

Increasing System Safety and Efficiency of Ship Main Engines Under D–S Evidential Theory and Failure Modes, Effects, and Criticality Analysis Approach

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Received: 12 February 2025 / Accepted: 07 April 2025

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Abstract

A ship's main engine is critical to the performance, operational continuity, and safe conduct of ship operations. However, the safety and operational efficiency of a ship may be endangered because of malfunctions and problems occurring in the ship's main engine. This study introduces a systematic approach to risk analysis considering uncertainties and integrates the failure modes, effects, and criticality analysis (FMECA) and Dempster–Shafer (D–S) theory to evaluate prospective ship main engine failures. By analyzing ambiguous data derived from expert judgments, the D–S theory offers a more trustworthy failure assessment than the conventional FMECA. In this study, a survey was conducted on maritime experts using main engine failures in the Kongsberg Maritime Engine Room Simulator, and analyses were conducted by integrating FMECA and the D–S theory. This integration allowed for a more accurate prioritization of ship main engine critical failures. Failure modes 2.3, 2.1, and 3.6 were found to be the riskiest failures. By better managing uncertainty, this study offers a more accurate safety analysis than the conventional FMECA method and helps ship operators and marine engineers create proactive maintenance plans. The outcomes of the research are expected to provide unique contributions to maritime safety professionals, safety researchers, and safety inspectors for improving the operational safety of ship main engines.

Keywords Ship main engine; Operational efficiency; Safety; Maritime transportation; Failure modes, effects, and criticality analysis

1 Introduction

Ships can reach their desired speeds and overcome resistance using propulsion and propeller systems. The propeller is connected to the main engine through a shaft, and it moves the ship forward by making a translational movement due to the forces created by the water on the propeller (Talay et al., 2014). Therefore, the performance of the

main engine strongly affects its operational efficiency as a more efficient main engine requires less fuel consumption and, therefore, less emissions.

To operate a ship's main engine efficiently, attention should be paid to the main engine values and its planned maintenance. A decreased main engine performance can lead to operational failures and even to a loss of ship control. Thus, the selection of a maintenance program appropriate to the operating conditions and properties of the main engine is important in reducing main engine malfunctions (Priharanto et al., 2023). This is because these malfunctions create risks to the ship, the crew, and the operational safety of the main engine itself. Therefore, potential failures that may occur in the main engine must be identified, classified, and analyzed. Risk analysis is required to improve safety on ships and prevent risks (Cicek et al., 2010). Thanks to the failure modes, effects, and criticality analysis (FMECA) method, system components can be rated, potential failure types and causal factors can be determined, and risk assessments can ultimately be conducted (Dutra et al., 2024). By combining this method with the Dempster–Shafer (D–S) theory, the method can be strengthened if the classical theory is insufficient.

Multiple studies on failure mode and effects analysis (FMEA) can be found in the existing literature. For instance,

Article Highlights

- Ship main engine failures were determined using the Marine Engine Room Simulator.
- FMECA and D–S theory were integrated to perform risk analysis.
- A perspective was presented on ship main engine failures, their effects and consequences on maritime safety.

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Zuki et al. (2023) determined the failure risks of high-speed diesel engines at sea and evaluated the failure risks of Motor and Turbine Union 538 engines in the service of maritime law enforcement agencies in Malaysia using FMEA as a preventive method. Possible failure modes of engine components were identified, and relevant precautions were suggested. Meanwhile, to reduce possible accident risks in ship bunkering operations, Doganay et al. (2023) identified hazards in ship bunkering operations using the FMEA method and offered mitigation recommendations. They concluded that the FMEA method provided a systematic strategy and allowed preventive measures to be taken. Ariany et al. (2023) preferred the FMEA approach in analyzing the risks of ferry construction and identifying risk sources and risk impact. By choosing the FMEA approach, Baroroh et al. (2023) evaluated the risks of ship repair delays and measured the possible failures that affected the repair times. Their study addressed the obstacles frequently encountered in ship repair services and how these obstacles prolonged ship repair times. Meanwhile, risk analysis of cooling systems on fishing vessels was conducted by Siahaan et al. (2024) using a fuzzy logic-based FMEA approach. Ceylan (2023) conducted a risk analysis of ship compressor systems with 33 failure modes using a rule-based fuzzy FMEA method.

As discussed, many studies have been done on FMEA. However, studies have shown that the FMEA approach has gradually been replaced by the FMECA approach, which is a more comprehensive and effective version of FMEA. For instance, to address epistemic uncertainty, Certa et al. (2017) developed a methodology that integrated the D–S theory into FMECA, allowing experts to better represent their assessments of risk parameters. Siswantoro et al. (2020) preferred the FMECA fuzzy approach in their work and made a risk analysis of a cooling system by evaluating the critical level of the main engine support systems. Meanwhile, Daya and Lazakis (2022) identified performance degradation and critical failures in ship systems using FMECA and artificial neural networks. Their proposed methodology aimed to improve maintenance priorities and failure prevention strategies by identifying mission-critical components and failure patterns. Ahmed et al. (2022) conducted an FMECA analysis of the pod propulsion system based on an actual accident report on a Norwegian Star ship and used the IT-2 fuzzy expert system to identify the fault with the highest risk prioritization number (FRPN). The study evaluated 13 failure modes with contributions from marine engineering experts and found that drive stator failure was the most critical problem. Uflaz et al. (2024) used rule-based Bayesian network modeling techniques, FMECA, and D–S theory to assess the risks of ship bridge systems against cyberattacks. In particular, they determined that automatic identification system (AIS) spoofing

and GPS jamming attacks have the highest risk values. In this context, they developed risk assessment and management strategies for ship cybersecurity. Shams et al. (2024) applied the D–S evidence theory (which is useful for assessing subjective and ambiguous information) to environmental risk assessment and employed the FMEA approach to identify environmental risks in oil and gas operational facilities. Sezer et al. (2024) integrated FMECA and D–S evidence theory to perform a thorough risk assessment in ship recycling procedures. By controlling epistemic uncertainties, they identified the most important failure modes and produced a more trustworthy risk analysis, hence promoting safe and sustainable ship recycling procedures.

According to the results of the literature research, there has been no detailed risk analysis using the FMECA method on ship main engine failures and operational efficiency. Generally, studies have been focused on specific failures in a system, such as the fuel system. As shown in Table 1, the areas where FMECA and D–S methods have been generally used in the maritime field include marine boilers, propeller shaft systems, and cyber security of ship bridge systems. There has been no comprehensive study on ship main engine failures using FMECA and D–S methods and simulators. This study was thus conducted to close this gap in the literature.

The novelty of this study lies in its improved system safety and efficient ship main engines for sustainable maritime transportation as the findings of this research highlight the most significant criteria in ship main engines. Thus, chief engineers, second engineers, superintendents, and naval engineers can focus on the potential hazards requiring urgent care to minimize ship main engine failures.

The organization of this study is given as follows: This chapter begins with the purpose of the study and the reasons for the selection of the method. Chapter 2 explains how the D–S theory is integrated with the FMECA approach. Chapter 3 provides definitions of main engine failures, applications of main engine faults, and analyses of the study. The nomenclature used in the study is listed in Table 2.

2 Material and method

This chapter provides an overview of the D–S evidence theory and the methodological framework of the study for integrating the FMECA approach. While FMECA systematically analyzed the failure modes, the D–S theory managed epistemic uncertainties and integrated the differences in expert opinions in a balanced way. In this way, a more reliable and flexible risk analysis than traditional methods was provided and the identification of critical hazards was made more sensitive.

Table 1 Summary of literature related to the study

Article	Application Area	Method	Contributions
Quantifying potential cyber-attack risks in maritime transportation under Dempster–Shafer theory FMECA and rule-based Bayesian network modeling (Uflaz et al., 2024)	Cyber security of ship bridge systems	FMECA, D–S	It has been determined that AIS spoofing and GPS jamming attacks pose the highest cyber risks for ship bridge systems and it has been suggested to develop effective cyber security strategies against these threats
A holistic risk assessment under the D–S evidential theory and FMECA approach of ship recycling process hazards in the maritime environment (Sezer et al., 2024)	Ship recycling process	FMECA, D–S	The most critical failure modes were identified, and D-S theory provided a more reliable analysis by managing epistemic uncertainties
A Dempster–Shafer evidence theory for environmental risk assessment in failure modes and effects analysis of Oil and Gas Exploitation Plant (Shams et al., 2024)	Oil and gas operating facilities	FMECA, D–S	The D-S evidence theory-based model has been found to provide more reliable results in risk prioritization by reducing uncertainties
Operational risk assessment of ballasting and de-ballasting onboard tanker ship under FMECA extended Evidential Reasoning (ER) and Rule-based Bayesian Network (RBN) approach (Elidolu et al., 2023)	Ballasting and deballasting operations on tanker ships	FMECA, Evidential Reasoning, Rule-based Bayesian Network (RBN)	It provides significant contributions to tanker ship owners, operators and safety managers in increasing safety and minimizing risks in ballast operations
Accident-based FMECA study of Marine boiler for risk prioritization using fuzzy expert system (Ahmed and Gu, 2020)	Marine boiler	Rule-based fuzzy model FMECA	The method is useful to assess critical risks associated with Marine Engineering and offshore transportation problems and a Fuzzy RPN can help in addressing the same RPN issue across different failure modes
Failure criticality evaluation of ship propeller shaft system based on Fuzzy FMECA method (Wang et al., 2021)	Propeller shaft system	Fuzzy FMECA	Findings can be used as a crucial guide for ship design and repair, to direct the strengthening of the weak link in the propeller shaft system's reliability, and to guarantee the ship's safe navigation
A hybrid failure analysis model design for marine engineering systems: A case study on alternative propulsion system (Cicek et al., 2025)	Alternative propulsion system	FMEA-Variable Weighted Synthesis Analytic Hierarchy Process (VWS-AHP)	It offers a thorough foundation for comprehending how marine engineering systems fail
A quantitative dynamic risk assessment for ship operation using the fuzzy FMEA: The case of ship berthing/unberthing operation (Goksu and Arslan, 2023)	Ship berthing/unberthing operation	Rule-based fuzzy FMEA	This paper, which is based on fuzzy risk ranking, will help seafarers by offering valuable information for removing or lessening the effects of dangers during regular ship operations and for carrying out safe ship operations

Table 2 Nomenclature

Abbreviation	Definition	Abbreviation	Definition
FMECA	Failure modes, effects and criticality analysis	<i>O</i>	Occurrence
FMEA	Failure mode and effects analysis	<i>S</i>	Severity
D–S	Dempster–Shafer	<i>D</i>	Detection
RPN	Risk priority number	FM	Failure mode
FRPN	Fuzzy risk prioritization number	ME	Main engine
FOD	The frame of discernment	<i>M</i>	Mass
BPA	Basic probability assignment	Bel	Belief function
°	Degree	Pl	Plausibility function

2.1 Failure modes, effects, and criticality analysis

FMECA, a customized iteration of FMEA, identifies possible failure modes and assesses the corresponding level of risk. All possible ways in which individual components of a system could fail are recognized, and the reasons behind each failure mode and their consequences on the functioning of a system are assessed (Dinmohammadi et al., 2016). This approach assists in prioritizing these failures and proposing appropriate measures to address the most significant concerns. The risk priority number (RPN) plays a vital role in FMECA as it quantifies and arranges risks in order of importance (Akyuz, 2017). Criticality analysis, which is an expanded form of FMEA, is employed to plot the likelihood of failure modes in relation to the magnitude of their impacts (Juhaszova, 2013). The implementation of FMECA considerably contributes to bolstering the safety and dependability of equipment functionality, thereby reducing potential hazards that lead to bodily harm, loss of property value, and environmental threats (Zhou et al., 2024). By evaluating each failure mode, this approach provides an opportunity to gauge their level of criticality, facilitating their ranking and subsequent identification of suitable measures to mitigate risks (Scheu et al., 2019).

The evaluation of criticality is extensively conducted through either i) the computation of an RPN or ii) the determination of an item criticality number (Bowles and Peláez., 1995). By evaluating risk parameters, estimating their impact on a system, considering the frequency of occurrence within a specific time frame, and factoring in the probability of detection, the criticality of each failure mode is determined (Carpitella et al., 2017). When assessing failure modes, the factors of risk typically considered are occurrence (*O*), severity (*S*), and detection (*D*). The *O* factor represents the likelihood of a failure occurring (Garcia and Schirru, 2005). *S* indicates the level of seriousness associated with the failure. Meanwhile, *D* denotes the potential for detecting a failure (Sharma et al., 2005).

By multiplying the *O*, *S*, and *D* values, the RPN value shown in Equation (1) is obtained.

$$\text{RPN} = O \times S \times D \quad (1)$$

According to the above formula, the inputs *O*, *S*, and *D* have the same level of impact on the RPN value. This approach's primary drawback thus lies in its potential for various permutations of *S*, *O*, and *D*, leading to identical RPNs. Additionally, given the subjective nature of assessments, considerable ambiguity exists within the gathered data (Gaonkar and Pai, 2022). For this reason, spaced grading is required to enable experts to more effectively convey their knowledge on the subject (Sezer et al., 2022). Although FMECA is an effective approach, one of its drawbacks is that its ratings lead to the same results (Chanamool and Naenna, 2016). Even though the inputs entered when

calculating the RPN are different, the same RPN values can be obtained. For example, the RPN value obtained from the product of the 4, 8, and 3 inputs of two different events and the RPN value obtained from the product of the 6, 2, and 8 inputs are the same. Therefore, risk assessment is inadequate here.

2.2 D–S evidence theory

The theory of evidence proposed by Dempster (1967) was theorized by Shafer and presented as an influential mathematical framework for the exploration of epistemic uncertainty (Shafer, 1976), thus making Dempster's rule more comprehensive. It began to be used as the D–S theory of evidence. The D–S theory consists of three principles (Zhang et al., 2023; Sezer et al., 2022):

- 1) Frame of discernment (FOD).
- 2) Basic probability assignment (BPA).
- 3) Dempster combination principle.

FOD is represented by the symbol Θ . This collection encompasses all possible scenarios that are comprehensive and distinct from one another. Equation (2) depicts the expression of FOD, with *H* representing individual propositions (Sezer et al., 2022).

$$\Theta = \{H_1, H_2, \dots, H_n\} \quad (2)$$

2^Θ is the power set indicating the degree of priority of FOD, which includes all subsets.

$$2^\Theta = \{\emptyset, \{H_1\}, \{H_2\}, \dots, \{H_n\}, \{H_1 \cup H_2\}, \dots, \{H_1 \cup H_2 \cup \dots H_i\}, \dots, \{H_1 \cup H_2 \cup \dots H_n\}\} \quad (3)$$

BPA describes the connection between the power set and any subset *A* in the power set. Additionally, it indicates the belief associated with subset *A*. The mass function (*m*) serves as an indicator for BPA and is assigned a value from 0 to 1. The requirements for BPA are as follows:

$$m(\emptyset) = 0 \quad (4)$$

$$\sum_{A \in 2^\Theta} m(A) = 1 \quad (5)$$

The element that meets the aforementioned criteria is referred to as the focal element. Considering a set *A* in the sample space, there are Belief (Bel) and Plausibility (Pl) measures attached to each mass function.

$$\text{Bel}(A) = \sum_{B \subseteq A} m(B) \quad (6)$$

$$\text{Pl}(A) = \sum_{A \cap B \neq \emptyset} m(B) \quad (7)$$

The belief function $\text{Bel}(A)$ is obtained as the sum of all BPAs of subsets B in set A . This shows the confidence level of proposition A . $\text{Pl}(A)$ measures the possible uncertainty associated with A . The sum of the BPAs at the intersection of subsets A and B is the plausibility of A . Naturally, $[\text{Bel}(A), \text{Pl}(A)]$ indicates an indefinite range, and it is concluded that $\text{Pl}(A)$ is equally larger than $\text{Bel}(A)$. As shown in Equation (8), $\text{Bel}(A)$ and $\text{Pl}(A)$ are the lower and upper bounds of the probability, respectively.

$$\text{Pl}(A) = [1 - \text{Bel}(\bar{A})] \quad (8)$$

The D–S theory enables the integration of data from different and independent sources. According to Dempster's rule, which is the beginning of the fusion process, Equations (9) and (10) are used to combine multiple mass functions from the same FOD. Here, $m_1(B)$ and $m_2(C)$ denote two distinct sources defined across Θ . The parameter k signifies the level of discordance between $m_1(B)$ and $m_2(C)$, referred to as the conflict coefficient.

$$m_{12}(A) = \begin{cases} \frac{\sum_{B \cap C \neq \emptyset} m_1(B)m_2(C)}{1 - k}, & A \neq \emptyset \\ 0, & A = \emptyset \end{cases} \quad (9)$$

$$k = \sum_{B \cap C = \emptyset} m_1(B)m_2(C) \quad (10)$$

2.3 Proposed approach: D–S evidence and FMECA

Although the D–S theory is used in many fields, it is rarely used together with the FMECA approach (Certa et al., 2017). Epistemic uncertainty can be managed when FMECA and the D–S evidence theory are used together. That is, integrating D–S with FMECA allows uncertainties in the FMECA process to be handled more effectively.

The FMECA method based on D–S evidence is applied using belief and plausibility distributions. The method consists of three steps (Sezer et al., 2022), and the flowchart of the methodology used is presented in Figure 1.

- 1) Conduct an expert evaluation of risk parameters for failure modes (O , S , and D).
- 2) Considering all possible combinations, specify RPN with clear or spaced values.
- 3) Draw a curve based on the determined confidence

and plausibility values to complete the ranking.

Step 1. Data recognition: The conventional approach of FMECA has certain limitations when it comes to assessing risks and dealing with uncertainty. Given the subjective and uncertain nature of human judgments, experts face significant challenges in assigning precise numerical values to O , S , and D . N experts solve this problem by using interval or absolute value methods to calculate risk parameters for all failure modes (Pillay and Wang, 2003; Carmignani, 2009; Akyuz and Celik, 2018). When experts evaluate risk parameters using the D–S theory, the $[1, 10]$ range is determined for each parameter. The BPA, denoted as $m_{i,r,f}(X)$, represents the weight of the evidence derived from the responses of the i th expert ($i = 1, \dots, N$) to the r th risk factor ($r = O, S, D$) of the f failure mode. This BPA is calculated as $1/N$, where $X \subseteq 2^\Theta$. Equation (5) is created by equally distributing the total evidence regarding the r th risk factor of failure mode F to N experts, and the total evidence becomes 1 (Baraldi et al., 2013; Certa et al., 2017; Kalathil et al., 2020).

Step 2. Data dissemination: The first stage is conducted by evaluating each risk factor (r) of the failure modes (f) with interval or precise values by N experts. RPN is obtained by multiplying O , S , and D values without any fusion process. All possible combinations of z depending on the failure mode (f) are then considered. N^3 indicates the number of combinations of each failure mode. Furthermore, the relevant RPN is also denoted as $\text{RPN}_{f,z}$. Although the values are determined intermittently, the BPA equivalent of the failure mode is $m(\text{RPN}_{f,z})$, z . In other words, the criteria evaluated by experts are calculated through Cartesian multiplication.

Step 3. Prioritizing failure modes: After the acquisition of N^3 RPNs for each failure mode, the prioritization phase begins to improve the quality of existing data. In this phase, each RPN_f is compared with a predefined threshold value RPN_f^* . Recall that we use $\bar{E} = \{\text{RPN}_f > \text{RPN}_f^*\}$. If an RPN value increases, it represents a serious failure mode; as such, evidence underpinning $\bar{E}$ must be quite compelling. The belief and plausibility distributions for $\bar{E}$ event are then graphed for each failure mode f based on the obtained N^3 RPNs.

To organize the plotting process, the intervals of $\text{RPN}_{f,z}$ are sorted in ascending order, with lower and upper bounds for each interval. If a crisp value exists for $\text{RPN}_{f,z}$, it is maintained by assigning the same value to both the lower and upper bounds.

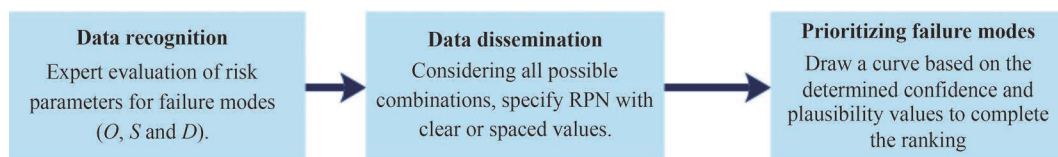


Figure 1 Flowchart of the methodology used

The conviction regarding the complementary event $E = \{RPN_f \leq RPN_f^*\}$ is established by aggregating the belief masses across all $RPN_{f,z}$ intervals within the range $[0, RPN_f^*]$. This relationship can be expressed using the following equation:

$$Bel(E) = Bel(RPN_f \leq RPN_f^*) = \sum_{RPN_{f,z} \in [0, RPN_f^*]} m(RPN_{f,z}) \quad (11)$$

The plausibility of event $E = \{RPN_f \leq RPN_f^*\}$ is gauged by aggregating the belief masses from the $RPN_{f,z}$ intervals that coincide with $[0, RPN_f^*]$. This is represented by the following equation:

$$Pl(E) = Pl(RPN_f \leq RPN_f^*) = \sum_{RPN_{f,z} \cap [0, RPN_f^*] \neq \emptyset} m(RPN_{f,z}) \quad (12)$$

For this purpose, the belief and plausibility distributions pertaining to event $\bar{E}$ are presented as

$$Bel(\bar{E}) = Bel(RPN_f > RPN_f^*) = 1 - Pl(RPN_f \leq RPN_f^*) \quad (13)$$

$$Pl(\bar{E}) = Pl(RPN_f > RPN_f^*) = 1 - Bel(RPN_f \leq RPN_f^*) \quad (14)$$

To prioritize failure modes, the FMECA method employs Equation (14), which assigns greater significance to failure modes with higher RPNs. The prioritization begins by establishing a line with a credibility mass of m , denoted as $y = m$. The point where this line intersects with $Pl(\bar{E})$ determines the RPN_f^* value for each failure mode f . These failure modes are then ranked in descending order from most severe to least severe. In situations where different failure modes have identical RPNs and are in the same position, the value at the intersection of the $x = RPN_f^*$ line and the belief curve is considered. Further ranking of the failure modes is based on decreasing belief value. The flow diagram in Figure 2 visually represents this prioritization process. It is imperative to improve upon the FMECA

method, as discussed in detail in the preceding section, to address its limitations (Certa et al., 2017).

The utilization of the D–S evidence-based FMECA methodology offers a solution to the limitations encountered in traditional FMECA processes, where disparate O , S , and D scores may yield identical RPN values. Whereas the traditional FMECA method does not sufficiently account for uncertainties, the D–S theory provides a more reliable risk assessment by considering the differences in expert opinions. With the D–S theory, epistemic uncertainties are better managed while determining the risk level of each failure mode and critical differences between failure modes are revealed more clearly. Furthermore, this approach mitigates epistemic uncertainty inherent in risk parameter evaluations by enabling experts to furnish interval-valued ratings.

3 Application example: Increasing the operational safety and efficiency of ship main engines

In this section, the D–S-theory-based FMECA approach is applied to assess the risks of possible failures in a ship's main engine.

3.1 Possible malfunctions in ship main engines

Malfunctions resulting from a ship's main engine can potentially lead to serious accidents. These hazards can affect the navigation of a ship and the safety of its crew and cause environmental damage. Thus, correct and effective operation of a ship's main engine is vital for operational safety. The range of failures that can affect a ship's main engine is very wide, and the resulting damage can be equally diverse. Neglecting, overlooking, or not addressing minor failures that previously occurred can lead to serious damage. The accumulation of minor failures can ultimately cause irreparable damage and render main engines unusable (Aydin et al., 2024; Özsoysal, 2008).

In the event of a malfunction, it must be decided quickly whether to stop the main engine. This is because if the main engine continues to operate under abnormal conditions,

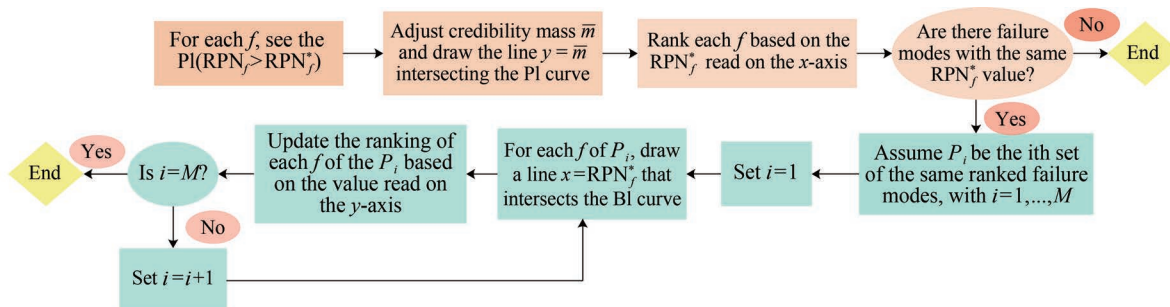


Figure 2 Flowchart of the prioritization phase

much bigger failures will probably occur. For example, increased exhaust temperatures, high temperatures in certain parts of the scavenge area, and sparks and smoke coming from the scavenge area drains are signs of a scavenge fire. When these symptoms are observed or an alarm occurs, the bridge is immediately notified, and the main engine is slowed down. The fuel in the cylinder where the fire occurred should be cut off. To prevent possible damage and deterioration, the amount of lubricating oil and cylinder oil drop-lets for the affected cylinder is slightly increased, and the chamber drains are closed to prevent air ingress. With the implementation of these measures, small fires are quickly extinguished, and these situations gradually return to normal. In these scenarios, the main engine must be operated at low loads to prioritize safety. However, if the fire does not go out on its own and there is a risk of it spreading to other scavenge areas, the main engine must be stopped. Continuous cooling must be ensured, and the main engine must be turned rapidly with the turning gear by opening the indicator valves to prevent any malfunction. If the main engine is not rotated, it may lead to other complications, such as piston or piston rod failure due to local heating (Kucuksahin, 2016).

When a turbocharger malfunction occurs, its escalation is usually prevented by stopping the main engine immediately. In the case of an unstoppable main engine, the speed of the ME (and therefore the speed of the turbocharger) is greatly reduced to avoid endangering the ship. Particular care is taken to ensure that no vibration occurs in the faulty turbocharger at a reduced speed.

3.2 Numerical analysis for ship main engine malfunction

The primary source of propulsion power in this study is a Sulzer RTA84C diesel engine, which operates at low speeds and consists of 12 cylinders arranged in a 2-stroke configuration. This turbocharged, reversible engine is responsible for driving the propeller shaft, which is equipped with both a fixed-pitch propeller and a controllable-pitch propeller. The data of the main engine used for the study is given in Table 3.

The main engine failures in the engine room simulation are demonstrated one by one, and the values obtained from the simulation are given in Table 4.

The “Injection Time Early” fault is explained in detail in the simulation. “Injection Time Early” occurs when the cam slides forward. It can be understood as a result of the decrease in exhaust temperature. When we run the “Injection Time Early” failure in the simulation, the injection opening time becomes -13.8° , whereas it is -1.8° at normal values. This indicates that the cam has shifted forward by 12° . Meanwhile, $P_{\max}$ is the highest pressure formed at the end of combustion. P_{comp} is the highest pressure without fuel. There is no significant change in the P_{comp} value.

Table 3 Data of the main engine

Main engine parameter	Value
Continuous service rating ME (MW)	48.6
Corresponding engine speed (r/min)	102
Cylinder bore (mm)	840
Number of cylinders	12
Piston stroke (mm)	2400
Scavenge air pressure (bar)	2.30
Turbine speed (r/min)	8800
Number of prop. blades	5
Mean indicated pressure (bar)	18.4
Specific fuel consumption (g/kWh)	171
Number of air coolers	3
Number of turbo chargers	3
Propeller pitch (P/D)	1.08

Because this failure creates a difference in the fuel, the mechanical movement of the piston or the air ratio is not interfered with. The ignition delay is calculated by subtracting the moment the injector starts spraying from the moment combustion begins. Whereas spraying starts at 1.8° in the normal cylinder ($T_{\text{injo}} = 1.8^\circ$), it starts at 13.8° in this error. Whereas the start of combustion ($T_{\text{ign}} = 0.4^\circ$) is 0.4° dgr in the normal cylinder, it is 10.5° in the cylinder with the error. When the T_{ign} value is subtracted from the T_{injo} value, the ignition delay is observed to be 2.2 in the normal cylinder and 3.3 in the cylinder with the failure. In other words, the ignition delay time is extended. This means that 60% more fuel is given to the cylinder where the failure occurred. As the fuel is given in large amounts and there is a long delay, faster combustion occurs, and the $P_{\max}$ is reached early.

Primarily, an FMECA worksheet was prepared for risk analysis related to ship main engine failures. To achieve this, the engine room simulator of a container with a Sulzer 12RTA 84C model diesel engine was taken as a basis. The data were collected through a structured and multisource approach to ensure reliability and validity. First, an extensive literature review of ship main engine failures, safety assessments, and reliability analysis was conducted to identify common failure modes and critical factors influencing system performance. Second, historical failure reports and maintenance records, simulator runs, class reports, ME instruction manuals, and books from tanker and cargo ships were gathered to establish a practical foundation for failure mode identification. Additionally, expert interviews and surveys with experienced marine engineers, chief engineers, and maintenance personnel were performed to obtain domain-specific knowledge and expert opinions. Accordingly, a total of 20 failure modes and five failure mode categories were obtained from FMEA analysis, as listed in Table 5. For FMECA analysis, risk parameters associated

with each failure mode were evaluated by four experts. The expert group comprised academicians who had experience working as marine engineers on board and were then conduct-

ing research in marine engineering safety. In this context, the experts used 10-point numerical scales for the evaluation process, and their judgments are presented in Table 6.

Table 4 Simulation data of main engine failures

Failure mode category	Failure mode	Exhaust (°C)	$T_{\max}$ (°)	$P_{\max}$ (bar)	P_{comp} (bar)	T/C Speed (r/min)	I_{kW} (kW)	T_{injo} (°)	T_{ign} (°)	MIP (bar)	Fuel Cyl (kg/h)	Fuel M/E (kg/h)
		350.8	14.9	137.4	96.6	8785.4	4049	−1.8	0.4	17.9	647.5	7770
Exhaust valve	Exhaust opening early	344.8	15	138.5	98.1	8814.4	3770	−1.7	0.4	16.6	651.3	7820
	Exhaust opening late	709.4	15	131.1	92.6	8838.9	3925	−1.8	0.6	17.3	647.2	7780
	Exhaust valve leakage	395	16.4	92.6	81.7	8837.6	3501	−1.7	0.9	15.5	652.9	7840
	Exhaust valve stuck (open)	56.5	3.4	3	3	8985.3	0	−1.4	2.6	0	685.4	8230
Turbocharger	T/C compressor dirty	445.1	14.8	130	83.6	10194.1	4057	−2.6	−0.3	17.9	650.3	7810
	T/C Ex turbine dirty	529.5	14.8	122.5	73.8	6524.5	4050	−3.6	−0.6	17.9	654.1	7850
Injection	Injection time early	333.2	7.2	198.4	97	8780.6	4289	−13.8	−10.5	18.9	649.9	7800
	Injection time late	404.4	17.4	61.8	98	8842.2	3463	14.2	16.5	15.3	653.7	7850
	Injection nozzle wear (poor atomization)	406.5	11.5	79.5	98.1	8853.4	3282	−1.6	10.5	14.5	658.4	7900
	Injection nozzle deposit (clogging)	263	14.3	114.1	97.4	8765.3	2821	−1.7	0.8	12.4	451.8	7760
	Injection line rupture	56.4	0	98.7	98.7	8692	0	0	0	0	0	7790
	Injection line gas content	56.7	0	97.3	97.3	8689.5	0	11.8	0	0	0	7720
Scavenge air	Scavenge air box fire	417.7	14.9	136.6	96.5	8818.5	4007	−1.8	0.4	17.8	647.3	7770
	Scavenge air box dirty	410	15.2	131.6	91.4	8786.2	4002	−1.8	0.6	17.7	646.2	7760
Piston	Piston crown wear	363.4	15	114.8	78.2	8800.8	3886	−1.8	1	17.9	648.6	7790
	Piston ring (all) sealing (wear)	376.5	15.2	126.9	89.7	8801.5	3910	−1.8	0.4	17.2	649.2	7790
	Cylinder lubricator pump wear	351.5	15	136.9	96.4	8788.7	4052	−1.8	0.4	17.9	648.9	7790
	Liner crack	341.5	15.1	131.1	92.2	8777.7	3956	−1.8	0.5	17.5	647.9	7780
	Piston crown deposits	355.4	14.8	141.4	101.5	8783.6	4077	−1.8	0.5	18	647.6	7770
	Piston ring stiction (general)	359.4	15	136.8	96.2	8785.7	4034	−1.8	0.4	17.8	646.9	7760

Table 5 Failure modes and their categories obtained from FMEA analysis

Categorization of failure modes	Failure number	Failure modes	Failure causes	Failure effect
Exhaust valve	FM 1.1	Exhaust opening early	Timing failure Incorrect clearance setting	Loss of power Fuel consumption increases Reduction in brake torque
	FM 1.2	Exhaust opening late	Clearance greater than the normal value	Abnormal noise Excessive wear Amount of air taken into the cylinder decreases
	FM 1.3	Exhaust valve leakage	Valve corrosion by high-temperature combustion products Deterioration of valve surfaces	Valve seats wear out Engine may stop due to loss of compression in the cylinders and inability to create combustion Exhaust temperatures increase
	FM 1.4	Exhaust valve stuck (open)	Insufficient lubrication Soot formation Wear (valve spindle, valve guide, valve spring) Heat-related deterioration (expansion as a result of overheating)	Fuel consumption increases

Table 5 Failure modes and their categories obtained from FMEA analysis (continue)

Categorization of failure modes	Failure number	Failure modes	Failure causes	Failure effect
Turbocharger	FM 2.1	T/C compressor dirty	Dirty air filter	Abnormal noise Exhaust temperatures increase rpm does not remain constant. (surging) Since half the amount of air enters, the air is cooled very much without changing the amount of water in the cooler, and the scavenge air temperature decreases
	FM 2.2	T/C Ex turbine dirty	Soot formation as a result of Poor combustion Fuel not separated well	Imbalance of the turbine shaft caused by vibration Exhaust temperatures increase
Injection	FM 3.1	Injection time early	Camshaft slipped and is ahead	Exhaust temperature decreases P_{max} increases
	FM 3.2	Injection time late	Incorrect camshaft position Worn or effective injector	Exhaust temperature increases P_{max} decreases
	FM 3.3	Injection nozzle wear (poor atomization)	Partial blockage of holes due to accumulation of soot Increase in hole diameter Decrease in viscosity Fuel separator not work well	Knocking Fuel consumption increases Exhaust temperature increases P_{max} decreases I_{kw} decreases
	FM 3.4	Injection nozzle deposit (clogging)	Soot formed in the cylinder due to incomplete combustion	Slow combustion as a result of long-term operations Loss of power Retention in piston ring seats Damage to injector parts
	FM 3.5	Injection line rupture	Fuel whip leaks	No fuel comes to the nozzle P_{max} and P_{omp} values are the same because no fuel is supplied Fuel consumption does not change as it is allocated to other cylinders Shut down happens
	FM 3.6	Injection line gas content	Fuel filter not replaced or partly clogged Air in the pump not been purged	Failure to start the engine Fuel consumption decreases
Scavenge air	FM 4.1	Scavenge air box fire	Incompletely burned or partially burned fuel or cylinder oils passing between the cylinder liners and pistons of the engine into the scavenge area Dirty scavenge space Poor compression Partially clogged exhaust ports Overload operation of the engine Broken piston rings or excessively worn piston rings Over-lubricated cylinder liners and their faulty timing “Gas leaks” between the cylinder liners and the piston	Exhaust temperature increases Sparks and smoke coming from scavenge area drains
	FM 4.2	Scavenge Air Box Dirty	Inadequate maintenance of the engine	Scavenge air temperature increases excessively Exhaust temperature increases Scavenge fires

Table 5 Failure modes and their categories obtained from FMEA analysis (continue)

Categorization of failure modes	Failure number	Failure modes	Failure causes	Failure effect
Piston	FM 5.1	Piston crown wear	Temperature change	Concavity of the piston increases Exhaust temperature increases
	FM 5.2	Piston ring (all) sealing (wear)	Insufficient lubrication Overheating of pistons Piston ring and piston ring Groove bottom wear	Piston ring's knock Cylinder oil consumption increases Blue smoke is seen in the exhaust Fuel consumption increases Power loss The crank can rotate, but ME cannot start
	FM 5.3	Cylinder lubricator pump wear	Pollution and foreign matter Using wrong oil	ME cylinder oil flow decrease ME cylinder liner metal temperatures increase Piston ring wears out Liner wears out
	FM 5.4	Liner crack	Abnormal thermal stresses Overload operation of the engine Decreased cooling efficiency Soot formation	Cooling water pressure fluctuates constantly Expansion tank makes boils
	FM 5.5	Piston crown deposits	Soot formation	Concavity of the piston decreases
	FM 5.6	Piston ring stiction (general)	When usage times at maximum load exceed the mentioned time	Slow down occurs Temperatures of lubricating oil, cooling water, exhaust, etc., increase Knocking begins in the crankshaft main bearings Bearing may seize

Table 6 Experts' evaluations of the *O*, *S*, and *D* parameters

Failure mode	<i>O</i>				<i>S</i>				<i>D</i>			
	Expert 1	Expert 2	Expert 3	Expert 4	Expert 1	Expert 2	Expert 3	Expert 4	Expert 1	Expert 2	Expert 3	Expert 4
1.1	[1, 2]	2	[1, 2]	[1, 2]	[8, 9]	[7, 8]	[7, 8]	[9, 10]	[6, 7]	[7, 8]	[9, 10]	[7, 8]
1.2	[1, 2]	[2, 3]	[1, 2]	[1, 2]	[8, 9]	7	[9, 10]	[8, 9]	[6, 7]	[6, 8]	[7, 8]	[7, 8]
1.3	[4, 5]	4	[3, 4]	[3, 4]	[6, 7]	[5, 7]	[7, 8]	[7, 8]	[7, 8]	[7, 8]	[8, 9]	[8, 9]
1.4	[3, 4]	[3, 4]	[2, 3]	[1, 2]	[8, 9]	[8, 9]	[9, 10]	[9, 10]	[7, 8]	[6, 7]	[8, 9]	7
2.1	[9, 10]	[8, 9]	[8, 9]	[9, 10]	4	6	[4, 5]	6	[7, 8]	8	[8, 9]	[8, 9]
2.2	[9, 10]	[7, 9]	[8, 9]	[9, 10]	[8, 9]	8	[8, 10]	[7, 8]	8	[6, 8]	[8, 9]	[8, 9]
3.1	[1, 2]	[2, 3]	[1, 2]	[2, 3]	[8, 9]	[7, 8]	[9, 10]	[7, 8]	8	[7, 8]	[9, 10]	[9, 10]
3.2	[1, 2]	2	[1, 2]	[1, 2]	[8, 10]	[7, 8]	[9, 10]	[7, 8]	[5, 7]	[4, 6]	[5, 6]	[6, 7]
3.3	[4, 5]	[5, 6]	[5, 6]	[2, 3]	[7, 8]	[6, 8]	[7, 8]	[7, 8]	[6, 7]	[5, 6]	[5, 7]	6
3.4	[4, 5]	[3, 4]	[4, 5]	3	[6, 7]	[5, 6]	[7, 8]	[8, 9]	[6, 7]	[5, 6]	[5, 6]	7
3.5	[1, 2]	2	[1, 2]	[1, 2]	[9, 10]	[8, 9]	[8, 10]	[9, 10]	[9, 10]	[8, 9]	[9, 10]	[9, 10]
3.6	[3, 4]	4	[3, 4]	[3, 4]	[9, 10]	[7, 8]	[8, 10]	[9, 10]	[9, 10]	[8, 9]	[9, 10]	[9, 10]
4.1	[2, 3]	[2, 3]	[1, 2]	1	[9, 10]	9	[9, 10]	[9, 10]	[9, 10]	[8, 9]	[9, 10]	[9, 10]
4.2	[4, 5]	[5, 6]	[3, 5]	[4, 5]	[6, 8]	[6, 7]	[7, 8]	[7, 8]	[5, 6]	[5, 7]	[4, 6]	[7, 8]
5.1	[1, 2]	[2, 3]	[1, 2]	[1, 2]	[6, 8]	[6, 8]	[7, 8]	[7, 8]	[2, 4]	[5, 6]	[5, 6]	[3, 4]
5.2	[2, 4]	[3, 4]	[2, 4]	[2, 3]	[8, 10]	8	[8, 10]	[8, 9]	[8, 9]	[7, 8]	[8, 9]	[7, 8]
5.3	[1, 2]	2	[1, 2]	[1, 2]	[8, 9]	[6, 8]	[8, 9]	[9, 10]	[4, 5]	[3, 5]	[5, 6]	[5, 6]
5.4	[1, 3]	[3, 4]	[1, 2]	[1, 2]	[8, 9]	[6, 7]	[7, 9]	[8, 9]	[7, 9]	[6, 8]	[8, 9]	[9, 10]
5.5	[2, 3]	4	[2, 3]	[3, 4]	[5, 6]	[5, 6]	[6, 7]	[6, 7]	[8, 9]	[6, 8]	[7, 8]	[7, 8]
5.6	[1, 2]	[2, 3]	[1, 2]	[1, 2]	[9, 10]	[8, 9]	[8, 10]	[9, 10]	[8, 10]	[7, 8]	[8, 10]	[8, 9]

According to the proposed approach, all four marine experts are equally reliable and credible. In this context, the BPA for each expert's assessment of each risk factor in the failure modes was calculated as $1/N$, where $N = 4$. Next, all possible RPN combinations were determined by multiplying the O , S , and D parameters directly without any additional aggregation process. As this study was conducted with the participation of four experts, there were $4^3 = 64$ combinations for each failure mode. The BPA for each combination was $(1/4)^3$, and the combinations yielded a crisp or interval-valued RPN. For instance, Table 7 illustrates 64 combinations pertaining to failure mode 2.2 (T/C Ex Turbine Dirty). Belief and plausibility curves were plotted based on the RPN combinations for each failure mode. Additionally, Figure 3 displays the belief and plausibility curves for failure mode 2.2.

Table 7 Combinations of expert judgments on failure mode 2.2

Combination	O	S	D	RPN
1	[9, 10]	[8, 9]	8	[576, 720]
2	[9, 10]	[8, 9]	8	[432, 720]
3	[9, 10]	[8, 9]	[8, 9]	[576, 810]
4	[9, 10]	[8, 9]	[8, 9]	[576, 810]
5	[9, 10]	8	8	[576, 640]
6	[9, 10]	8	[6, 8]	[432, 640]
7	[9, 10]	8	[8, 9]	[576, 720]
8	[9, 10]	8	[8, 9]	[576, 720]
9	[9, 10]	[8, 10]	8	[576, 800]
10	[9, 10]	[8, 10]	[6, 8]	[432, 800]
11	[9, 10]	[8, 10]	[8, 9]	[576, 900]
12	[9, 10]	[8, 10]	[8, 9]	[576, 900]
13	[9, 10]	[7, 8]	8	[504, 640]
14	[9, 10]	[7, 8]	[6, 8]	[378, 640]
15	[9, 10]	[7, 8]	[8, 9]	[504, 720]
16	[9, 10]	[7, 8]	[8, 9]	[504, 720]
17	[7, 9]	[8, 9]	8	[448, 648]
18	[7, 9]	[8, 9]	[6, 8]	[336, 648]
19	[7, 9]	[8, 9]	[8, 9]	[448, 729]
20	[7, 9]	[8, 9]	[8, 9]	[448, 729]
21	[7, 9]	8	8	[448, 576]
22	[7, 9]	8	[6, 8]	[336, 576]
23	[7, 9]	8	[8, 9]	[448, 648]
24	[7, 9]	8	[8, 9]	[448, 648]
25	[7, 9]	[8, 10]	8	[448, 720]
26	[7, 9]	[8, 10]	[6, 8]	[336, 720]
27	[7, 9]	[8, 10]	[8, 9]	[448, 810]
28	[7, 9]	[8, 10]	[8, 9]	[448, 810]
29	[7, 9]	[7, 8]	8	[392, 576]
30	[7, 9]	[7, 8]	[6, 8]	[294, 576]

Table 7 Combinations of expert judgments on failure mode 2.2 (continue)

Combination	O	S	D	RPN
31	[7, 9]	[7, 8]	[8, 9]	[392, 648]
32	[7, 9]	[7, 8]	[8, 9]	[392, 648]
33	[8, 9]	[8, 9]	8	[512, 648]
34	[8, 9]	[8, 9]	[6, 8]	[384, 648]
35	[8, 9]	[8, 9]	[8, 9]	[512, 729]
36	[8, 9]	[8, 9]	[8, 9]	[512, 729]
37	[8, 9]	8	8	[512, 576]
38	[8, 9]	8	[6, 8]	[384, 576]
39	[8, 9]	8	[8, 9]	[512, 648]
40	[8, 9]	8	[8, 9]	[512, 648]
41	[8, 9]	[8, 10]	8	[512, 720]
42	[8, 9]	[8, 10]	[6, 8]	[384, 720]
43	[8, 9]	[8, 10]	[8, 9]	[512, 810]
44	[8, 9]	[8, 10]	[8, 9]	[512, 810]
45	[8, 9]	[7, 8]	8	[448, 576]
46	[8, 9]	[7, 8]	[6, 8]	[336, 576]
47	[8, 9]	[7, 8]	[8, 9]	[448, 648]
48	[8, 9]	[7, 8]	[8, 9]	[448, 648]
49	[9, 10]	[8, 9]	8	[576, 720]
50	[9, 10]	[8, 9]	[6, 8]	[432, 720]
51	[9, 10]	[8, 9]	[8, 9]	[576, 810]
52	[9, 10]	[8, 9]	[8, 9]	[576, 810]
53	[9, 10]	8	8	[576, 640]
54	[9, 10]	8	[6, 8]	[432, 640]
55	[9, 10]	8	[8, 9]	[576, 720]
56	[9, 10]	8	[8, 9]	[576, 720]
57	[9, 10]	[8, 10]	8	[576, 800]
58	[9, 10]	[8, 10]	[6, 8]	[432, 800]
59	[9, 10]	[8, 10]	[8, 9]	[576, 900]
60	[9, 10]	[8, 10]	[8, 9]	[576, 900]
61	[9, 10]	[7, 8]	8	[504, 640]
62	[9, 10]	[7, 8]	[6, 8]	[378, 640]
63	[9, 10]	[7, 8]	[8, 9]	[504, 720]
64	[9, 10]	[7, 8]	[8, 9]	[504, 720]

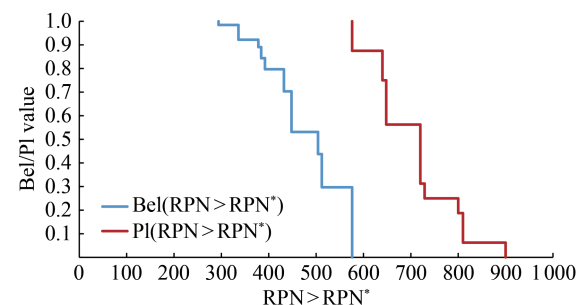


Figure 3 Belief and plausibility curves of failure mode 2.2

With the mass of evidence $\bar{m}$ set to 0.9 (Sezer et al., 2024; Certa et al., 2017), the threshold value RPN_f^* for each failure mode f is determined at the point where the corresponding $Pl(RPN_f > RPN_f^*)$ intersects the line $y = 0.9$. Table 8 presents the ranking of failure modes based on the identified RPN_f^* , arranged from highest to lowest. Table 8 indicates failure mode 2.2 as the most crucial.

Table 8 Ranking failure modes based on plausibility curves

Failure mode	RPN_f^*	Ranking
2.2	576	1
2.1	320	2
3.6	320	2
4.2	240	3
5.2	240	3
1.3	224	4
5.6	160	5
3.3	144	6
3.4	144	6
5.5	144	6
1.4	140	7
5.4	140	7
3.1	128	8
1.1	112	9
1.2	112	9
3.2	96	10
3.5	90	11
4.1	90	11
5.3	80	12
5.1	64	13

Table 4 reveals failure modes ranked alike; hence, additional steps are required for equal RPN_f^* values. A vertical line at $x = RPN_f^*$ is drawn on belief curves to determine the belief value for the event $(RPN_f > RPN_f^*)$. Failure modes 2.1 (T/C Compressor Dirty) and 3.6 (Injection Line Gas Content) share the same rank in Table 4 with $RPN_f^* = 320$ (refer to Figures 4 and 5 for illustrations of belief and plausibility curves to help distinguish the differences between them). To differentiate the criticality of these two failure modes, the vertical line at $x = 320$ plotted on intersections with the line include $Bel(RPN_{2.1}) > 320 = 0.5$ and $Bel(RPN_{3.6}) > 320 = 0.047$. Thus, failure mode 2.1 is considered more critical than failure mode 3.6 in the same way that all other failure modes that share equal RPN_f^* values are approached. The end outcome of these efforts leads to the tabular representation presented in Table 9, which summarizes the final results and rankings.

Table 9 Ultimate ranking of failure modes

Failure mode	RPN_f^*	$Bel(RPN_f > RPN_f^*)$	$Pl(RPN_f > RPN_f^*)$	Final ranking
2.2	576	—	—	1
2.1	320	0.500	0.9	2
3.6	320	0.047	0.9	3
4.2	240	0.031	0.9	4
5.2	240	0	0.9	5
1.3	224	—	—	6
5.6	160	—	—	7
3.3	144	0.593	0.9	8
3.4	144	0.281	0.9	9
5.5	144	0.125	0.9	10
1.4	140	0.531	0.9	11
5.4	140	0.203	0.9	12
3.1	128	—	—	13
1.1	112	0.094	0.9	14
1.2	112	0.031	0.9	15
3.2	96	—	—	16
4.1	90	0.500	0.9	17
3.5	90	0.250	0.9	18
5.3	80	—	—	19
5.1	64	—	—	20

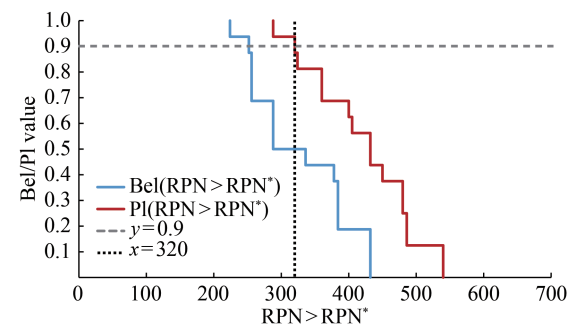


Figure 4 Belief and plausibility curves of failure mode 2.1

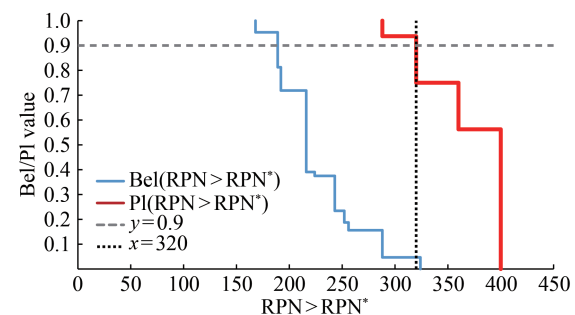


Figure 5 Belief and plausibility curves of failure mode 3.6

4 Results and discussions

Twenty potential failures that may occur on a ship's main engine in the Kongsberg Maritime Engine Room Simulator were divided into five main categories and examined. A questionnaire survey was conducted with four marine experts to evaluate the risks of these failures. From the analysis, failure modes 2.3, 2.1, and 3.6 were in the top 3 (in order of importance) in terms of their high RPN values.

According to Table 5, FM 2.2 T/C Ex Turbine Dirty had the highest risk with an RPN value of 576. This is because the turbocharger gets dirty every day the ship is navigating, and this can be easily detected. In the simulation, when the "T/C Ex Turbine Dirty" mode was run, the turbine inlet/outlet temperatures and exhaust temperatures first increased excessively, and the main engine then activated a slow-down mode.

The failure mode with the second highest RPN was 2.1 T/C Compressor Dirty in the Turbocharger category. If the compressor side of the turbocharger is dirty, the engine speed does not increase, although more fuel is sent to the cylinders to make the ship go faster. The power in the main engine remains the same because not enough air can be absorbed. Another indication that the compressor side is excessively dirty is oil accumulation on the inner walls of the intake manifold. When there is any backflow from the intake valve to the manifold, there is a high probability of fire occurrence in the intake manifold (Özsoysal, 2008). Its effect on the main engine is relatively minor compared with the contamination of the turbine side. When the turbine and compressor side of the turbocharger become dirty, surging, which is an audible vibration, may occur (Kucuk-sahin, 2016). The compressor side of the turbocharger, like the turbine side, gets dirty every day it is driven, and this can be easily detected. Therefore, when regular maintenance is conducted, these risks are significantly decreased.

FM 3.6 Injection Line Gas Content ranked third with its RPN value of 320. Although the probability of this situation occurring is low, if it does occur, its impact is great with high detectability. When FM 3.6 is started in the simulation, the exhaust temperature of the relevant cylinder instantly drops from 350° to 120°. An excessive increase in the exhaust temperatures of other cylinders is also observed. Following this situation, the "ME cyl exh dev temp signal" alarm appears, no power is produced in the cylinder, and the main engine slows down. When the remaining failure modes are examined, the RPN scores are as given in Table 5, respectively.

Therefore, the risk assessment of potential malfunctions that may occur in a ship's main engines was conducted by integrating the D-S evidence theory and FMECA. Ship main engine failures in the Kongsberg Maritime Engine Room Simulator were used. The analysis revealed the major impact of the contamination of the turbine and compressor sides of the turbocharger. This study contributes to

the literature on the maritime industry.

5 Conclusions

The range of malfunctions that can affect a ship's main engine is extensive, and the resulting damage can be equally diverse. Neglecting or failing to notice small faults that occur beforehand can lead to significant damage. Therefore, the operational parameters of ship main engines must be closely monitored to prevent potential malfunctions and damages. Identifying the cause of a malfunction and addressing it promptly is essential. If a simple malfunction is not anticipated and precautions are not taken, it can escalate into a larger issue. These chain reactions of faults can rapidly grow and even result in irreparable damage. Aside from material losses, there is also the unfortunate possibility of loss of life. Thus, conducting risk analyses for failures is of utmost importance.

In this study, the risk assessment of possible malfunctions that may occur in a ship's main engine was conducted by integrating the D-S evidence theory and FMECA. While FMECA systematically analyzed failure modes, the D-S theory managed epistemic uncertainties and integrated the differences in expert opinions in a balanced way. In this way, a more reliable and flexible risk analysis was provided, and the identification of critical hazards was made more sensitive. However, certain shortcomings must be addressed. One may be the number of experts involved in the study. Although all responders had prior experience with the topic and associated marine activities, further research could enhance their numbers and credentials.

Meanwhile, in creating failure modes, ship main engine failures in the Kongsberg Marine Engine Room Simulator were used and applied. The failure types obtained from the simulator were asked of the marine experts and evaluated with intermittent values. According to the analysis results, the contamination of the turbine (FM 2.2) and compressor side (FM 2.1) of the turbocharger had the highest RPN values.

This study provides unique perspectives for stakeholders working in the maritime industry. It not only prioritizes main engine failures but also provides a reference for improving operational safety and efficiency. Although there have been studies in the maritime field integrating FMECA and D-S, this study is the first to use this method in the risk analysis of ship main engine failures.

This study offers practical benefits to maritime safety professionals. For instance, it allows them to focus on critical failure modes of ship main engines so that they can develop relevant management skills and conduct safe monitoring to reduce risks and prevent potential failures. Once a quantitative risk assessment is conducted, the results should be assessed by maritime safety professionals such as ship chief engineers, second engineers, superintendents, and ship

owners. This will involve determining whether the current ship's main engine safety controls in place are effective and whether any improvements should be made.

Competing interest The authors have no competing interests to declare that are relevant to the content of this article.

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