling, meaning that respondents or informants were determined as the main data sources without deviating from the research objectives [18]. The selection of respondents was based on their proximity to information sources [19], complemented by the snowball technique. The total number of survey respondents was 30, selected based on socioeconomic criteria and location. Data collection techniques included secondary data inventory, in-depth interviews with government officials and community leaders, as well as focus group discussions [20]. Needs analysis was carried out using the Sustainable Livelihood Approach (SLA) systematically, as presented in the following scheme.

Figure 1. Sustainable Livelihood Approach (SLA)

The methodology can be divided into one or more parts according to the research requirements. The needs analysis was conducted using the Sustainable Livelihood Approach (SLA) (Figure 1) through three methods: Mind Mapping to connect and structure problem concepts, the Risk Assessment Framework to evaluate the level of risk, and Expert Judgment to strengthen and validate the analysis results.

Result and Discussion

a. Respondent Characteristics

This study involved a total of 23 respondents, all of whom work as fishermen in Karangharjo Village. All respondents were male, accounting for 23 individuals (100%). The largest age group was 51–60 years (36.4%), followed by 41–50 years (27.3%), while the smallest group was 21–30 years with 3 respondents (13.6%). Educational attainment was relatively low, with the majority having completed only elementary school (60.9%), junior high school (21.7%), senior high school (4.3%), while 13% had never received formal education. In terms of sailing experience, most respondents had between 1–10 years of experience (42.9%). This condition indicates the limited human resource capacity, which directly affects their understanding and adoption of sailing safety technologies.

b. Sailing Activities

The majority of fishermen (Figure 2) use the Jaring Kantong (bag net) method for fishing, reported by 82.6% of respondents. Several other methods were also identified, such as Jaring Poursin, Garu, Jaring Payung, and Jaring Anak Harimau, though these were used by only a few fishermen. The sailing range of fishermen for fishing activities is mostly within 6–15 miles (39.1%) and up to 5 miles (34.8%). The main commodity caught by fishermen is squid, reported by 73.9% of respondents, along with several fish species such as Batek, Petek, Kamojan, Layang, Rajungan (blue crab), and Trisi.

Figure 2. The fisherman

Regarding government assistance and participation in safety training, fishermen reported very limited access. As many as 78.3% of respondents stated that they had never received nor participated in government-led assistance or training on sailing safety.

c. Fishing Production Facilities

The fishing production facilities exhibit relatively uniform characteristics across several aspects (Table 1). All vessels used by the 23 respondents are made of teak wood, with an average gross tonnage of 6.61 GT and years of construction ranging from 2001 to 2023. The vessel length varies between 6.5 and 12 meters, with widths ranging from 1.9 to 5.5 meters and depths between 0.7 and 1.75 meters. The majority of vessels are powered by 23 HP engines, used by 82.6% of fishermen, with diesel fuel as the primary energy source.

Furthermore, in terms of vessel maintenance, most fishermen (52.2%) carried out irregular maintenance, while 47.8% only performed maintenance and repairs when the vessel experienced damage. The limited innovation in vessel structure, combined with a reactive maintenance pattern, increases the vulnerability to accidents during sailing.

d. Availability of Safety Equipment on Fishing Vessels

The analysis of vessel safety aspects reveals a significant gap between the availability of basic safety equipment and modern safety devices (Table 2). The ownership level of safety equipment is very low. None of the fishermen possessed nautical charts, lifeboats, immersion suits, or thermal protective aids. Only 26.1% of respondents owned a compass, while ownership of echosounders and fire extinguishers (APAR) was even lower, at 13%. Emergency signaling devices such as flare guns, smoke signals, and emergency whistles were found on only one vessel (4.3%).

Conversely, simple equipment such as ropes and emergency flashlights were owned by all respondents. Buckets with ropes, which are also vital tools in emergency situations, were owned by almost all fishermen (91.3%). This condition highlights a substantial disparity between actual practices and international maritime safety standards.

Table 1. Fishing production facilities

Year Built	Length (m)	Width (m)	Depth (m)	Height (m)	GT	Material	Brand	Type/Model	Power (HP)	Fuel Type
2019	7	3	1	1	4	Teak Wood	MKK, Wangli	ZS	23 HP	Diesel
2014	7	2,5	1,1	1	6	Teak Wood	Imoto, Yamaoke, Pedang, JP	ZS	23 HP	Diesel
2020	7,25	2,8	0,8	1,5	6	Teak Wood	Yamamoto, Pedang, Paus	ZS	23 HP	Diesel
2015	7,5	2,8	0,8	1,5	6	Teak Wood	JP, Namaoke, TR	ZS	23 HP	Diesel
2022	7,25	2,8	1	1,1	6	Teak Wood	Pedang, Imoto	ZS	23 HP	Diesel
2019	7,5	3	0,8	1,2	6	Teak Wood	Ninja, Turbo, Jettop	ZS	23 HP	Diesel
2010	7,5	2,2	1	1	4	Teak Wood	Ninja	ZS	23 HP	Diesel
2012	7	2,5	0,8	1,15	6	Teak Wood	Wangli, Jettop	ZS	23 HP	Diesel
2023	7	2,5	1	1	6	Teak Wood	Wangli, Ninja	ZS	23 HP	Diesel
2025	7,25	2,90	0,8	1,15	10	Teak Wood	Ninja	ZS	23 HP	Diesel
2010	12	5,5	1,75	2	30	Teak Wood	Mitsubishi, Fuso	D16	50 HP	Diesel
2019	7,5	2,9	0,8	1	4	Teak Wood	Ninja	Z5	23 HP	Diesel
2023	6,5	2,7	1,75	2	3	Teak Wood	Yamaoki	Z6	23 HP	Diesel
2011	7	1,9	0,7	0,9	4	Teak Wood	Amex	Z7	16 HP	Diesel
2021	7,25	2,8	1	1,15	6	Teak Wood	JF	Z8	24 HP	Diesel
2019	7	2,5	0,8	1	6	Teak Wood	Marcy, JP	Z9	23 HP	Diesel
2018	7,5	2,5	0,8	1	6	Teak Wood	Marcy, Ninja	Z10	23 HP	Diesel
2020	7,3	3	1	1,1	6	Teak Wood	Ninja	Z11	23 HP	Diesel
2013	7	2,6	0,8	1	6	Teak Wood	Batja	Z12	23 HP	Diesel
2007	7	2,7	0,8	1	6	Teak Wood	JP, Marcy	Z13	23 HP	Diesel

Year Built	Length (m)	Width (m)	Depth (m)	Height (m)	GT	Material	Brand	Type/Model	Power (HP)	Fuel Type
2017	7	2,7	1	1,15	6	Teak Wood	Ninja, JF	Z5	23 HP	Diesel
2019	6,75	2,8	0,7	0,95	3	Teak Wood	Ninja, JF	Z6	24 HP	Diesel
2001	7	3	1	1,1	6	Teak Wood	Wangli, Jettop	ZS	23 HP	Diesel

Table 2. Safety equipment on fishing vessels

Safety Equipment	Number of Owners	Ownership Percentage (%)
Mooring Rope	23	100
Emergency Flashligth	23	100
Bucket with Rope	21	91.3
Compass	6	26.1
Paddle	4	17.4
Echosounder	3	13
Fire Extinguisher (APAR)	3	13
Emergency Whistle	1	4.3
Flare Gun	1	4.3
Smoke Signal	1	4.3
Nautical Chart	0	0
Lifeboat	0	0
Immersion Suit	0	0
Thermal Protective Aid	0	0

e. Availability of Personal Safety Equipment and Personal Protective Equipment (PPE)

In terms of personal safety, the data indicate an unfavorable condition, as the ownership level of life-saving equipment is very low (Table 3). Only 4.3% of respondents owned a life jacket, and 8.7% owned either a life buoy or a first aid kit. This reflects the low awareness of and limited access to basic safety equipment.

Meanwhile, the availability of Personal Protective Equipment (PPE) is relatively better and generally adapted to daily work needs. Raincoats were owned by 95.7% of respondents, gloves by 78.3%, and work shoes by 69.6%. However, more specific protective equipment remained scarce, with only 8.7% of respondents owning a safety helmet, and none owning protective goggles. aids. Only 26.1% of respondents owned a compass, while ownership of echosounders and fire extinguishers (APAR) was even lower, at 13%. Emergency signaling devices such as flare guns, smoke signals, and emergency whistles were found on only one vessel (4.3%).

Table 3. Personal safety equipment

Safety Equipment	Number of Owners	Ownership Percentage (%)
Raincoat	22	95.7
Gloves	18	78.3
Work Shoes	16	69.6
Safety Helmet	2	8.7
Protective Goggles	0	0

f. Level of Work Equipment Availability

An analysis of work equipment shows a noticeable gap between basic tools and modern mechanical equipment in supporting fishing operations (Table 4). All fishers (100%) possess essential equipment such as hand tools, workshop kits, and ropes, which are used for both operational activities and emergency repairs. However, the adoption of modern mechanical equipment remains very low, with only 8.7% of respondents owning power blocks and rollers, while none of the fishers possess a stand joy. These findings indicate that fishing activities are still predominantly carried out manually, with very limited utilization of mechanical technology.

Table 4. Work equipment availability

Work Equipment	Number of Owners	Ownership Percentage (%)
Tool and workshop kits	23	100
Ropes	23	100
Power block	2	8.7
Roller	2	8.7
Stand joy	0	0

g. Level of Work Equipment Availability

In terms of emergency communication, the data indicate a very high dependence on mobile devices. Mobile phones serve as the primary means of communication for all respondents (100%), while the use of specialized maritime devices is very limited, with radios owned by only 8.7% of respondents and dedicated GPS units by 4.3%. Reliance on mobile devices is hindered by poor network quality at sea. Under normal conditions, GPS signals are accessible to all respondents (100%), and mobile phone signals are relatively strong (87%); however, internet access is entirely unavailable. During adverse weather conditions, mobile phone signals decrease drastically, with only 8.7% of respondents able to access them, although GPS signals remain stable. These findings highlight the high vulnerability of fishermen's emergency communication systems.

This study identifies the needs for a safety information system for small-scale fishermen through the Sustainable Livelihood Approach (SLA), which emphasizes the interconnection of five livelihood capitals.

1. Human Capital as a Determinant Factor
   A survey of 23 fishermen revealed that human capital is a critical factor, with the majority having only primary education (60.9%) or no formal education (13%), and 78.3% having never attended any training. As a result, safety awareness and technology adoption remain low. The study also found a positive correlation between education and safety awareness, consistent with previous findings that emphasize the role of human capital as a catalyst for sustainable livelihood transformation.

2. Dynamics of Natural Capital and Operational Challenges
   Karangharjo Village possesses natural capital in the form of access to the Java Sea, which is rich in fish resources. However, variability in sea conditions poses a major challenge to sailing safety. A total of 39.1% of fishermen sail 6–15 miles offshore and 26.1% more than 15 miles, which increases accident risks, especially given the lack of safety equipment. Climate change has disrupted weather patterns, rendering traditional prediction methods less accurate, while fishermen still rely heavily on intuition. This condition highlights the urgent need for a data-driven, real-time weather information and early warning system to mitigate risks.

3. Comprehensive Analysis of Physical Capital and Safety Gaps
   An evaluation of physical capital indicates a substantial gap between fishing production facilities and safety equipment. Most fishing boats are made of teak wood, with an average tonnage of 6.61 GT, but safety innovations are minimal. Modern equipment is almost absent; only 26.1% own a compass, 13% have an echo sounder or fire extinguisher (APAR), while nautical charts, life rafts, and standard lifesaving devices are entirely unavailable. At the individual level, only 4.3% of respondents own a life jacket, far lower than raincoat ownership (95.7%), reflecting a priority on weather protection rather than life safety.

4. Dynamics of Financial Capital and Implications for Safety
   An analysis of financial capital reveals extreme income fluctuations, from 90 kg of fish per day during harvest to only 10 kg during the west wind season. This 900% fluctuation creates significant economic instability, causing fishermen to prioritize basic needs over safety investments, which are perceived as non-profitable. Consequently, purchases of safety equipment are often postponed, creating a negative spiral that heightens accident risks and financial losses from damaged fishing gear or even loss of life.

5. Social Capital and Collective Potential
   The existence of 25 fishermen's groups with a total of 250 members indicates significant social capital potential. However, coordination and communication between groups remain weak. The absence of an integrated information system hinders emergency response, although this collective strength has the potential to serve as the foundation for a community-based safety system.

h. Synthesis of Safety Information System Needs for Small-Scale Fishermen

Based on the analysis of the five livelihood capitals, the design of a safety information system for small-scale fishermen must be holistic and adaptive to local conditions. The system should be simple, use the local language, and be easy to understand in order to address human capital limitations, while simultaneously strengthening social capital through community-based communication features. From the perspective of natural capital, the system must be able to provide real-time weather and navigation information to minimize risks arising from sea variability. Financial constraints require cost-effective solutions that remain affordable for fishermen with unstable incomes.

In terms of physical capital, the technology applied must be compatible with traditional fishing vessels without imposing additional costs. The main features should include GPS-based position monitoring, real-time weather alerts, an emergency panic button linked to SAR (Search and Rescue), and a user-friendly safety database. The system must also meet the criteria of Usability, Reliability, Affordability, and Scalability, supported by backup energy sources such as solar panels and long-lasting batteries to ensure functionality at sea. A phased implementation strategy is recommended, beginning with pilot projects and gradually expanding to cover the entire coastal area.

i. Synthesis of Safety Information System Needs for Small-Scale Fishermen

Based on the analysis of needs and existing constraints, this study recommends a phased implementation model that begins with strengthening human capital through training and socialization. The initial stage focuses on the use of basic safety equipment such as life jackets, simple GPS trackers, and emergency communication devices. Subsequently, weather and navigation information systems are integrated with an interface tailored to local capacities, followed by the development of community-based communication for monitoring and emergency assistance. The final stage involves the integration of all components into a comprehensive sailing safety system supported by adequate technological infrastructure.

Conclusion

The analysis of safety information system needs in Karangharjo Village shows that the design of such a system cannot be understood solely from a technical perspective but must also consider socio-economic aspects through a sustainable livelihood approach. The sailing safety condition of small-scale fishermen in Karangharjo Village is alarming, as indicated by the minimal ownership of standard maritime safety equipment such as life jackets, nautical charts, and life rafts, which are entirely absent within the community.

The Sustainable Livelihood Approach highlights disparities among livelihood capitals, with low levels of human and financial capital identified as the primary barriers to implementing safety practices. Therefore, the development of a safety information system must adopt a holistic design that accounts for the socio-economic limitations of fishermen, encompassing real-time monitoring, early warning systems, emergency communication, and a safety database with a simple interface and affordable costs.

The recommended implementation model follows a phased approach, starting with the strengthening of human resource capacity and gradually progressing toward the adoption of more advanced technologies in line with improvements in community capacity and sustainable adaptation. The success of this program will depend heavily on synergy among stakeholders, comprehensive policy support, sufficient budget allocation, and long-term commitment from all parties.

This study contributes to the development of a conceptual framework for a safety information system that is contextually relevant to the characteristics of small-scale fishermen in Indonesia and may serve as a blueprint for developing system prototypes, conducting pilot testing, and evaluating the impacts of implementation on sailing safety and fishermen's welfare.

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DEVELOPING A DATA-DRIVEN METHOD FOR YACHT DIMENSION PREDICTION

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ABSTRACT

A yacht's principal dimensions can be found in many ways. However, due to the massive technological advancements in the yacht industry, using these ancient methods is just a waste of time. A new statistical method is necessary to determine yacht dimensions in an easy and effective way. In this paper, 122 modern yacht data have been used to investigate the relationship between length, breadth, draught, speed, gross tonnage, and power, and to perform regression analysis to develop a new method for estimating yacht dimensions. This study developed two predictive models: Model 1 utilizes empirical ratios and trendline equations, while Model 2 employs sequential stepwise multiple regression. The models effectively estimate breadth, draft, gross tonnage (GT), speed, and power from a specified length, with geometric parameters (e.g., GT prediction R^2=0.97 in Model 1) showing higher reliability than performance parameters. The minimum and maximum ratio of Length to Breadth, draught to breadth, for a different range of ship length is also determined. This research is conducted in such a way that the owner's requirement for a new yacht is the length, and other particulars are determined accordingly.

Keywords: Yacht, regression, polynomial trendline, linear regression, power trendline

Introduction

A yacht should have modern technologies, facilities, as well as economically beneficial. In particular, the length of the yacht represents the main discriminating factor with regard to the technical and commercial typologies of the vessels, which have given rise to the category's 'superyachts', 'mega yachts', 'giga yachts', and 'dream yachts' [1]. However, the exact definition of these categories in terms of length is, to a certain degree, subjective and not clearly defined, and the only objective classification is that which divides the fleet into vessels below 24 m in length ('small yachts') or over 24m ('superyachts') [1]. A yacht has a linear relation between its length, breadth, and draught. Analyzing modern yachts, a new method for determining dimensions can be found.

There is a clear need for simpler, data-driven tools that reflect contemporary yacht practice. A regression-based approach can leverage databases of recent yacht designs to predict one dimension from others. In particular, if an owner specifies a desired length, it should be possible to estimate beam, draft, volume, speed, and power requirements using statistical correlations. To our knowledge, such methods are scarce in the published literature. For example, [2] used regression on 20-40 meter yachts to determine LOA, beam, draft, and related parameters in early design, and [3] developed formulas for light displacement from length, breadth, and draft on 240 yachts. However, these studies focus on displacement or tonnage prediction. In contrast, the present work aims to directly predict hull dimensions and performance metrics from length.

Although regression has been used in previous studies on the design of yachts [3], the studies tend to address the specific output of the regression, such as displacement. The uniqueness of this work is in presenting a detailed, coherent combination of basic empirical equations obtained solely out of contemporary yacht data, which are able to forecast the entire array of major dimensions and essential performance indicators directly and consecutively out of a single owner-keyboard input, the length overall (LOA). The strategy is to bridge the gap with a fast, data-driven preliminary design tool.

The main aim of the research is to work out and prove a functional and regression-based methodological framework for the quick initial dimensioning of contemporary motor yachts. The framework is designed to offer a dependable tool to the naval architects that, given one input parameter from the owner of Length Overall (LOA), gives correct first-estimates of the main dimensions (Breadth and Draught), volumetric measurement (Gross Tonnage), and important performance measures (Speed and Power). This study aims to simplify the design stage to produce explicit equations, which are based on current data, and not the conventional, time-consuming, displacement-based computation.

First, it makes use of a filtered set of 122 yachts (since 2005), so that the predictive models are up to date with the current tendencies in designing the yachts and their technological features, as opposed to using the results of the old-fashioned empirical data. Second, it presents a two-model solution: Model 1 will provide flexibility by allowing empirical ratios and trendline equations to provide independent parameter estimates, whereas Model 2 will provide a sequential and integrated method of calculation, with each of the predicted parameters serving as the input to the model, with only LOA as the input. Third, it presents a generalized set of straightforward, explicit equations of an expanded variety of outputs (B, T, GT, V, P) directly based on length, which fills a literature gap that frequently discusses predictive displacement or tonnage separately but does not provide a holistic, sequential sizing instrument to be used in the preliminary design discovery.

The initial design of the yacht used in the past has depended on rules of thumb, experience, and extrapolation of the existing vessels, and on the tradition practiced by commercial ship designers. Nonetheless, the current design of a yacht has changed hugely owing to the high demands of an owner, the swift change in technology, and a broad diversity in hull shapes and performance objectives. Research on yacht design also highlights that length overall (LOA) is the main parameter that is placed at the concept phase, and other key dimensions are calculated later, which explains the necessity of systematic and data-driven estimation tools that are specific to yachts [1].

Recent studies have shown that the principal dimensions of motor yachts, length, breadth, and draught, show high interdependences and strong scaling properties over the variations in size. The statistical results of modern databases of yachts indicate that these geometric relations can be appropriately utilized in preliminary design in an attempt to predict dimensions and volumetric features [2]. These findings suggest that geometrical parameters tend to be more predictable than performance-based parameters, which are affected by other design and operational aspects.

Computational intelligence and regression-based applicant techniques have been successively applied to the design of yachts and ships. Cepowski demonstrated that regression and neural-network-based methods are capable of reliably predicting light displacement of motor yachts based on simple design parameters, and regression models with similar efficiency are less complex and more transparent [3]. This justifies the appropriateness of regression methods in estimating the dimensions of a yacht at the initial stages, especially when very little information is found.

The increased use of artificial intelligence and machine learning in the field of maritime engineering also contributes to the utilization of data-driven models in design-associated work. Vessel identification, resistance prediction, and performance estimation have been successfully performed using machine learning methods and have proven that meaningful patterns can be identified through large datasets [4] [5]. Nevertheless, these papers always indicate higher uncertainty in the forecasting of dynamic performance parameters like speed, resistance, and power than in geometric dimensions, and this indicates inherent variability in performance forecasts.

In terms of design methodology, rational and risk-based ship design frameworks note the significance of sound early-stage estimation tools since preliminary design choices have a potent impact on safety, cost, and performance issues in the lifecycle of the vessel [6]. It has been a well-established fact that simplified analytical and statistical models are needed to reduce the design space prior to the process of more detailed analyses [7]. The latest numerical research on the added resistance and ship performance further proves that geometry-based predictions are stronger compared to those that consider operational conditions and environmental impact [8].

Extensive analyses of machine learning and modelling in ship design indicate that, although highly advanced AI methods are emerging rapidly, regression-based and statistical models are still of great value in preliminary design since they are interpretable, inexpensive to compute, and simple to implement [9]. However, the available body of literature is predominantly concerned with the prediction of single parameters - i.e., displacement, resistance, or classification - but not a combined, length-based framework that would be able to estimate all the main dimensions and the main performance indicators of the modern yachts.

Methodology

The study was intended to offer contemporary, fast, and reliable predictive tools to the modern naval architect, particularly, the complexity and time-intensive nature of the older, displacement-driven empirical method of determination. The methodology was based on fitting trendlines and sequential stepwise multiple linear regression, which means that the formulated equations would be representative of the contemporary superyacht design practice.

a. Data Source and Sampling

The corpus of raw data (Table 1) was collected from the SuperYacht Times database, which is a reliable source of industry information specializing in documenting and tracking the large modern pleasure boats and providing relevant information on the contemporary design tendencies, and making the statistical models applicable to a wide range of classifications [10].

To place this study under a valid foundation, the dataset used contained more modern vessel specifications so that the resulting predictive equations applied would more accurately represent the current state of practices in naval architecture and technological development, and as such, the foundation was more reliable than the dependence on the old-fashioned empirical methods.

a.1 Sample Characteristics and Variables

A total sample size of 122 contemporary yacht data points was collected to be analysed.1 The length overall of data sampled vessels ranges extensively (between a minimum of 24.0 m and a maximum of 162.5 m). This extensive range is essential to the creation of statistically significant models, since it will enable the equations to mirror effects of scale between vessels between the standard superyachts and giga-yachts, avoiding extrapolation error when predicting the dimensions of large vessels.

Table 1. Yacht raw data description

Parameter	Unit	Min. Value	Max. Value
Length overall (L)	m	24	162.5
Breadth (B)	m	5.65	25.7
Draught (T)	m	1.46	6.15
Speed (V)	knots	8	29
Power (P)	kw	306	8200
Gross Tonnage (GT)	-	70	15917

b. Analytical Framework and Validation Criteria

The basic analysis method was to fit mathematical models to the observed correlation in the obtained data (e.g., L vs. B and L vs. T and the volumetric proxy L*B*T vs. GT).

b.1 Model Selection Criterion: Coefficient of Determination (R^2)

In all of the generated trendline equations (Model 1) and multiple regression equations (Model 2), the Coefficient of Determination (R^2) was used as the model validation and selection measure. The study required a very strict standard; the equations with greater values of R^2 were accepted only. This was used to make sure that the final selected equations made the maximum percentage of the overall variance in the dependent variable that could be statistically explained by the independent variables, creating a level of great confidence in the empirical data fitting.

One important point made by the analytical framework is the predictability order amongst the parameters. The model results showed that the geometric parameters (L, B, T, GT) had a consistently high R^2 value (more than 0.8), indicating that there was a strong, predictable linear or non-linear relationship between scales depending on the sample data. On the other hand, the dynamic performance parameters, which include speed (V) and power (P) calculated in Model 2, showed a significantly lower statistical fidelity (R^2 was 0.1182 and 0.5839, respectively). This difference confirms the complexity and variability inherent in the prediction of dynamic parameters in the specific cases of various hull forms and technological applications in comparison with the more stable relationships between fixed geometrical dimensions.

c. Model 1: Empirical Ratio and Trendline Analysis

Model 1 was aimed at giving a flexible initial dimension forecast by using either the required length of the yacht or the set hull form ratios (e.g., L/B and B/T). Linear, power, and polynomial trendline fitting are the methods that were used to come up with this model.

c.1 Initial Data Transformation and Ratio Analysis

The first step was to compute three key empirical ratios of all 122 sampled yachts L/ B, B/T ratio, and the product of major dimensions (L*B*T), which served as a proxy of volume. To provide context to preliminary design and hull shape assumption, the dataset was grouped categorically by length, which enabled the determination of the current ratio ranges of L/B and B/T in particular classes of designs, which serves as a guidepost to the designer when choosing the hull form parameters prior to creating the particular dimensions shown in Figure 1.

c.2 Trendline Generation and Modelling Dependencies

Many types of trendlines have been tested and implemented to determine the deterministic relationships among the major dimensions; only the ones having the highest value of the R2 were accepted.

- Breadth Prediction (Linear Trendline): The width of the yacht was adequately modelled as a linear expression of the length.
- Draught Prediction (Polynomial Trendline): Draught was predicted as a second-order polynomial function of breadth.
- Alternative Draught Prediction (Linear Trendline): This is the simplest alternative model that was used to forecast draught as a linear regression of length.
- Gross Tonnage Prediction (Power Trendline): Gross Tonnage is a measure of internal volume directly and was represented as a power defect of the volumetric proxy (L x B x T).

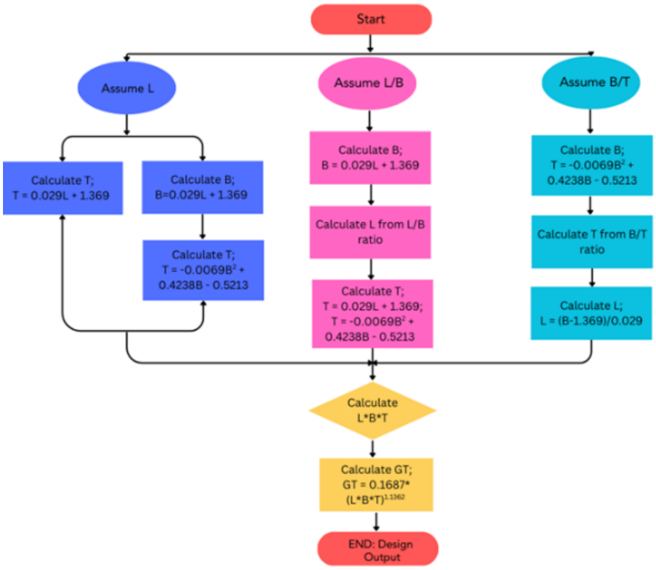

Figure 1. Flowchart of Model 1

d. Model 2: Sequential Stepwise Multiple Regression Analysis

This structure led to Model 2, which set out to design a fully integrated and simplified preliminary design tool using only the owner-specified yacht length as the input variable. The regression process was performed in five different steps, where L is the initial parameter, whose value is known at the outset of the series.

- Breadth Prediction: This step defined the basic transverse dimension using a univariate linear regression. Here, yacht length is the input variable.
- Draught Prediction: Draught was calculated with multiple linear regression, including the recalculated and predicted breadth to enhance the statistical accuracy, as the

draught is strongly dependent on length and beam.

- Speed Prediction: The four-dimensional dynamic parameter of performance, speed, needed all three initial hull sizes 9length, breadth, draught) to be predicted using multiple linear regression.
- Power Prediction: Multiple linear regression was used to determine required engine power, including the calculated dimensions (length, draught) and the target speed calculated.
- Prediction of Gross Tonnage: Gross Tonnage, which is the height of the vessel in terms of internal volume, was modelled by taking into consideration only the three physical dimensions (L, B, T). The particular decision to exclude V and P will keep the volumetric estimation unchanged and reduce the possibility of the volatile performance parameters affecting it.

The regression analysis follows the given procedure below (Figure 2):

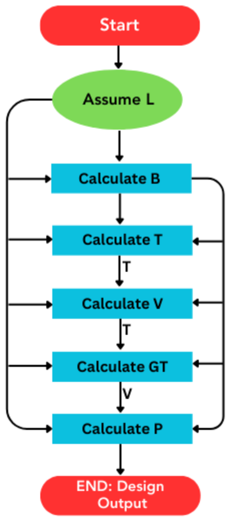

Figure 2. Flowchart of Model 2

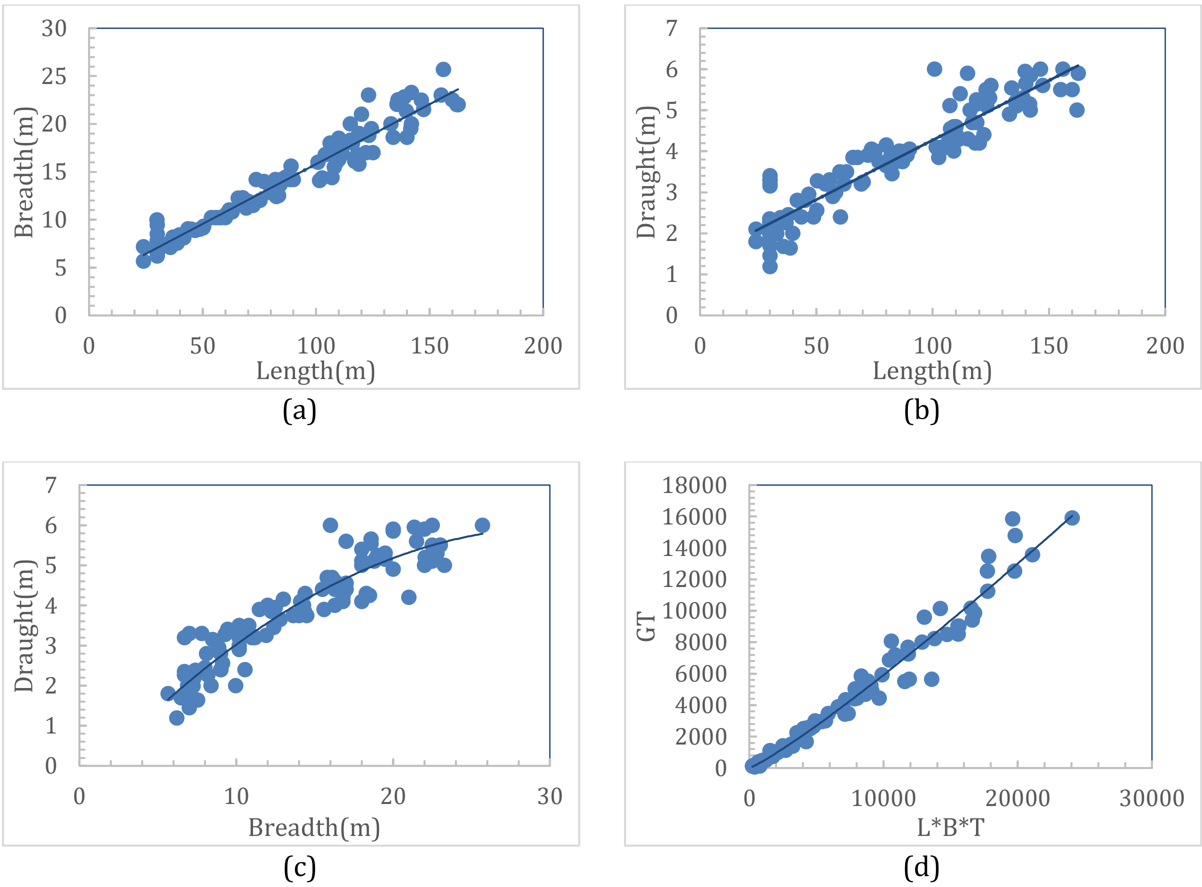

Figure 3. Relation between a) Breadth & Length, b) Draught & Length, c) Breadth & Draught, d) L*B*T & GT

Result and Discussion

a. Model 1

Figure 3 illustrates the foundational relationships within the dataset, which informed Model 1: (a) Breadth vs. Length shows a strong linear correlation; (b) Draught vs. Length displays more scatter by linear correlation (c) Draught vs. Breadth is better captured by a polynomial trend; and (d) Gross Tonnage scales predictably with the volumetric proxy (LBT) via a power-law relationship.

Generated Equations-

For Yacht length $20<L<50$:
$L/B = 3.00\text{-}5.42$, $B/T = 2.01\text{-}5.21$
For Yacht length $50<L<100$:
$L/B = 5.18\text{-}6.68$, $B/T = 2.84\text{-}4.40$
For Yacht length $L>100$:
$L/B = 5.35\text{-}7.52$, $B/T = 2.67\text{-}5.00$

$$B = 0.029L + 1.369 \quad (1)$$
$$T = -0.0069B^2 + 0.4238B - 0.5213 \quad (2)$$
$$T = 0.029L + 1.369 \quad (3)$$
$$GT = 0.1687*(L*B*T)^{1.1362} \quad (4)$$

Proposed Method to Estimate Main Dimensions of a New Yacht:

- For equations 1, 2, and 3, assume any yacht length as per client demand and put it in equation 1 to determine yacht breadth. Then put the breadth value in equation 2 to determine the yacht's draught or use the length in equation 3. Using the term L*B*T, determine the GT value from equation 4.
- If the owner's requirement is the L/B & B/T ratio, then determine the L value from the L/B ratio and put it in equation 1 to get breadth. Then, from the B/T ratio, put the B value in equation 2 or use L in equation 3 to determine draught. Finally, using the L*B*T term, GT can be found.

b. Model 2

The following equations were found through regression analysis:

$$B = 3.64 + 0.12*L \quad (5)$$
$$T = 1.07 + 0.02*L + 0.08*B \quad (6)$$
$$V = 19.83 + 0.05*L – 0.04*B – 2.11*T \quad (7)$$
$$P = -1429.88+9.46*L+277.28*B-474.82*T+80.80*V \quad (8)$$
$$GT = -4246.96 + 60.05*L + 279.46*B – 205.01*T \quad (9)$$

Proposed Method to Estimate Main Dimensions of a New Yacht-

- Take any Length value as the owner wants and put it in equation 5 to get the breadth value.
- Put length and breadth values in equation 6 to get the draft value.
- Put length, breadth, draught value at equations 7 & 9 to determine the Velocity & GT value.
- Then determine the power value from equation 8 using length, breadth, draft, and velocity.

This paper has given the minimum and maximum ratio of L/B & B/T with principal particulars dimension prediction. This ratio will help to assume the hull shape. This paper also categorized yachts in different ranges as 20-50 m, 50-100 m, and >100 m in length. It helps to accurately predict the L/B & B/T ratio. Model 1 (Table 2) was designed to predict breadth, draught, and GT from yacht length or the L/B, B/T ratio. Whereas model 2 (Table 3) was designed to predict breadth, draught, velocity, power, and GT from yacht length. The findings of this paper can be used for all sizes of yachts, as data from all sizes of yachts were used in this paper. All types of trendlines and interpolation have been used in the paper, and only equations with higher R^2 values were accepted.

Table 2. Model 1 coefficient of determination values

Equations	R^2
$B = 0.029L + 1.369$	0.9546
$T = -0.0069B^2 + 0.4238B - 0.5213$	0.8876
$T = 0.029L + 1.369$	0.8724
$GT = 0.1687*(L*B*T)^{1.1362}$	0.9725

The regression models showed that yacht dimensions were strongly interrelated. The beam grows nearly linearly with length: both Model 1 and Model 2 yielded linear fits (e.g., $B = 0.029L + 1.369$, $B = 3.642677426+ 0.122562498L$) with $R^2 \approx 0.92$–0.95. This implied a relatively uniform length-to-beam ratio across the sample, reflecting that larger yachts were generally slender (typical L/B ratios are on the order of 8–10). The draft depended nonlinearly on beam: a quadratic fit, $T = -0.0069B^2 + 0.4238B - 0.5213$ ($R^2 \approx 0.89$) captured the variation well. This quadratic form makes sense because hull volume (and thus draft) scales roughly with cross-sectional area.

Gross tonnage (GT) was also well-predicted by geometry: using the volume-based power law, $GT = 0.1687*(L*B*T)^{1.1362}$ gave $R^2 \approx 0.97$, indicating that

GT is essentially proportional to displaced volume for our yachts. A multiple linear regression in L, B, and T also achieved R^2 ≈0.86–0.97. These high R^2 values agree with the expectation that superyacht GT is primarily a function of hull volume and shape.

Table 3. Model 1 coefficient of determination values

Equations	R^2
B = 3.64 + 0.12*L	0.9205
T = 1.07 + 0.02*L + 0.08*B	0.8229
V = 19.83 + 0.05*L – 0.04*B – 2.11*T	0.1182
P = -1429.88+9.46*L+277.28*B-474.82*T+80.80*V	0.5839
GT = -4246.96 + 60.05*L + 279.46*B – 205.01*	0.8628

By contrast, predictions for speed and power were less accurate. In Model 2, the cruise speed regression (V vs. L, B, T) had a very low R^2 (~0.12), meaning that length, beam, and draft alone do not strongly determine yacht speed in our dataset. This reflects reality: yachts of the same size can have widely different design speeds depending on engine choice and intended use. Similarly, the power regression (P vs. L, B, T, V) yielded R^2 ≈ 0.58. This moderate fit suggests that factors beyond hull dimensions—such as propulsion efficiency, hull roughness, and load conditions—contribute significantly to required power. In other words, while larger yachts need more power on average, there is considerable scatter. Designers should therefore use the speed and power estimates as rough guides; detailed resistance calculations would be needed for final specifications.

Overall, the models were most reliable for estimating geometric dimensions and volume (beam, draft, tonnage) and less so for performance (speed, power). This hierarchy of accuracy was expected: the relationships between L, B, and T were constrained by geometry and stability requirements, whereas V and P also depend on non-dimensional coefficients and operating conditions. The strength of the regression fitted for B and T (R^2≥0.87) means that, given a length, a designer can predict beam and draft with confidence.

These findings provide actionable insight. In early design, one can use the equations to quickly size a hull: assume an LOA, compute B and T, then check that the implied L/B and B/T ratios fall within acceptable ranges (e.g., typical yachts have L/B around 8–11 and B/T around 3–4). The GT estimate (from volume) indicates the interior volume and regulatory tonnage, useful for cost and classification considerations. If a particular speed or power is required, one could use the inverse form of our equations to adjust the other variables, though such tuning should be validated by further analysis.

This research paper considered length, breadth, draught, velocity, power, and gross tonnage. But net tonnage and displacement were not considered. In the future, equations for these two parameters can be found. There are 2 models in this paper. More models can be found using more yacht data in the future.

Conclusion

The research was able to create and test an empirical-based, regression-oriented methodology framework for the quick preliminary determination of motor yacht base dimensions and the main performance indicators. With the help of a filtered set of 122 contemporary yachts, two unique predictive models were developed: Model 1, using accumulated ratios and trendline analysis, and Model 2, a stepwise model of multiple regression that only needs Length Overall (LOA) as an input.

The analysis established the predictability of geometric parameters: breadth (B), draught (T), and gross tonnage (GT) with high statistical accuracy based on length, which is indicated by R^2 values that are always greater than 0.87 and even near 0.97 when predicting the gross tonnage (GT) in Model 1. These high correlations are demonstrations of the underlying geometric and volumetric principles of the modern yacht design. Moreover, the research developed useful bands of critical hull form ratios (L/B and B/T) in various size groups (20-50 m, 50-100m, and over 100m), which is an important guide in the early assumptions of hull form.

Predictions of parameters of performance, speed (V), and power (P), in contrast, exhibited substantially less statistical fidelity (R^2 of 0.12 and 0.58, respectively). The outcome highlights the increased complexity and contributing variables to these metrics, such as hull form efficiency, propulsion technology, and operational profile, that are not completely represented in principal dimensions only.

One weakness of this study is that it dwells on the major dimensions and GT, with the omission of other significant parameters like displacement and net tonnage. Future studies need to consider these variables and increase the number of variables in order to improve the robustness of the models. Also, it might be better to investigate non-linear regression algorithms or machine learning algorithms to enhance the performance parameter prediction. Finally, the models suggested in this paper will provide a consistent empirical base for the preliminary sizing of contemporary motor yachts to balance the needs of the owner and the comprehensive design of the naval architect.

Data Availability Statement

The raw yacht data were obtained from the publicly accessible SuperYacht Times website (https://www.superyachttimes.com/). The authors processed and organized the data for analysis. The processed dataset is available from the corresponding author upon reasonable request.

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ANALYSIS OF PROCESS TIME AND COPPER SLAG REQUIREMENTS IN THE SHIP HULL BLASTING PROCESS

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ABSTRACT

The blasting process in the shipping industry aims to clean the surface of the plate from dirt, rust, and mill scale, and provide surface roughness so that the paint layer can adhere well. In the blasting process, abrasive materials are often used once or twice, but in field practice, reused copper slag has been used as an abrasive material. This study aims to analyze the weight of abrasive material requirements and process time during the blasting process using the Analysis of Variance (ANOVA) method with variations in new copper slag use, reused copper slag 1 and 2 as abrasive materials reaching the standard cleanliness level of SA 2.5 and the surface roughness level according to the International Maritime Organization (IMO) Performance Standard for Protective Coatings (PSPC) 30 – 75 mikron and the International Organization for Standardization (ISO) 8501-1. The results of this study indicate that fresh copper slag and reused copper slag-1 exhibit lower effectiveness in the blasting process; both types of copper slag require a longer time to reach the SA 2.5 cleanliness standard, resulting in increased abrasive material requirements. On the other hand, reused copper slag-2 exhibits better performance with shorter blasting time and minimal abrasive material requirements in accordance with the ISO 8501-1 SA 2.5 cleanliness level.

Keywords: ANOVA, blasting, copper slag, ISO 8501-1, process time

Introduction

The shipbuilding industry encompasses two main aspects: new shipbuilding and repairs, which require the removal of surface dirt and rust from steel plates to allow for subsequent painting. Therefore, blasting is necessary. The blasting method produces optimal surface cleanliness with a relatively high productivity rate of approximately 7 to 8 square meters per hour. This blasting technique is applied to remove rust caused by oxidation, caused by the interaction between seawater and air, remove mill scale from new plates, and create surface roughness to improve adhesion between the material and the coating during painting. The advantages of the blasting process lie in its speed and flexibility in adapting to the complex curves of the workpiece during the forming process. Factors that influence the results of blasting include the human element, the air pressure used for firing, the abrasive material used, the firing time, and the firing distance.

Blasting is divided into two categories, namely dry blasting and wet blasting. Dry blasting is generally applied to metal materials that are not at risk of burning, for example, for corrosion removal or paint removal. On the other hand, wet blasting is applied to metals that are at risk of burning or that are in areas with the potential for fire, for example, in fuel tanks, offshore oil refineries, and fuel stations. In the wet blasting method, the sand used for spraying is mixed with special chemicals that have anti-rust properties, aiming to reduce sparks when the sand comes into contact with the metal during the blasting process [1]. The success of the coating process is highly dependent on the surface preparation stage, which influences the bond strength of the material [2]. One common surface preparation method used in industry is blasting. This method involves cleaning a surface by spraying an abrasive material onto the surface at high pressure, creating friction or impact. The surface is then cleaned and roughened. Selecting and using the right abrasive material will improve paint adhesion [3,4]. Paint functions as a coating with three main functions: decoration, increasing adhesion, and protecting the object's surface from corrosive environments. The basic components of paint are four elements: binder, pigment, solvent or thinner, and additives [5]. Based on [6] Indonesian Classification Bureau (BKI) regulations in vol G "Guidance for Coating performance Standards" section 3 sub-chapter coating inspection agreement which refers that the cleanliness standards and surface roughness level for ship hull plates follow the IMO PSPC (Performance Standard for Protective Coatings) ANNEX 1 standard in paragraph 2 that the surface cleanliness level must reach the ISO 8501-1 SA 2.5 standard and the surface roughness level achieved is between 30 μm to 75 μm [7].

In general, blasting uses silica sand as an abrasive material. However, over time, the use of silica sand has shifted to other abrasive materials. This is because silica sand contains heavy metal elements exceeding the quality standards based on PP No. 101 of 2014, so it is classified as a hazardous and toxic material (B3). Fly ash from silica sand is categorized as toxic and hazardous waste by the Environmental Impact Management Agency (Bapedal) [8]. Blasting can be a dangerous process because it can produce airborne particles that are harmful if inhaled, and can also produce significant amounts of dust and debris. Proper safety precautions, including the use of protective clothing, respiratory protection, and control measures, are essential when performing blasting operations [9].

Blasting processes carried out outdoors will produce dust pollution in the atmosphere, which is very risky for the ecosystem, especially related to the health of workers in the surrounding area. The dust particles created will be dispersed in the air according to the direction of the wind until they reach areas outside the port and shipyard. The most dangerous particles, with a size of less than 2.5 μm, can trigger respiratory tract diseases such as coughs, colds, and sore throats, as well as disrupt lung function, which can increase the risk of heart disease. Based on Government Regulation of the Republic of Indonesia No. 22 of 2021 concerning the Implementation of Environmental Protection and Management and Regulation of the Minister of Environment and Forestry of the Republic of Indonesia No. 14 of 2020 concerning the Air Pollution Standard Index for Ambient Air Quality Standard Values that have been established, the port and shipyard industry must pay attention to the extent of the spread of dust particles in the air due to sandblasting activities which have the potential to harm the environment, especially for workers in the port and shipyard areas and the surrounding environment [10]. Continuous exposure to fly ash from silica sand can cause silicosis in human lungs [11]. In 1983, Shaman estimated that over one million US workers were at risk of developing silicosis and that over 100,000 of these workers were sandblasters. Because of its potential health hazards, NIOSH has recommended that silica sand (or substances containing more than 1% crystalline silica) be banned from blasting abrasives and that less hazardous materials be used as substitutes. As part of this recommendation, NIOSH identified metallurgical slag abrasives, such as copper slag, as acceptable substitutes for silica sand. Although NIOSH reports that metallurgical slag is used in only 3.1 percent of facilities performing abrasive blasting, its increasing use has been recognized in other literature [12]. Therefore, alternatives to silica sand as an abrasive are needed, one of which is copper slag. Much research has been conducted to determine the properties of copper slag in blasting operations. This material offers fast cleaning applications and saves material because the product can be reused several times. Copper slag is one of the most sought-after blasting materials in Europe and was first introduced in 1960. Since then, copper slag has been widely used to remove rust, old paint layers, and contaminated layers on metal, stone, concrete, and brick surfaces, especially in the metal, automotive, shipbuilding, and petrochemical industries.

Copper slag has been used in the shipping industry as an abrasive material in the blasting process on the surface of ship hull material. Its physical and chemical properties recommend this material as one of the most effective explosives, which can be used on almost all types of surfaces, both indoors and outdoors. Copper slag is an ecological and non-toxic product (free silica content < 0.1%) [13] which sets the technical specifications for copper slag as a safe and effective non-metallic abrasive medium and [14] which ensures that copper slag has been tested and passed international standard test methods regarding quality, chemical composition, hardness, and safety of its use in the blasting process. Copper slag is a popular choice for abrasive blasting due to its fast-cutting speed and low dust content. When compared to coal slag, copper slag has a higher density (around 20%) and can be recycled many times.

This makes copper slag a more cost-effective option, as it results in faster blasting and reduced product consumption [15]. To determine the efficiency of copper slag as a blasting material, which includes the area cleaned per hour, and the consumption of abrasive to clean the reference surface [16,17]. It stated that the use of abrasive materials is only for one-time use, which means that the residue from the first use will be discarded [18]. This used abrasive material has several options for reuse, including being reused as abrasive material for blasting processes, building materials, road construction materials, and being processed into non-hazardous waste. University of New Orleans, Department of Civil and Environmental Engineering. It is considered that copper slag is a very efficient blasting material, with excellent properties for cleaning and blasting various types of surfaces. Because it is an ecological product, copper slag can be successfully used in open-air blasting, with minimal impact on the environment. The possibility of material reuse allows material savings.

Methodology

a. Flow Chart

This study aims to analyze the blasting process time and weight of copper slag requirements on ship hull plates with variations of new copper slag and reused copper slag 1 and 2. This methodology is systematically illustrated in a flow chart (Figure 1) and begins with basic steps before proceeding to the preparation, testing, and analysis phases.

In the literature study stage, a theoretical basis or literature review is carried out by searching for references or sources of information to help complete this research. The literature review was taken from books, the internet, journals, and from the supervising lecturers. A survey was conducted regarding the parameters used as research objects. Such as a survey of the blasting process location, abrasive materials, etc. In the problem identification stage, many things need to be considered in order to achieve useful and refined research results [19]. Then, the preparation of test specimens was carried out, especially carbon steel samples with dimensions of 50 cm long x 50 cm wide and 8 mm thick. Next, the blasting process was carried out using new copper slag material and reused copper slag 1 and 2 to clean and prepare the specimens [20].

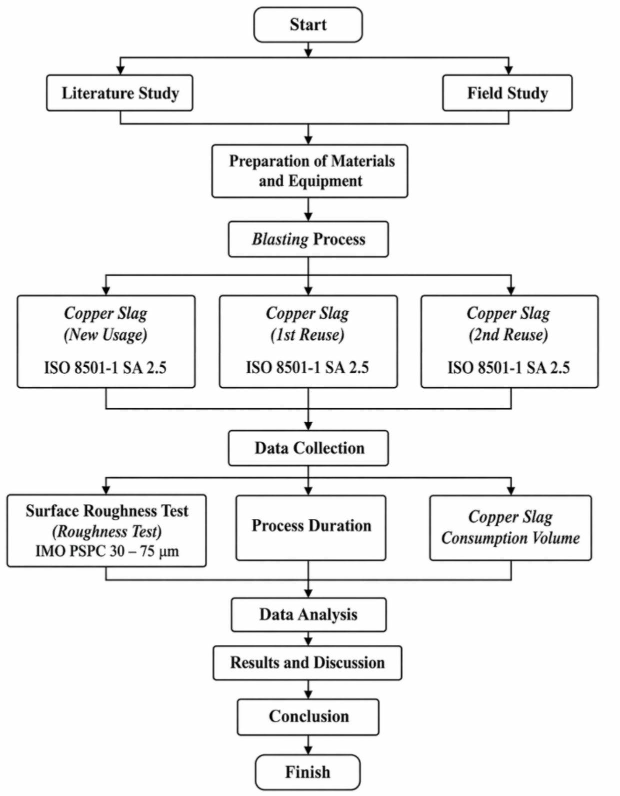

Figure 1. Flowchart

Before the blasting process was carried out, the area humidity was calculated using an Elcometer for 2 minutes. Next, the sand tank was filled with copper slag. The abrasive material that enters must be a maximum of 80% of the sandbox volume so that the abrasive material does not spill during the blasting process, before the abrasive material is put into the sandbox, the initial weight (input) is weighed and after the blasting process, the weight (output) of the remaining abrasive material in the sandpot is weighed again to determine the weight needed for the blasting process. The blasting process is carried out to calculate the blasting process time using a stopwatch to determine the time needed to achieve the cleanliness level according to the ISO 8501-1 SA 2.5 standard. Repeat the blasting process on other specimens with reused copper slag 1 and 2. Visual inspection is carried out to comply with the ISO 8501-1 SA 2.5

standard. After the data on the process time and the weight of the requirements are obtained, the results of the data are analyzed using Analysis of Variance (ANOVA) to determine the significance of copper slag variations on the blasting process time and the weight of the copper slag requirements.

b. Test Materials and Equipment

1) Test Materials
   - ASTM A36 Carbon Steel
   - Abrasive materials, new copper slag, and reused copper slag 1 and 2
2) Test Equipment
   - Compressor
   - Hose
   - Nozzle
   - Sandpot
   - Elcometer 319
   - Digital Scale
   - Stopwatch

c. Research Procedure

1) The steel material that is the main material of the research object is ASTM A36 steel with dimensions of 500 mm long x 500 mm wide x 8 mm thick. The abrasive material used is copper slag. The variation of this research lies in the abrasive material, with a comparison between the new abrasive material, reused abrasive material 1, and reused abrasive material 2. The material shown in Figure 2 illustrates one of the specimens that will be used during the blasting process.

Figure 2. One example of a specimen before the blasting process

2) Before the blasting process is carried out, the temperature of wet and dry air is measured using an electrometer for 2 minutes. The difference between the wet and dry air temperatures is entered into the Dew Point (DP) and Relative Humidity (RH) to obtain the Dew Point (DP) and Relative Humidity (RH) values. Environmental conditions are ensured so that the relative humidity is below 85% and the substrate temperature is 3°C greater than the dew point. Figure 3 presents a visual depiction of the process of measuring the humidity of the area temperature.

Figure 3. The process of measuring the temperature and humidity of the area

3) The sandbox is filled with new copper slag abrasive material. The abrasive material entering here must be a maximum capacity of 80% of the sandbox volume to prevent the abrasive material from spilling during the process. Before the abrasive material is put into the sandbox, the initial weight (input) is weighed, and after the blasting process, the weight (output) of the remaining abrasive material in the sandpot is weighed again to determine the weight required for the blasting process. Figure 4 shows the process of putting copper slag into the sandpot.

Figure 4. Put copper slag into the sandpot

4) The blasting process was carried out, and the process time was calculated using a stopwatch to determine the time required to achieve surface cleanliness of SA 2.5 according to the ISO 8501-1 standard. The used material from the first blasting was collected in a container and sieved, but this shipyard had already gone through the process, so that the used abrasive material was ready stock in the workshop. Repeat the blasting process on other specimens with reused abrasive material 1 and continue with reused abrasive material 2. Figure 5 shows a visual of the plate after the blasting process.

Figure 5. One of the specimens after the blasting process

d. Research Work

1) Weighing copper slag requirements

Weighing abrasive material requirements is carried out using a digital scale to obtain accurate consumption data. Before the blasting process begins, the initial weight of the abrasive is measured when the material is loaded into the sandpot and recorded as the input weight. After the blasting process is complete, the remaining abrasive in the sandpot is weighed again using the same digital scale. The difference between the initial and residual weights is then calculated as the abrasive requirement weight during the blasting process (see the weighing process in Figure 6.

Figure 6. Process of weighing the weight of copper slag requirements

2) Calculating the Blasting Process Time
At this stage, data is collected to measure the blasting process time until it reaches a cleanliness level of SA 2.5 through direct observation using a stopwatch on a mobile phone. Before the measurement begins, the operating parameters are ensured to be in accordance with standards, including working pressure, abrasive type, and initial surface condition. The stopwatch is reset, and the time is recorded from the time the operator begins blasting. Figure 7 illustrates the process of calculating the time during the blasting process.

Figure 7. Process of taking data on the blasting process time towards SA 2.5

3) Visual inspection of cleanliness level SA 2.5
   After the blasting process, a visual inspection of the blasting results is performed by comparing them to the ISO standard: 8501-1 1988 "Preparation of Steel Substrates Before Application of Paints and Related Products – Visual Assessment of Surface Cleanliness. The desired cleanliness level, SA 2.5 (very thorough blast cleaning), is shown in Figure 8.

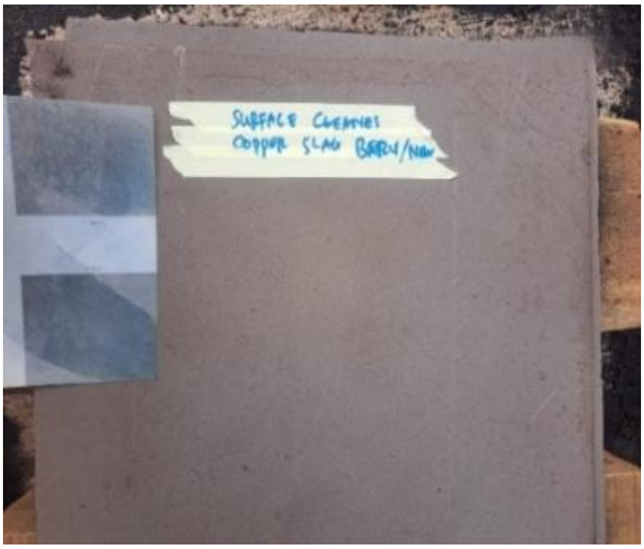

Figure 8. Cleanliness level inspection process according to ISO 8501-1 SA 2.5 standard

4) Data Collection
   At this stage, data was collected directly from the blasting process results, including the time required to reach the SA 2.5 cleanliness standard using a stopwatch and the weight of copper slag required in the blasting process to reach the SA 2.5 cleanliness standard, with variations of new copper slag, reused copper slag -1, and 2.

5) Data Analysis Using ANOVA
   This study used Analysis of Variance (ANOVA). This technique is used to determine whether there are significant differences between the means of three or more groups based on one independent variable. Before conducting both studies, the data underwent a normality test. Data analysis used IBM SPSS 27 statistical software.

Result and Discussion

a. Results of the blasting process time

The recorded time reflects the optimal pressure, abrasive type, and operator technique in achieving that level of cleanliness. Consistent duration indicates the process is operating within stable operating parameters, while too short or too long a time can indicate inappropriate operating conditions [21]. Thus, blasting time serves as an indicator of process performance and compliance with applicable surface cleanliness standards. Using fresh copper slag and reused copper slag 1 and 2 in the blasting process, the surface processing time data is obtained in Table 1.

Table 1. Blasting process time data results

Sample	Time for Area 0.25 m^2 (min)	Time for Area 1 m^2 (min)
Copper slag new use I	1,18	4,72
Copper slag new use II	1,20	4,80
Copper slag new use III	1,19	4,76
Average	1,19	4,76
Copper slag reuse– 1 I	1,04	4,16
Copper slag reuse– 1 II	1,00	4,00
Copper slag reuse– 1 III	1,01	4,04
Average	1,01	4,07
Copper slag reuse– 2 I	0,42	1,68
Copper slag reuse– 2 II	0,49	1,96
Copper slag reuse– 2 III	0,44	1,76
Average	0,45	1,80

Based on Table 1, specimens with new copper slag variations have an average blasting process time value towards SA 2.5 for an area of 0.25 m^2 of 1.19 min and for an area of 1 m^2 of 4.76 min, specimens with reuse copper slag variations-1 have an average blasting process time value towards SA 2.5 for an area of 0.25 m^2 of 1.01 min and for an area of 1 m^2 of 4.07 min, specimens with reuse copper slag variations-2 have an average blasting process time value towards SA 2.5 for an area of 0.25 m^2 of 0.45 s and for an area of 1 m^2 of 1.80 min.

Table 2. Results of data on the weight of copper slag required

Sample	Weight Required for an Area of 0.25 m^2 (kg)	Weight Required for an Area of 1 m^2 (kg)
Copper slag new use I	4,80	19,20
Copper slag new use II	4,65	18,60
Copper slag new use III	4,50	18,00
Average	4,65	18,60
Copper slag reuse– 1 I	4,30	17,20
Copper slag reuse– 1 II	4,15	16,60
Copper slag reuse– 1 III	4,10	16,40
Average	4,18	16,73
Copper slag reuse– 2 I	3,35	13,40
Copper slag reuse– 2 II	3,45	13,80
Copper slag reuse– 2 III	3,15	13,60
Average	3,31	13,27

b. Weight results of copper slag requirements

The results of the weight of the abrasive material required in the blasting process towards SA 2.5 indicate the level of efficiency of abrasive material use during surface cleaning. The weight of the abrasive material used indicates how effective the particles are in removing rust, mill scale, and old coatings to achieve the ISO 8501-1 visual standard. Low abrasive material consumption can indicate particle effectiveness and stable operating parameters, while high consumption can indicate a heavy initial surface condition, insufficient pressure, or poor surface finish. optimal, or decreased abrasive quality. The data on the weight of requirements obtained is presented in Table 2.

Based on Table 2, specimens with new copper slag variations have an average value of the weight of the blasting process requirements towards SA 2.5 for an area of 0.25 m^2 of 4.65 kg and for an area of 1 m^2 of 18.60 kg, specimens with reused copper slag variations-1 have an average value of the weight of the blasting process requirements towards SA 2.5 for an area of 0.25 m^2 of 4.18 kg and for an area of 1 m^2 of 16.73 kg, while specimens with reused copper slag variations-2 have an average value of the weight of the blasting process requirements towards SA 2.5 for an area of 0.25 m^2 of 3.31 kg and for an area of 1 m^2 of 13.27 kg.

Table 3. Results of the normality test for blasting process time

Test of Normality						
Types of Copper Slag	Kolmogorov-Smirnov			Shapiro-Wilk		
	Stat.	df	Sig.	Stat.	df	Sig.
Copper Slag New Use	0.175	3		1.000	3	1.00
Copper Slag Reuse–1	0.292	3		0.923	3	0.46
Copper Slag Reuse–2	0.276	3		0.944	3	0.53

c. Results of the analysis of the blasting process time

Statistical analysis was performed to determine the significance of the effect of variations in new copper slag and reused copper slag grades 1 and 2 on blasting process time. Normality and homogeneity tests were performed as a preliminary evaluation to select the appropriate statistical method. The results of the normality test are presented in Table 3, while the results of the homogeneity test are shown in Table 4.

When the data met the assumptions of normality and homogeneity, Analysis of Variance (ANOVA) was used to analyze differences between groups. The ANOVA results for the blasting process time data are shown in Table 5. The ANOVA results indicate that copper slag variation has a statistically significant effect on blasting process time.

Table 4. Results of the homogeneity test of the blasting process time

Tests of Homogeneity of Variances				
	Levene Statistic	**df1**	**df2**	**Sig.**
Based on Mean	2.681	2	6	0.147
Based on Median	0.704	2	6	0.531
Based on Median and with adjusted df	0.704	2	3.547	0.533
Based on the trimmed mean	2.477	2	6	0.164

Table 5. ANOVA Results for Blasting Process Time

ANOVA					
	Sum of Squares	**df**	**Mean Square**	**F**	**Sig.**
Between Groups	14.38	2	7.19	735.3	0.0
Within Groups	0.05	6	0.001		
Total	14.43	8			

In addition, the results of the post hoc test used after the ANOVA for the bending test are presented in Table 6, which shows which specific groups showed significant differences.

Table 6. Results of the post hoc test of the blasting process time

Post hoc			
Tukey HSDa			
Nilai Kekasaran	**N**	**Subset for alpha = 0.05**	
		1	**2**
Copper Slag Reuse– 2	3	1.8000	
Copper Slag Reuse– 1	3	4.0667	4.0667
Copper Slag New Use	3		4.7600
Sig.		1.000	0.070

Overall, this analysis confirms that the variation of new copper slag and reused copper slag 1 and 2 is an important parameter affecting the blasting process time. Optimal blasting process time was achieved with reused copper slag-1, while a higher blasting process time was observed with new copper slag. Therefore, selecting the right copper slag variation is crucial to balance the blasting process time duration [22]. The blasting process time results are graphically depicted in Figure 9.

d. Results of the analysis of the weight of copper slag requirements

Statistical analysis was conducted to identify the significant influence of variations in the use of new copper slag and the reuse of copper slag 1 and 2 on the weight of copper slag requirements. Normality and homogeneity tests were conducted as initial steps to determine the appropriate statistical method. The results of the normality test can be seen in Table 7, while the results of the homogeneity test are shown in Table 8.

Table 7. Results of the normality test for the weight of copper slag requirements

Test of Normality						
Types of Copper Slag	**Kolmogorov-Smirnov**			**Shapiro-Wilk**		
	Stat.	**df**	**Sig.**	**Stat.**	**df**	**Sig.**
Copper Slag New Use	0.175	3		1.000	3	1.00
Copper Slag Reuse–1	0.292	3		0.923	3	0.46
Copper Slag Reuse–2	0.276	3		0.944	3	0.53

Table 8. Results of the homogeneity test for the weight of copper slag requirements

Tests of Homogeneity of Variances				
	Levene Statistic	**df1**	**df2**	**Sig.**

Based on Mean	0.184	2	6	0.836
Based on Median	0.143	2	6	0.870
Based on Median and with adjusted df	0.143	2	5.723	0.870
Based on the trimmed mean	0.181	2	6	0.839

When the data met the normality and homogeneity test criteria, Analysis of Variance (ANOVA) was applied to evaluate differences between groups. Table 9 presents the results of the ANOVA test for the copper slag weight requirement data. The ANOVA analysis results indicate that variations in copper slag have a statistically significant impact on the copper slag weight requirement.

Table 9. Results of the ANOVA test on the weight of copper slag requirements

ANOVA					
	Sum of Squares	**df**	**Mean Square**	**F**	**Sig.**
Between Groups	43.947	2	21.973	72.70	0.0
Within Groups	1.813	6	0.302		
Total	45.760	8			

Additionally, the results of the post hoc test used after the ANOVA for the bending test are presented in Table 10, which shows which specific groups showed significant differences.

Table 10. Results of the post hoc test for copper slag weight requirements

Post hoc			
Tukey HSDa			
Nilai Kekasaran	**N**	**Subset for alpha = 0.05**	
		1	**2**
Copper Slag Reuse– 2	3	13.2667	
Copper Slag Reuse– 1	3	16.7333	16.733
Copper Slag New Use	3		18.600
Sig.		1.000	0.070

Overall, this study indicates that the variation of innovative copper slag usage and reuse 1 and 2 are important elements that influence the copper slag weight requirement. The most optimal copper slag weight requirement is achieved by the application of reuse-1 copper slag, while a higher copper slag weight requirement is observed with the new copper slag. Therefore, selecting the right copper slag type is crucial to achieve a balance in copper slag weight requirement [23]. The results of the copper slag weight requirement are presented graphically in Figure 10.

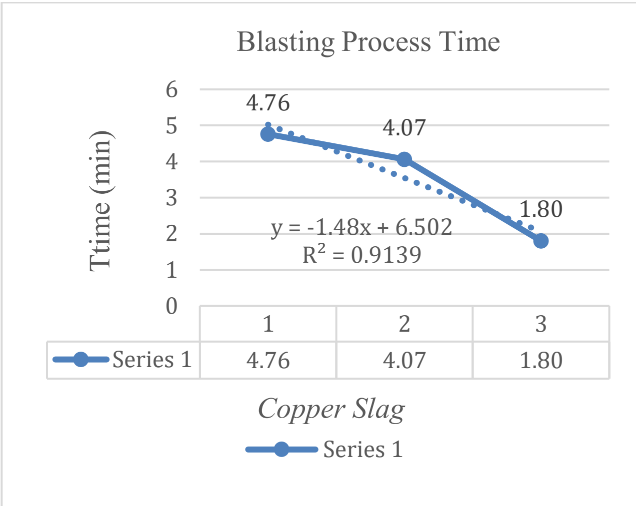

Figure 9. Graph of the blasting process time function

Based on Figure 9, the duration function graph can be explained as follows: the variables entered are copper slag (X) and the duration of the process time (Y). It is known that the new copper slag has a blasting process time of 4.76 minutes, the reused copper slag-1 has a process time of 4.07 minutes, the reused copper slag-2 has a process time of 1.80 minutes, and the results of the weight analysis of the requirements will also be depicted graphically in Figure 10.

Figure 10 shows the weight function graph, which explains that the variables entered are copper slag (X) and the duration of the process time (Y). It is known that the new copper slag yields the weight of the abrasive material required for an area of 1 m^2 of 18.6 kg, the reused copper slag-1 yields the weight of the abrasive material required for an area of 1 m^2 of 16.73 kg and the reused copper slag-2 yields the weight of the abrasive material required for an area of 1 m^2 of 13.27 kg.

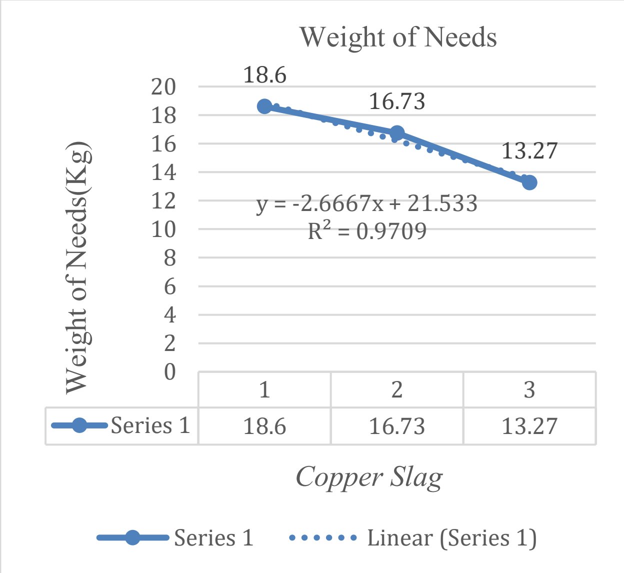

Figure 10. Graph of the weight function of copper slag requirements

Conclusion

Based on the results of research on blasting methods using variations of new copper slag, first and second reuse copper slag, it can be concluded that in the variable equation (X), namely, new copper slag and reuse copper slag-1. Blasting process time and weight requirements are variables (Y). It can be concluded that the use of new copper slag and reused copper slag-1 requires a longer blasting time, this is because the new copper slag particles still have hardness and are difficult to break. This long duration results in an increase in the weight of the abrasive material requirement, because the longer the erosion process takes place, the more abrasive volume is required.

Meanwhile, in the second reuse, copper slag with variables (X) and blasting process time, the surface roughness of the plate and the required weight are variables (Y). Although this copper slag is a second use, the copper slag for this second reuse has a more optimal blasting process time, which shows that this second-use copper slag has sharper particle characteristics when compared to the new-use copper slag. This is caused by the fragments from the previous use of copper slag and is able to clean the surface effectively without requiring excessive impact energy. This time efficiency has a direct impact on reducing the use of less abrasive material, so that the blasting process becomes more economical without reducing the quality of the cleanliness level.

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STRENGTHENING CYBER SECURITY IN PORT FACILITIES: NEW THREATS AND MITIGATION STRATEGIES

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ABSTRACT

The development of digital technology and automation in port facilities increases the risk of cyberattacks that can disrupt logistics operations and maritime security. According to a recent report, 72% of port facilities in Indonesia have experienced attempted cyberattacks in the past three years, with potential losses reaching USD 5.2 million per incident. This study aims to analyze cyberthreats in port facilities and evaluate mitigation strategies. The research method used was descriptive quantitative, with data collected through a survey of 120 port security officers, interviews with 15 operational managers, and an analysis of 10 related cybersecurity policy documents. The results showed that 68% of facilities had a moderate to low level of cybersecurity readiness, 74% of respondents emphasized the importance of human resource training, and 63% of facilities had not implemented a real-time intrusion detection system. Recommended mitigation strategies include the implementation of comprehensive network security protocols, multi-layered digital surveillance, and regular training programs for all personnel. These findings emphasize the urgency of integrating cybersecurity policies with daily port operations to reduce the risk of disruption, improve operational reliability, and minimize economic losses.

Keywords: Threats, port facilities, cyber security, mitigation, strategy

Introduction

Ports are critical infrastructure in the international logistics and trade chain, playing a vital role in supporting economic growth and national security. With the increasing automation and digitalization of port operations, including terminal management systems, ship navigation, and security surveillance, new threats have emerged in the form of cyberattacks that can disrupt smooth operations and cause significant economic losses. Recent data shows that 72% of port facilities in Indonesia have experienced attempted cyberattacks in the past three years, with potential losses reaching USD 5.2 million per incident. These threats not only target information systems but can also affect physical equipment such as cranes, automated guided vehicles (AGVs), and ship control systems, posing complex operational risks.

Several previous studies have highlighted the importance of cybersecurity in the maritime sector. For example, Raymaker et al. (2025) emphasized the need for real-time threat detection systems in ship networks, while Rath et al. (2023) demonstrated rootkit vulnerabilities in ship microgrid systems that could lead to critical operational disruptions. A local study by Sahrudin (2023) identified gaps in human resource capabilities and port infrastructure readiness in Indonesia, with 68% of facilities having moderate to low levels of cybersecurity readiness. This study aims to address these gaps by combining current cyberthreat analysis, port facility readiness assessment, and mitigation strategies that can be practically implemented by port management.

The novelty of this research lies in its holistic approach, integrating a survey of port security officers, interviews with operational managers, and an analysis of existing cybersecurity policies. Furthermore, this research emphasizes empirical data-based risk assessment, including facility readiness levels and human resource awareness, thus providing a concrete picture of threats and mitigation strategies tailored to local conditions. The primary objective of this research is to identify key cyberthreats at port facilities, evaluate operational readiness for such attacks, and formulate effective countermeasures. Therefore, this research is expected to provide not only an academic contribution in the form of an understanding of cyber risks in the maritime sector but also practical guidance for port decision-makers in strengthening digital defenses and operational security.

The literature review indicates that cyberattacks in the maritime sector are multidimensional, encompassing technical, human, and policy aspects. The technical aspects include vulnerabilities in network systems, software, and automated equipment, while the human aspects relate to human resource awareness and compliance with security protocols. Policies and regulations, both national and international, serve as a framework that guides the implementation of cybersecurity in port facilities, such as the International Maritime Organization (IMO) directive on *Maritime Cyber Risk* and the Directorate General of Sea Transportation Circular Letter No. 16 of 2024 on cybersecurity procedures. The integration of these three aspects forms the foundation for designing a comprehensive mitigation strategy, encompassing real-time monitoring, routine training, and periodic security system updates. By combining empirical data and a literature review, this research strengthens the academic and practical position in the context of maritime cybersecurity. It emphasizes the urgency of proactive action in addressing increasingly complex cyber threats and makes a tangible contribution to the development of port operational policies and procedures in Indonesia. This holistic approach is a key strength of the research, as it not only assesses risks but also offers immediately applicable mitigation strategies, thereby strengthening the resilience of critical maritime infrastructure and ensuring operational continuity.

Methodology

a. Research Object

The research objects in this study include three main components (Figure 1), which are the focus of the study:

Port Facilities

The research focuses on container terminals, international docks, and loading and unloading facilities in several large ports in Indonesia that have implemented automation systems (e.g., automated cranes and automated guided vehicles) and operational digitalization (e.g., Terminal Operating System and Port Community System).

The selection of this object is based on the high dependence of ports on information and communication technology (ICT), which simultaneously increases the risk of cyber attacks.

Human Resources (HR)

The primary respondents included 120 port security officers directly involved in digital security implementation, as well as 15 port operational managers involved in strategic decision-making related to cyber risk management.

Human resources are an important asset because personnel awareness and competence have been proven to influence the level of vulnerability and resilience of cybersecurity systems.

Cyber Security Policy Document

Documents analyzed include:

- National regulations, such as Circular Letter of the Directorate General of Sea Transportation (SE DJPL) No. 16 of 2024 concerning cybersecurity procedures.
- International regulations, in particular the IMO guidelines on Maritime Cyber Risk Management.
- Internal port documents, including digital security SOPs, internal audit reports, and emergency response protocols.

b. Research Procedures

This research uses a quantitative descriptive approach combined with qualitative analysis. The research stages are carried out systematically as follows:

Identifying Problems and Objectives

Identifying key issues in the form of increasing cyber threats at port facilities. Formulate research objectives, namely analyzing threats, evaluating port readiness, and formulating mitigation strategies.

Literature Study

Collecting secondary data from scientific journals, official reports, and national and international policies. The aim is to identify global cyber-attack trends in the maritime sector as well as mitigation strategies that have been adopted in various countries.

Preparation of Research Instruments

Develop a questionnaire with a Likert scale (1–5) to assess aspects of infrastructure readiness, HR awareness, and SOP effectiveness. Developing a semi-structured interview guide to explore the mitigation strategies implemented by operational managers. Create document analysis sheets to evaluate the conformity of internal SOPs with IMO standards and national regulations.

Data Collection

Quantitative Survey:

Respondents: 120 port security officers. Objective: to measure the level of readiness, awareness, and implementation of digital security policies.

Qualitative Interview:

Respondents: 15 operational managers. Objective: to gain practical experience in dealing with cyber incidents and challenges in the field.

Document Analysis:

Analyze regulations, IMO guidelines, and internal port SOPs to see the conformity between rules and implementation.

Data Analysis

Quantitative:

Survey data is processed using descriptive statistics (frequency, percentage, and distribution) to describe the condition of port readiness.

Qualitative:

Interview data was analyzed using thematic analysis methods to find patterns of problems, obstacles, and mitigation strategies.

Document Analysis:

Comparing the content of internal policies with national and international regulations to find gaps.

Synthesis and Validation of Results

The results from quantitative data, interviews, and document analysis are integrated to provide a comprehensive picture. Validation was carried out through data triangulation to ensure the reliability of the findings.

Formulation of Strategy and Recommendations

Develop recommendations based on evidence-based practice, covering aspects of technology, human resources, and policy. Recommendations are aimed at direct implementation by port managers to strengthen digital defense.

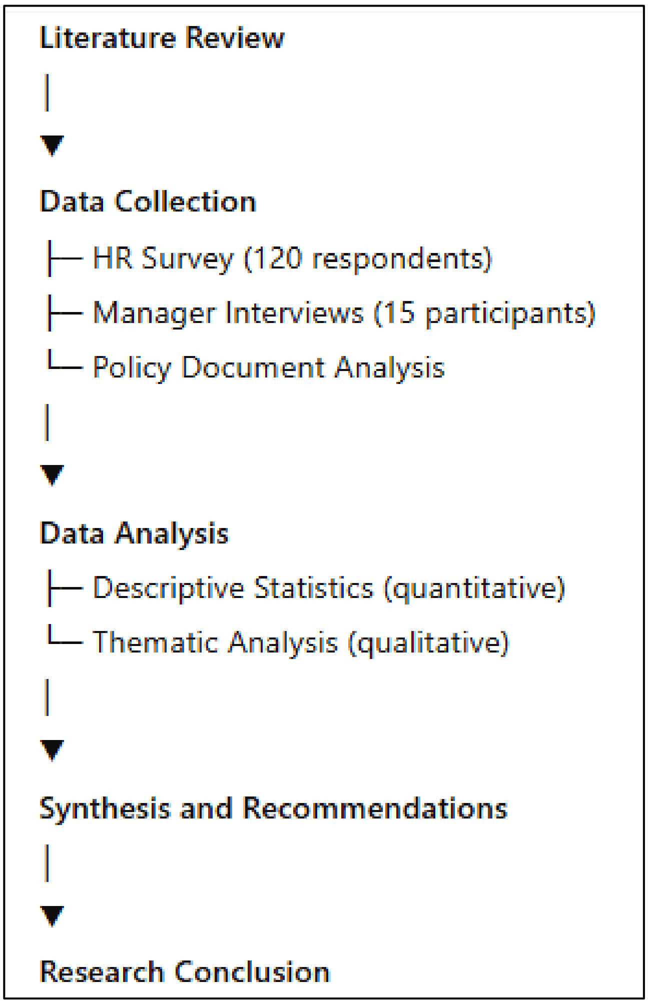

Figure 1. Methodology

Results and Discussion

The study revealed varying levels of preparedness (Table 1) among Indonesian port facilities for cyber threats, with the majority falling within the moderate to low category**.** Of the 120 port security officer respondents, 68% stated that the facilities they manage are not fully prepared for cyberattacks, 22% stated that they are moderately prepared, and only 10% considered their facilities optimally prepared. Key factors influencing this preparedness include limited real-time intrusion detection systems, inadequate maintenance of digital security devices, and inadequate training and awareness among human resources. Analysis of interviews with 15 operational managers revealed that most port facilities lack comprehensively integrated mitigation protocols. Only 37% of facilities implement multi-layered network monitoring, while 63% do not use real-time intrusion detection systems. Routine training for security personnel remains limited, with a frequency of less than once per year at 74% of facilities. Analysis of cybersecurity policy documents also revealed a gap between formal regulations and field practices.

Table 1. Level of readiness of facilities and human resources against cyber threats

Assessment Aspects	Very Ready (%)	Enough (%)	Less Ready (%)	Notes
Intrusion Detection System Readiness	10	22	68	63% of facilities do not yet use real-time detection
Layered Network Surveillance	37	26	37	Only some facilities implement layered monitoring.
HR Training and Awareness	16	10	74	Routine training less than once a year
Compliance of SOPs with Regulations	25	30	45	Many internal SOPs are not yet aligned

	with SE DJPL No. 16/2024

The development of digital technology and automation in port facilities offers numerous benefits, from operational efficiency to increased speed of logistics flows. However, this digital transformation also carries significant risks in the form of cyberattacks that have the potential to disrupt supply chains, maritime safety, and port operational reliability. Research shows that approximately 72% of port facilities in Indonesia have experienced attempted cyberattacks in the past three years, with estimated losses reaching USD 5.2 million per incident. This confirms that cyber threats are no longer a possibility but a real challenge that the maritime sector must face.

Analysis of port facility readiness levels shows that 68% of facilities are at a moderate to low level of readiness. This situation indicates a gap between the implementation of advanced technology and the facilities' ability to manage cyber risks. Key factors contributing to this low level of readiness include limited digital security infrastructure, the lack of real-time intrusion detection systems, and the lack of integration between cybersecurity policies and daily operational procedures.

From a human resources perspective, the study found that 74% of respondents emphasized the importance of human resource training in addressing cyber threats. This is consistent with global trends, where human error is a major contributing factor to cyber incidents. Lack of personnel awareness and competence can make it easier for attackers to exploit security gaps, such as unauthorized access to logistics management systems or disruption to terminal control systems. Furthermore, the study revealed that 63% of facilities have not implemented a real-time intrusion detection system, resulting in a slow response to cyberattacks. The lack of proactive monitoring allows attackers to stealthily penetrate systems, increasing the risk of operational disruption.

To address these challenges, the study recommends several key mitigation strategies:

1. Implementation of comprehensive network security protocols, including advanced firewalls, data encryption, and network segmentation to limit unauthorized access.
2. Layered digital surveillance, such as real-time intrusion detection systems (IDS/IPS),

automated log monitoring, and regular security audits to ensure system integrity.

3. Regular training programs for all personnel, including cybersecurity awareness, attack simulations, and emergency response procedures to enhance preparedness.

Overall, the research findings underscore the urgency of integrating cybersecurity policies into daily port operations. With a comprehensive approach—combining technology, procedures, and human resources—port facilities can reduce the risk of disruption, improve operational reliability, and minimize potential economic losses from cyberattacks.

Conclusion

1. The development of digital technology and automation in port facilities increases the risk of cyber attacks, which can disrupt logistics operations, maritime security, and cause significant economic losses.
2. The level of cybersecurity readiness of port facilities in Indonesia is still relatively low, with 68% of facilities at a moderate to low level, and most facilities have not implemented a real-time intrusion detection system.
3. Human resources are a key factor in cybersecurity, with 74% of respondents emphasizing the importance of regular training to improve personnel awareness and capabilities in dealing with cyber threats.
4. Effective mitigation strategies include implementing comprehensive network security protocols, layered digital surveillance, and regular training programs for all personnel.
5. Integrating cybersecurity policies into daily port operations is a critical step to reduce the risk of disruption, improve operational reliability, and minimize potential economic losses from cyberattacks.

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