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Ship Bunkering Operations Risk Assessment using Rule-Based Fuzzy Failure Mode Effect Analysis (FFMEA)

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Abstract

Ship bunkering operations play a critical role in sustaining maritime transportation; however, they also entail significant risks to the environment, vessels, and crew. This study conducts a comprehensive quantitative risk assessment of bunkering operations using the rule-based fuzzy failure mode and effect analysis method. A total of 27 critical failure modes were identified, and expert evaluations were performed for the severity, frequency, and detectability of each failure mode. These evaluations are processed through fuzzy membership functions, an inference engine, and a set of 125 rules to calculate the fuzzy risk priority numbers (FRPNs) for each failure scenario. The analysis results indicate that the three most risky failure modes, as measured by their FRPN scores, are FM19 - Lack of proper control mechanisms (7.04), FM18 - Incorrect valve operations (6.93), and FM14 - Ineffective communication between ship crew and shore or barge personnel (6.92). The findings of this study present practical recommendations regarding critical failure modes, with notable implications for improving regulatory compliance, strengthening operational safety, and reducing maritime risks. These outcomes highlight the necessity of systematic risk assessment approaches to guide decision-making and promote safer, more sustainable bunkering operations.

Keywords: Ship bunkering, marine engineering, FMEA, risk analysis, fuzzy logic, FRPN

1. Introduction

The maritime industry is a fundamental component of global trade and facilitates the transport of goods across the world's vast oceans [1]. Within this extensive sector, ship bunkering operations play a role by supplying fuel for maintaining the operational continuity of maritime vessels [2]. Despite its critical importance, ship bunkering is a multifaceted process involving a network of interconnected systems and procedures, each with its own risks and challenges. Consequently, careful attention is required to ensure both safety and efficiency throughout the operation.

The inherent dynamic nature of ship bunkering operations introduces significant risks. The process involves not only the transfer of fuel but also the coordination of various systems on the ship, barge, and at port. This complexity increases the likelihood of accidents and operational failures. In addition, the frequency of bunkering operations amplifies these risks. Each operation requires the seamless functioning of human and mechanical elements to prevent incidents.

Bunkering is particularly hazardous because of the potential for leaks and spills, which can have severe environmental and health impacts [3]. Although stringent safety protocols are in place, even minor incidents can escalate into major disasters, affecting marine environments and posing serious risks to life [4]. The routine nature of bunkering operations does not diminish the associated risks, which include potential accidents and environmental damage from spills. The impact of bunker spills is twofold: they can disrupt marine ecosystems through persistent oil pollution and lead to legal and financial consequences for involved parties, such as crew members and shipowners [5]. It is important to acknowledge that oil spills are not limited to oil or oil products transported as cargo; any vessel can potentially contribute to an oil spill incident due to bunker oil stored within its tanks [6]. Most oil pollution claims are related to bunker

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fuel rather than cargo oil, with many spills occurring during bunkering [4,7]. Furthermore, bunkering operations involve a broad range of risks beyond leaks, including potential injury to crew members and equipment damage. Thus, these operations require thorough preparation, strategic planning, and meticulous attention before, during, and after. Given the critical nature of bunkering, conducting a comprehensive risk analysis and implementing effective precautions are essential for mitigating risks and preventing accidents. This forward-looking strategy plays a critical role in maintaining operational safety while simultaneously optimizing efficiency and minimizing risks.

2. Literature Review

The maritime industry is inherently complex and dynamic, with high levels of risk. To effectively prevent accidents, risk analysis is critical. In high-risk sectors, such as maritime ones, it is essential to analyze risks and implement preventive measures. Consequently, risk analysis has become a fundamental aspect of the marine industry and is one of the most frequently studied and researched topics in recent years [8]. Through risk analysis, both existing hazards and potential future dangers can be identified, allowing effective preventive measures to be developed. This process is vital for improving the safety of maritime operations and reducing the risk of accidents.

Given the inherent risks and complex nature of maritime operations, various risk assessment methodologies have been developed to mitigate these risks. Methods such as fault tree analysis (FTA) [9], failure mode and effects analysis (FMEA) [10], event tree analysis [11], formal safety assessment [12], human error identification and reduction technique [13], Bow-Tie analysis [14], hazard and operability [15], Bayesian network (BN) [16], functional resonance analysis method [17], analytic hierarchy process (AHP) [18], and analytic network process [19], have been employed to evaluate and manage risks. FMEA, in particular, is a well-established tool used to identify and prioritize potential failure modes within systems and operations.Hybrid FMEA methodologies have emerged as a robust approach for addressing complex risk scenarios in various high-risk industries. These methods integrate traditional failure analysis techniques with advanced computational tools to enhance decision-making under uncertainty. For example, fuzzy logic and machine learning-based FMEA approaches have been successfully utilized in healthcare to prioritize patient safety risks [20]. In aviation, BN have been combined with FMEA to improve fault detection/detectability (D) and analyze critical component failures [21]. Similarly, in the energy sector, a fuzzy-AHP hybrid approach has been applied to evaluate risks in renewable energy projects and address sustainability challenges [22]. In manufacturing, genetic algorithm-based FMEA has been adopted to optimize production processes and minimize downtime [23]. Additionally, Dinmohammadi and Shafiee [24] proposed a fuzzy-FMEA framework specifically for offshore wind turbines and demonstrated its effectiveness in evaluating operational and maintenance risks. These advancements demonstrate the potential of hybrid FMEA methodologies to address the unique challenges of maritime operations, particularly in high-stakes scenarios like ship bunkering. Various fuels, including heavy fuel oil (HFO) and marine diesel oil (MDO), power ships. However, one of the primary concerns in the maritime industry is the environmental impact of ship operations, particularly the emissions generated by ships. The International Maritime Organization (IMO) has enforced rules to reduce these emissions, which include restrictions on sulfur oxide (SO_x) and nitrogen oxide (NO_x). To comply with these regulations and reduce their environmental footprint, ship operators are exploring emission-lowering technologies, such as selective catalytic reduction, scrubbers, exhaust gas recirculation, and alternative marine fuels. According to the literature, vital marine alternative fuels are liquefied natural gas (LNG), ammonia, hydrogen, ethanol, dimethyl ether, methanol, and biodiesels [25-27]. The fuel choice depends on cost, availability, and environmental considerations. Recently, there has been a growing concern about using alternative fuels such as LNG to reduce emissions and comply with environmental regulations. A review of studies on ship bunkering operations revealed a substantial body of research, with a particular emphasis on studies focused on LNG [28-35]. However, using alternative fuels presents challenges, including safety concerns and infrastructure requirements. Although alternative fuels are considered viable options for future utilization, most ships continue to use HFO and MDO fuels. Despite this fact, the extant literature on HFO and MDO, which are the fuels utilized by current vessels, exhibits a scarcity of risk analysis studies. The existing literature predominantly examines management techniques for bunkering operations, with a particular emphasis on optimizing costs, selecting appropriate ports, determining ship routes, and establishing contracts to mitigate fuel-related expenses [36-38].

The limited body of literature primarily concentrates on performing risk analyses for ship bunkering operations with the objective of reducing the risk of potential accidents. Akyuz et al. [4] addressed bunkering risks from the perspective of human factors. Their study focused on predicting human errors during bunkering operations through a case study of a chemical tanker platform. They employed the shipboard operation human reliability analysis method to analyze these risks. Their research provides recommendations for reducing human errors in the bunkering process. Kamal and Kutay [5] analyzed the causal mechanisms underlying oil pollution during bunkering by using a fuzzy BN (FBN) approach with 16 root nodes. Industry experts with extensive experience identified the causal factors in their model, enabling the establishment of probabilistic relationships among these factors. The results provided solutions for regulatory authorities, and shipowners could use the findings to mitigate the risk of oil pollution associated with bunkering operations. In another study, Çiçek and Topcu [39] introduced a risk-based decision-making framework to enhance the management of operational and managerial processes in ship fleet management. FTA and evidential reasoning methods were used to analyze failures. To address the lack of information and uncertainty inherent in these processes, the model incorporated fuzzy logic. Their model was specifically applied to bunkering, one of the most critical shipboard operations: bunkering. The results demonstrated that the proposed model can produce solutions to mitigate ship bunkering risks [39]. Finally, Doganay et al. [40] performed a comprehensive risk analysis of bunkering operations, covering key stages such as the berthing and anchoring of the fuel barge, the fuel transfer process, the underthing of the fuel barge, and the voyage preparation phase. The authors utilized the conventional FMEA method, identifying nine failure modes during operation. Through their analysis, they calculated the risk priority numbers (RPN) for the identified hazards and determined the necessary precautions for each hazard. Following the implementation of these measures, they reassessed the risks and calculated the residual risk scores for each hazard. Additionally, they provided recommendations to ensure the operation was conducted safely and efficiently.

This study aims to perform a comprehensive risk assessment of ship bunkering operations using FMEA. Although the FMEA is widely used, it has some limitations, especially in terms of managing the uncertainties and dynamic complexities associated with maritime environments [41,42]. To address these issues, this study employs fuzzy FMEA (FFMEA), which integrates fuzzy logic into the FMEA framework. This integration enhances the FMEA's ability to handle uncertainties and provides a more nuanced analysis of the failure modes. By incorporating fuzzy logic, this study delivers a thorough and precise evaluation of the risks associated with ship bunkering operations. The application of FFMEA is particularly relevant given the frequent occurrence (O) and inherent risks of bunkering operations. Through an evaluation of 27 key failure modes, this study aims to identify potential vulnerabilities and offer actionable recommendations for risk mitigation. The findings are expected to significantly contribute to improving safety practices in ship bunkering operations and advancing overall risk management strategies in the maritime industry.

3. Methodology

This section covers the materials and methods used in the study. The primary material of the study was the ship fuel system, and the method employed was the rule-based FFMEA.

3.1. Ship Bunkering

Marine fuels play a pivotal role in the operation of ships, serving as the primary power source for key components such as main engines, generators, and boilers [43]. The ship fuel system refers to the complete structure that encompasses several processes, including bunkering, storage, transfer, cleaning, heating, and modification of parameters such as temperature, pressure, and viscosity of fuel [44].

The fuel system of a vessel is generally initiated at the bunker line, which is strategically located on the deck to facilitate the transfer of fuel from external sources. This line serves as the primary conduit for receiving fuel during bunkering operations and is designed to ensure efficient and secure handling of fuel, minimizing the risk of leaks and contamination. This line encompasses the interconnections, valves, sampling locations, and control points where fuel is pumped into the vessel. From this pipeline, fuel is conveyed to an appropriate storage tank within the system via valve operation. Once in the storage tank, the fuel is heated and allowed to settle before being sequentially transferred to the settling and service tanks. During this process, the fuel temperature is increased, and the fuel undergoes separation. Subsequently, the fuel, which has the temperature, pressure, and viscosity values in the desired range, is sent to the ship's engines for use.

HFO and MDO are two types of fuel commonly used by ships and are accepted as benchmarks [46]. Various fuel tanks and pipelines are used to accommodate these two types of fuel. Nevertheless, it is worth noting that the two lines may also intersect at locations where fuel changeover procedures take place. Figure 1 shows an example of a ship bunker and transfer system. The graphic illustrates fuel flow dynamics, where the brown indicators represent the HFO pathways, and the yellow indicators denote the MDO pathways.

3.2. FFMEA

FMEA is a rigorous methodology that is used in a variety of industries to examine safety and risks [47]. The efficiency of this approach in detecting and preventing possible faults has contributed to its increasing popularity [48,49]. FMEA has three fundamental elements, namely, severity (S), O, and D, which are used in the computation of a RPN. The determination of the RPN involves the multiplication of these factors, resulting in a quantitative assessment of

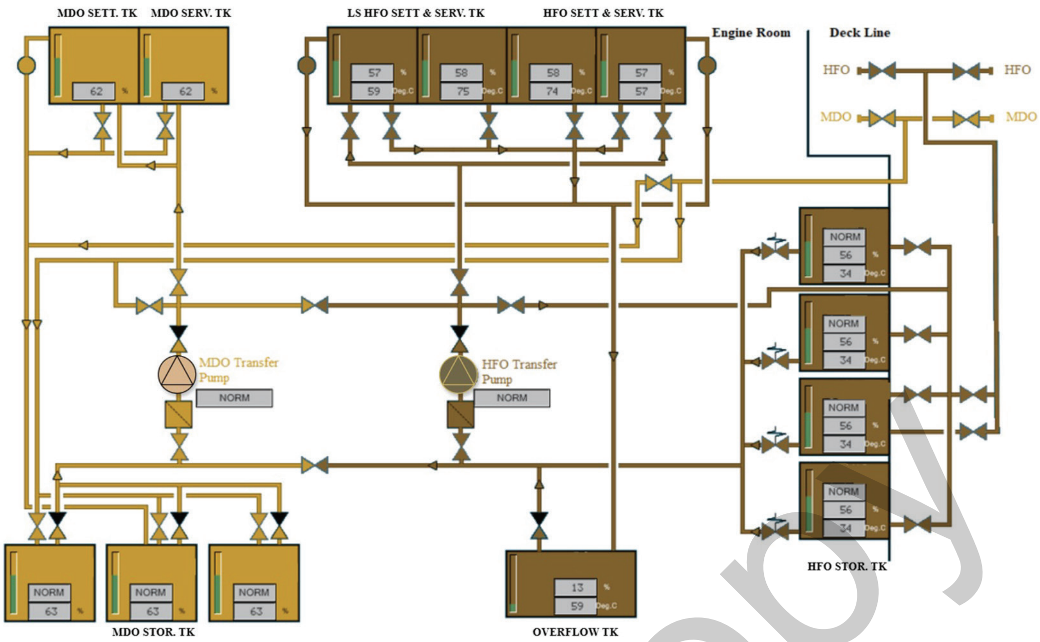


Figure 1. *Ship HFO-MDO bunker and transfer system [45]*

the risk associated with a certain failure mode [37]. The multiplication described below and given in Equation (1) forms the basis of FMEA.

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

The most commonly used rating system in the literature ranges from 1 to 10. The scale developed by Pillay and Wang [50], which is widely favored in academic literature, was used in this investigation. Tables 1-3 present this scale.

Despite the widespread use of FMEA methods, the use of risk scoring using multiplicative addition has been criticized by various authors in the literature [51,52]. The growing intricacy of the rapidly evolving environment has surpassed the constraints of conventional FMEA, resulting in the emergence of many hybrid models in recent scholarly works. The objective of these models is to improve the FMEA process and exploit its advantages [53]. The most popular method to improve FMEA is the fuzzy method [54]. Therefore, this work used fuzzy set theory to mitigate the limitations of RPN computation and improve the efficiency of the classical FMEA method. The methodological approach of the study is illustrated in Figure 2. The first step is to define the system. The failure modes of this study were then obtained from two primary data sets. The first section is a literature review; however, as mentioned in the introduction, risk analysis studies related to ship fuel bunkering are quite limited. Existing studies have identified only a small number of failure modes. Therefore, as a secondary data source, experts participating in the study were asked to identify the failure modes related to fuel bunkering. Once the failure

Table 1. *Scores for the probability of occurrence*

Score	Probability of occurrence	Possible failure rate
10	Very high	≥0.5
9	Very high	0.1
8	High	0.05
7	High	0.01
6	Medium	0.05
5	Medium	0.001
4	Medium	0.0005
3	Low	0.0001
2	Low	0.00005
1	Very low	≤0.00005

Table 2. *Scores for severity*

Score	Severity
10	Very high
9	Very high
8	High
7	High
6	Medium
5	Medium
4	Medium
3	Low
2	Low
1	Very low

modes were determined, the next step involved collecting expert scores. The fuzzy model with its inference engine and membership functions (MFs) was then established. After the fuzzification, inference engine, and fuzzification processes, the fuzzy RPN (FRPN) outputs were determined. The primary stages of the FFMEA process are described below.

Step 1. Define the system: Identify the system under consideration. The first step involves identifying the boundaries of the system, its components, and how they interact with each other and the external environment. Understanding the system is crucial for the subsequent steps in the FFMEA process.

Step 2: Provide failure modes and identify potential ways in which the system or its components can fail. This step involves brainstorming and analyzing data to identify possible failure modes.

Step 3. Get expert scores: Engage domain experts to assess the O, S, and D values of each failure mode. Experts provide their scores based on their knowledge and experience, which are crucial inputs for the FFMEA analysis.

Table 3. *Scores for probability of detection*

Score	Detectability	Detection probability (%)
10	Very high	0-5
9	Very high	6-15
8	High	16-25
7	High	26-35
6	Medium	36-45
5	Medium	46-55
4	Medium	56-65
3	Low	66-75
2	Low	76-85
1	Very low	86-100

Step 4. Construct the FFMEA model: The FFMEA model incorporates fuzzy logic to handle uncertainty and ambiguity in expert assessments. The model defines how the inputs (S, O, and D) are quizzified, processed through the rule base, and defuzzified to obtain the FRPN outputs.

Step 5. Define input MFs: Define MF for each input (S, O, D) to convert expert scores into fuzzy sets. These MF determine how each input value is mapped to a fuzzy set, capturing the linguistic variables used by the experts (e.g., "low," "medium," and "high").

Step 6. Define output MFs: Similarly, define MF for the output (RPN) to convert aggregated fuzzy scores into a FRPN. The output MF define how the FRPN values are mapped to linguistic variables (e.g., "low," "medium," "high").

Step 7. Define rule base and inference mechanism: Define rules governing how input fuzzy sets are combined to calculate the output FRPN. This involves defining the rule base (a set of if-then rules) and the inference mechanism (how the rules are applied to the input fuzzy sets).

Step 8. Obtain FRPN outputs: Apply the FFMEA model to the expert scores to obtain FRPN outputs for each failure mode. The FRPN values represent the prioritization of every possible failure mode, taking into account the uncertainties and expert judgments involved in the assessment.

4. Ship Bunkering Risk Evaluation

Ship bunkering risk assessment was carried out using the FFMEA framework. The subsequent sections encompass the risk analysis steps of the study.

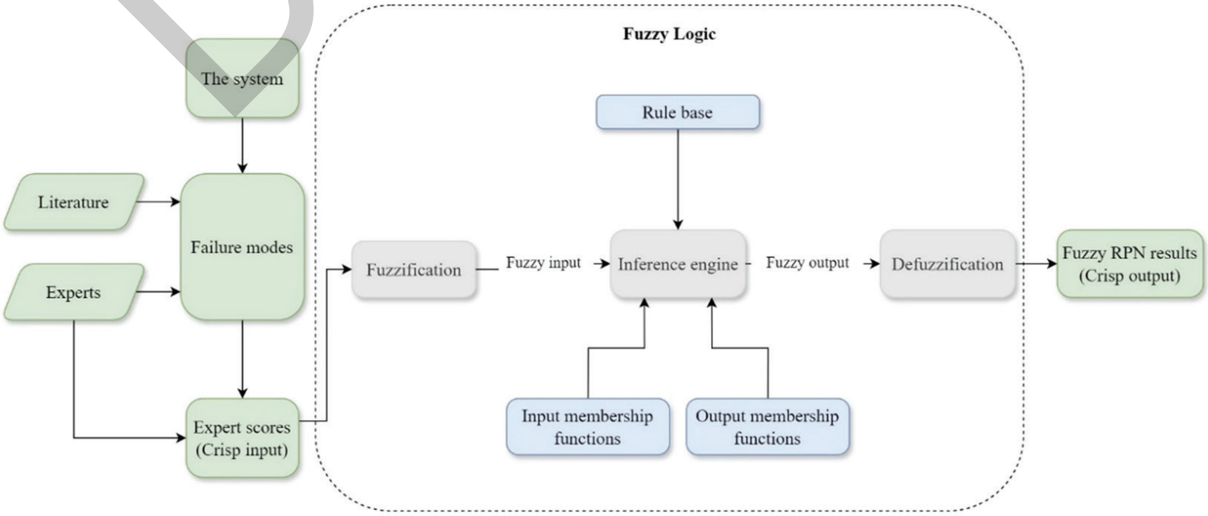


Figure 2. *Methodological framework of the study*

4.1. The System

The risk analysis system relates to bunkering operations for maritime vessels. The system consists of the following primary structural sections:

i. Failure modes concerning the vessel before berthing.

ii. Failure modes regarding the supplier before berthing.

iii. Failure modes related to preparations before transfer.

iv. Failure modes occurring during bunkering.

v. Failure modes pertaining to the completion of bunkering.

4.2. Failure Modes

The failure modes associated with bunkering have been recognized by marine engineering experts. The failure modes of the ship bunkering operations are illustrated in Table 4.

4.3. Expert Profiles

The methodological foundation of this paper is a numerical risk analysis structure based on expert systems. Consequently, expert opinions are required at certain points of the method. Since this study aims to be highly specific in the field of ship bunkering operations, the experts were selected meticulously. The experts who participated in the study were carefully selected, taking into consideration the complex technical aspects of ship bunkering operations. The research team includes five experts. To enhance the reliability of the expert evaluation, a preference was given to experts with a minimum of 15 years of professional experience. Four of the professionals hold the post of chief engineer at a tanker shipping company that operates in the seas. One of the employees of the shipping company currently occupies the role of a marine engineering technical inspector. Information about the participating experts is presented in Table 5.

4.4. Input and Output Variables

The study considered D, O, and S as the input factors. The outcome of the variable is FRPN.

4.5. Input and Output Variables

Experts submitted the failure mode O, S, and D scores generated in earlier steps. The scores obtained from the professionals are listed in Table 6.

According to the literature, the arithmetic mean (AM) and geometric mean (GM) were both used for ratings assigned by multiple experts. The AM is a simple average calculated by summing all the scores and dividing by the number of scores. This method is straightforward to understand. It works well when the dataset is relatively uniform and the scores are not significantly skewed. The geometric mean, on the other hand, is calculated by multiplying all the scores together and then taking the nth root, where n is the number of scores. This method is particularly useful when dealing with multiplicative data or when the data span several orders of magnitude. When conducting FMEA evaluations, the AM and GM approaches can be utilized interchangeably, as comparative studies have demonstrated that they yield highly similar results [55]. An examination of other FMEA studies in the existing literature indicates that both methods were employed. However, considering the FMEA's multiplicative nature, the GM might be more suitable for aggregating multiple experts scores

Table 4. *Failure modes*

Failure Mode	Definition of failure mode
FM01	Lack of knowledge or awareness about bunkering procedures
FM02	Improper bunkering procedures
FM03	Lack of familiarity with ship bunkering
FM04	Non-compliance with crew rest hour regulations
FM05	Inadequate planning and lack of pre-bunkering meetings
FM06	Blocked air vents in bunker tanks
FM07	Loose or improperly secured-sounding pipe caps
FM08	Malfunctioning low- and high-level alarms in bunker tanks
FM09	Non-operational bunker level monitoring systems
FM10	Incorrect tank-sounding measurements
FM11	Inadequate electrical insulation in bunker lines or supplier-to-ship connections
FM12	Deteriorated or damaged bunker hoses
FM13	Unsafe access between the ship and the supplier
FM14	Ineffective communication between the ship crew and the shore or barge personnel
FM15	Unplugged scuppers
FM16	Improperly designed or maintained bunker drip trays
FM17	Defective bunker manifold connections
FM18	Incorrect valve operation
FM19	Lack of proper control mechanisms
FM20	Absence of oil spill cleanup materials
FM21	Improper smoking bans
FM22	The presence of naked lights
FM23	Incorrect or substandard fuel supply
FM24	Material Safety Data Sheets for bunker fuel
FM25	Malfunctioning bunker supply line pressure and temperature gages
FM26	Improper bunker sampling procedures
FM27	Undrained bunker lines and hoses

because it mitigates the impact of outliers and provides a more robust measure of central tendency. This is especially important in risk assessment, where the goal is to obtain a reliable estimate of potential failure risks while preventing extreme values from disproportionately influencing the results. In this regard, the GM method was selected, which is a frequently preferred approach that estimates the GM of the multiple O, S, and D scores for this investigation [56]. The expert scores transformed a form suitable for fuzzy analysis by computing the GM. The expert scores geometric means are computed using the GM formula, as depicted in Equation (2).

$$\bar{X}_{geom} = \sqrt[n]{x_1 \times x_2 \times x_3 \times \ldots \times x_n} \qquad (2)$$

As an additional feature, the GM, O, S, and D values for each failure scenario are presented in Table 6.

4.6. FFMEA Model

The research is preoccupied with supplying inputs to the model and extracting outputs from the inference engine. Three input components constitute the methodological framework: O, S, and D. Input MF represent the input. The fuzzy inference engine is then provided with the inputs by using the MFs. The inference mechanism evaluates the current inputs based on the rule base. The MF for the generated outputs is then established. To assess the risks, prioritizing the RPN of identified cases is necessary. Nevertheless, in fuzzy expert systems, the final outcome following the inference stage is a fuzzy value. Accuracy and clarity of the imprecise data acquired from the fuzzy inference system are necessary. The output MF are used to achieve this objective. After fuzzification and fuzzification, the outputs (FRPN scores) are obtained. Figure 3 illustrates the FFMEA model.

4.7. Input and Output MF

Various MF can be used, such as the Gaussian MF (GMF), the trapezoidal MF (ZMF), and the triangular MF. In theory, the ZMF comprises four components denoted as s, t, u, and v. Equation (3) defines the function that determines the membership of a trapezoidal fuzzy set x= (s, t, u, v; w). The MF of variable x is denoted A (x). A normalized trapezoidal function is defined as x= (s, t, u, v; 1) when w=1.

Table 5. *Expert profiles of the study*

Expert number	International STCW competency	On-board experience	Current position
Expert No. 1	Ocean-going Chief Engineer	˃ 15-year experience	Ship Management Company: Marine Engineering Technical Inspector
Expert No. 2	Ocean-going Chief Engineer	˃ 15-year experience	Ship Management Company: Chief Engineer
Expert No. 3	Ocean-going Chief Engineer	˃ 15-year experience	Ship Management Company: Chief Engineer
Expert No. 4	Ocean-going Chief Engineer	˃ 15-year experience	Ship Management Company: Chief Engineer
Expert No. 5	Ocean-going Chief Engineer	˃ 15-year experience	Ship Management Company: Chief Engineer

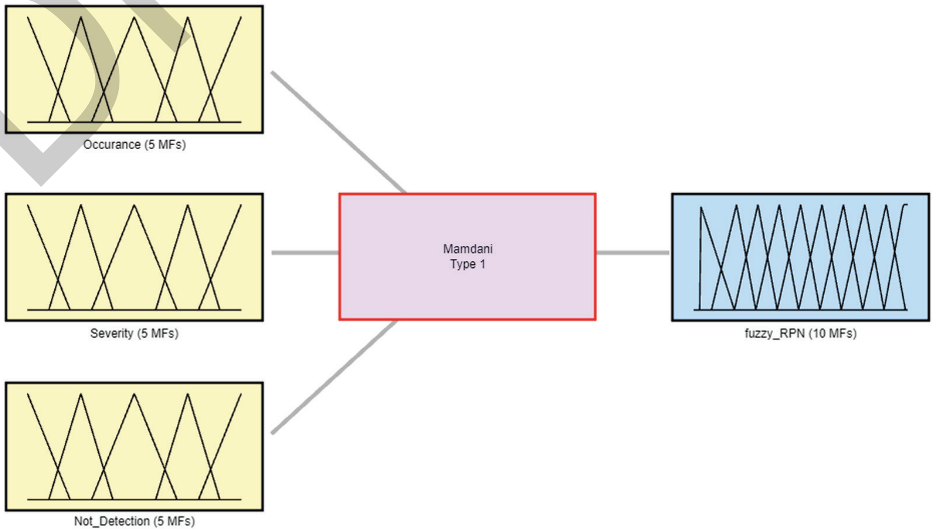


Figure 3. *FFMEA model of the study*

FFMEA: Fuzzy failure mode effect analysis

Table 6. *Expert scores of the ship bunkering operations*

FM	O_1	O_2	O_3	O_4	O_5	S_1	S_2	S_3	S_4	S_5	D_1	D_2	D_3	D_4	D_5	GM O	GM S	GM D
FM01	8	10	6	9	7	3	4	4	3	6	7	5	8	8	7	7.87	3.87	6.90
FM02	1	3	2	1	1	8	5	6	6	8	2	4	5	6	5	1.43	6.49	4.13
FM03	4	5	6	5	4	6	7	6	6	8	5	6	8	7	6	4.74	6.55	6.32
FM04	4	2	5	3	3	5	8	8	7	8	4	5	9	5	5	3.25	7.09	5.38
FM05	6	9	8	5	7	6	8	7	6	9	5	4	8	6	5	6.85	7.11	5.45
FM06	1	3	1	2	1	5	4	4	4	5	9	10	8	9	8	1.43	4.37	8.77
FM07	3	2	2	3	3	3	4	4	5	5	2	1	5	3	4	2.55	4.13	2.61
FM08	2	1	2	2	2	6	6	6	5	5	5	8	9	8	9	1.74	5.58	7.63
FM09	5	3	2	3	2	7	6	6	6	6	5	7	8	5	8	2.83	6.19	6.45
FM10	7	6	7	5	6	4	7	7	5	5	6	4	3	6	7	6.15	5.47	4.97
FM11	2	1	1	3	2	8	10	10	9	9	5	6	3	6	5	1.64	9.17	4.86
FM12	3	3	5	3	4	7	8	9	8	9	2	4	3	5	4	3.52	8.16	3.44
FM13	6	4	7	5	5	7	10	9	8	8	3	3	2	2	2	5.30	8.34	2.35
FM14	4	7	5	7	4	5	6	7	5	7	5	7	4	6	5	5.23	5.93	5.30
FM15	3	2	3	2	3	7	5	5	5	5	2	3	4	4	5	2.55	5.35	3.44
FM16	1	1	2	2	2	6	7	5	7	7	1	2	2	2	3	1.52	6.35	1.89
FM17	6	4	4	4	3	8	6	6	4	8	4	6	5	3	6	4.10	6.21	4.64
FM18	6	4	4	4	6	9	8	6	8	8	7	8	9	8	7	4.70	7.73	7.76
FM19	8	9	6	9	7	9	9	7	7	9	5	4	5	5	4	7.71	8.14	4.57
FM20	1	1	2	1	1	9	8	8	8	7	1	1	2	2	2	1.15	7.97	1.52
FM21	2	3	1	1	1	8	10	10	9	9	2	3	6	3	5	1.43	9.17	3.52
FM22	1	1	2	1	1	8	10	10	9	8	1	2	1	2	2	1.15	8.96	1.52
FM23	2	5	3	2	2	5	5	4	6	3	5	10	6	7	6	2.61	4.48	6.61
FM24	1	4	1	1	2	3	5	5	4	3	2	2	1	2	2	1.52	3.90	1.74
FM25	5	3	4	3	2	3	6	5	4	4	5	6	4	5	9	3.25	4.28	5.58
FM26	3	3	2	2	2	2	3	3	2	5	3	4	7	5	6	2.35	2.83	4.79
FM27	4	5	4	5	3	5	3	4	3	5	5	8	5	5	5	4.13	3.90	5.49

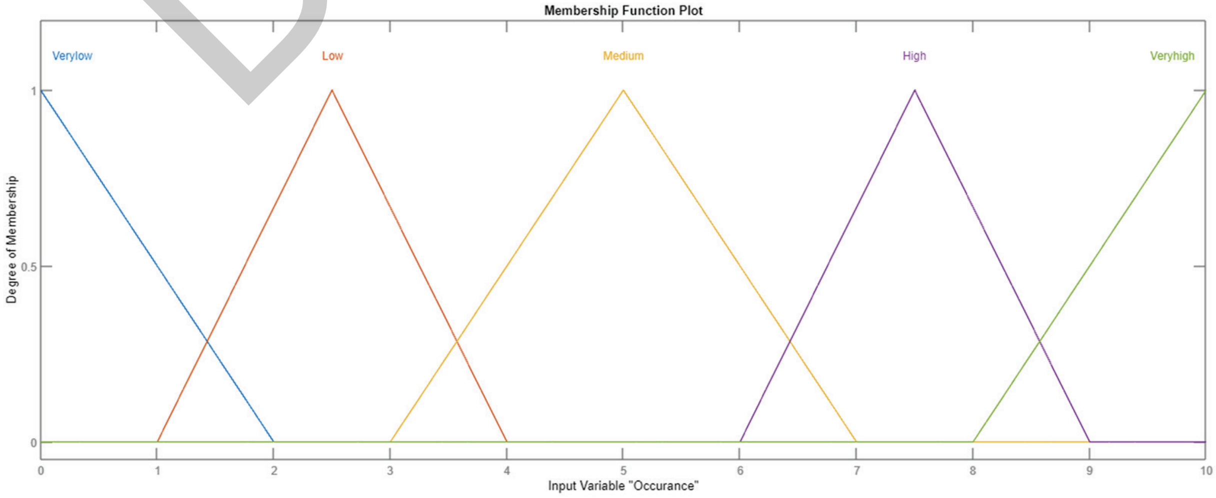


Figure 4. *Input triangular membership functions*

$$\mu A(x) = \begin{cases} \frac{w(x-s)}{t-s}, & s \le x \le t \\ w & t \le x \le u \\ \frac{w(s-v)}{u-v}, & u \le x \le v \\ 0, & otherwise \end{cases} \quad (3)$$

If the value of t is equal to u, then it is possible to simplify the trapezoidal fuzzy set to a triangular fuzzy set using Equation (4).

$$\mu A(x) = \begin{cases} 0, & x \le s \\ \frac{x-s}{t-u}, & s < x \le t \\ \frac{v-x}{v-t}, & t < x < v \\ 0, & x \ge v \end{cases} \quad (4)$$

The GMF, which is a fundamental component for modeling uncertainty in fuzzy logic systems, is expressed in Equation (5).

$$\mu A(x) = e^{\frac{-(x-m)^2}{2\sigma^2}} \quad (5)$$

The variables denoted as "m" and "σ" correspond to the AM and standard deviation, respectively [57]. The triangle MF is frequently used in academic research, especially for risk assessment, among several types of MF [58]. In addition, a triangle fuzzy MF with 5 levels was employed in this study due to its user-friendly nature. As shown in Figure 4, there are five distinct zones within the function, including the "very low", "low", "medium", "high", "very high" sections.

In contrast, the study's output MF employed a triangle MF with ten levels. As shown in Figure 5, the functional framework comprises 10 distinct zones: "none", "very low", "low", "high-low", "low-medium", "medium", "high-medium", "low-high", "high", "very high".

4.8. Rule Base

The model employs if-then rules to generate FRPN outputs as part of its inference mechanism. A 5-level input MF of O, S, and D was employed in this study. Hence, the study's rule base has 125 (5x5x5) if-then rules. Equation (6) presents the initial form of fuzzy rules.

Ri: IF o is Oi, s is Si, and d is Di, then RPN is

Ri = 1, 2, …, K (6)

Here, Ri represents the rule number, K represents the total number of rules, variables o, s, and d are antecedents, input fuzzy sets are Oi, Si, Di, and Ri, and RPN refers to the end variable. The following are a few examples of fuzzy If-then rules:

IF "O" is low and "S" is low and "D" is high, then "FRPN" is a low medium.

IF "O" is medium and "S" is medium and "D" is High, then "FRPN" is high.

IF "O" is very high and "S" is very high and "D" is high, then "FRPN" is very high.

4.9. Inference Engine

The existing literature proposes several different approaches to fuzzy inference systems, including Takagi Sugeno Kang, Mamdani, and Tsukamoto. These approaches vary according to the intended output. According to the literature, a more natural and human-like definition of expertise has been made possible by the Mamdani method [59]. Because

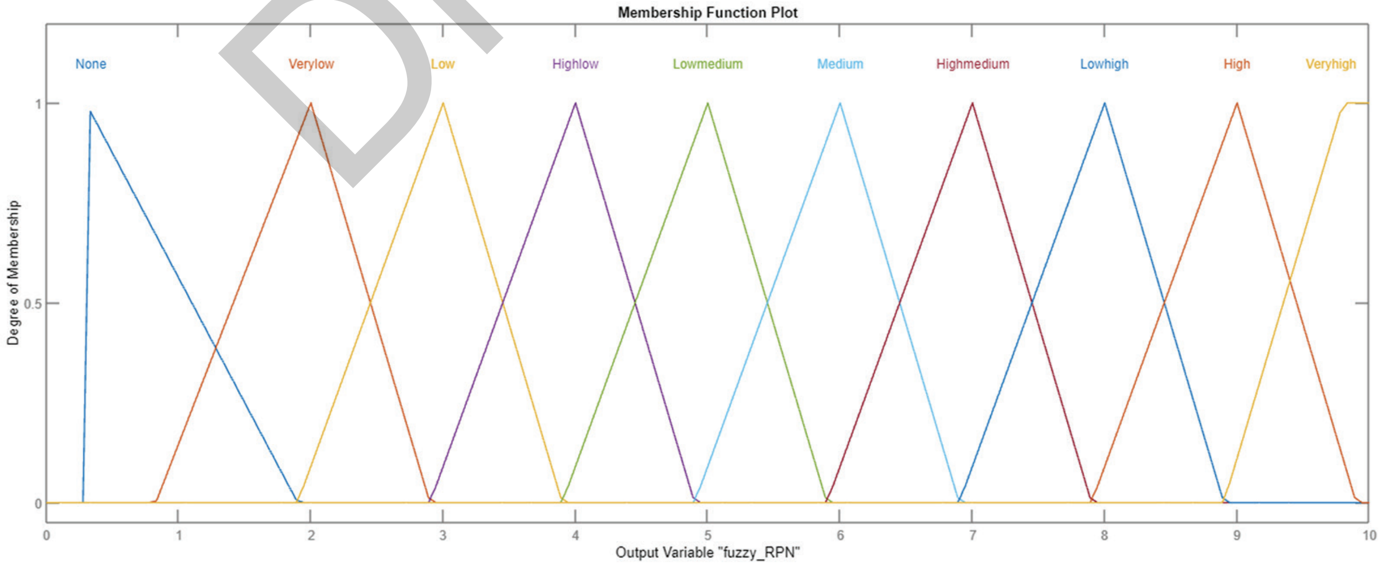


Figure 5. *The output triangular membership function*

of this, the Mamdani technique is used most often in the interface of academic studies software to combine non-linear components [60,61]. The inference approach minimizes the input and maximizes the aggregate. This approach was implemented to mitigate the issues associated with the use of multiplicative sums. The equation provided in Equation (7) is used for this method.

$$\mu_{Ri''}(RPN)=\max_{i=1,2,\ldots K}(\mu_{Ri''}(RPN)) \quad (7)$$

Several defuzzification methods have been described in the literature, such as the mean of the largest values method, the center of gravity (COG) method, the two regions method, the center of total values method, and the arranged height method. As stated in the literature, the center-of-gravity method is widely recognized as the primary fuzzification methodology, particularly in the context of FFMEA risk analysis [51,62]. In this study, the COG was used for defuzzification. Equation (8) represents the mathematical expression for the center of gravity.

$$COG=\frac{\int_a^b \mu A\ (X)\ xdx}{\int_a^b \mu A\ (X)\ xdx} \quad (8)$$

4.10. FRPN Outputs

A calculation is made using Equation (1) to determine the RPN of the per-failure. Through the process of inputting the GM, O, S, and D into the study's model, FRPN values were obtained. To illustrate the application of the fuzzy rules, an example is provided for FM18-incorrect valve operations. Based on the GM values derived from the expert assessments, the inputs for this failure mode were O (O=4.70), S (S=7.73), and D (D=7.76). These values were first quizzified into linguistic labels using triangular MFs. The fuzzification process mapped O to "medium" (membership degree: 0.7) and "high" (membership degree: 0.3), S to "high" (membership degree: 0.8) and "very high" (membership degree: 0.2), and D to "high" (membership degree: 0.9) and "very high" (membership degree: 0.1). Subsequently, the fuzzy inference system applies relevant rules from the 125-rule fuzzy rule base. For example, the rule "If O is medium and S is high and D is high then FRPN is high-medium" contributed significantly with a weighted output of 0.7×0.8×0.9=0.504. Another rule, "If O is high and S is high and D is very high then FRPN is high" contributed 0.3×0.8×0.1=0.024. The fuzzification process, which uses the COG method, aggregates the contributions from all relevant rules. Adjustments were made to align the weights and crisp values with the fuzzy logic model. For instance, crisp values of 6.8 for "high-medium" and 7.5 for "high" were used. The contributions were calculated as 6.8×0.57=3.876 and 7.5×0.04=0.3. The final defuzzified FRPN was calculated as (3.876+0.3)/(0.57+0.04)≈6.93.

The high contribution of rules involving "high" and "very high" S and D values reflects the critical nature of FM18. This result emphasizes the importance of the rule base in accurately capturing and weighing expert assessments. The rules assigned a higher weight to situations where D and S were significant, underscoring the necessity of strict valve operation protocols and enhanced D systems to effectively mitigate the risks associated with this failure mode. This robust rule-based framework ensures that the most critical failure modes are prioritized accurately for risk mitigation. The corresponding outputs of the study (FRPN) are shown in Figure 6.

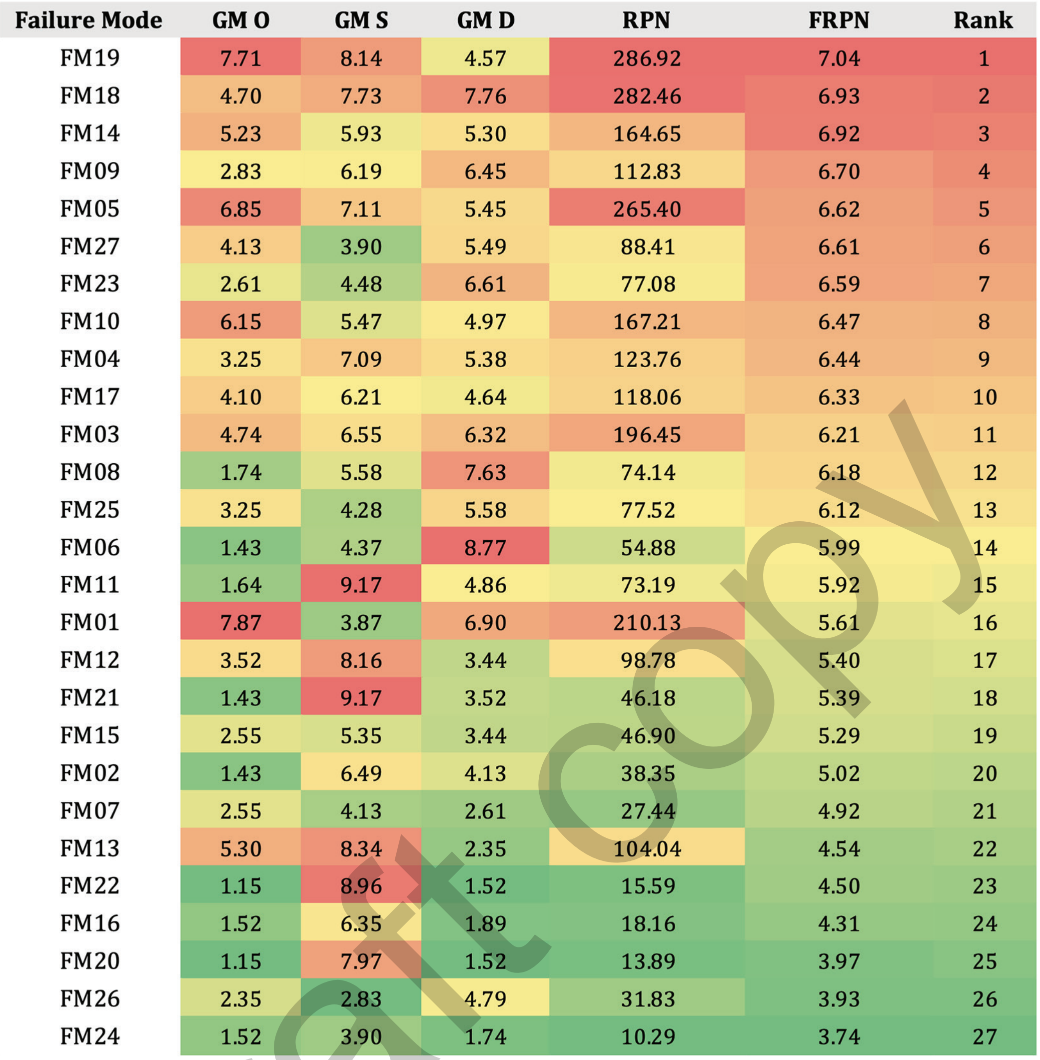
5. Discussion

The rule-based FFMEA method was used to identify the failure modes and assign corresponding weights. The analysis results yielded the following rankings based on FRPN values: FM19 (7.04), FM18 (6.93), FM14 (6.92), FM09 (6.70), FM05 (6.62), FM27 (6.61), FM23 (6.59), FM10 (6.47), FM04 (6.44), FM17 (6.33), FM03 (6.21), FM08 (6.18), FM25 (6.12), FM06 (5.99), FM11 (5.92), FM01 (5.61), FM12 (5.40), FM21 (5.39), FM15 (5.29), FM02 (5.02), FM07 (4.92), FM13 (4.54), FM22 (4.50), FM16 (4.31), FM20 (3.97), FM26 (3.93), FM24 (3.74).

FM19, which is the most critical failure mode with an FRPN score of 7.04, is defined as the "lack of proper control mechanisms." This failure mode had notably high average values for O frequency (GM O) and S (GM S). Continuous monitoring of several factors, including the pressure, tank level, and circuit leakage, is essential at each stage of the bunkering operation. These controls enable the D and correction of faults in other components prior to an accident. Control mechanisms are widely acknowledged as vital elements of modern automation systems, acting as highly effective preventive measures in both manual and automatic operations.

FM18, "incorrect valve operations" ranked second with an FRPN of 6.93. This failure mode is particularly significant because of its high GM S and GM D values. Failing to close valves at the start of the bunkering operation or opening them incorrectly can lead to leaks in the bunker/fuel line, fuel leakage, hose rupture, or fuel transfer to an incorrect tank. Furthermore, the capacity to detect improperly executed valve actions is exceedingly limited. Enhancing human factors is crucial for effectively mitigating the risks linked to this failure mechanism because it directly influences decision-making, situational awareness and adherence to company procedures.

In third place, FM14, "Ineffective communication between ship crew and shore or barge personnel" is ranked with an



Failure Mode	GM O	GM S	GM D	RPN	FRPN	Rank
FM19	7.71	8.14	4.57	286.92	7.04	1
FM18	4.70	7.73	7.76	282.46	6.93	2
FM14	5.23	5.93	5.30	164.65	6.92	3
FM09	2.83	6.19	6.45	112.83	6.70	4
FM05	6.85	7.11	5.45	265.40	6.62	5
FM27	4.13	3.90	5.49	88.41	6.61	6
FM23	2.61	4.48	6.61	77.08	6.59	7
FM10	6.15	5.47	4.97	167.21	6.47	8
FM04	3.25	7.09	5.38	123.76	6.44	9
FM17	4.10	6.21	4.64	118.06	6.33	10
FM03	4.74	6.55	6.32	196.45	6.21	11
FM08	1.74	5.58	7.63	74.14	6.18	12
FM25	3.25	4.28	5.58	77.52	6.12	13
FM06	1.43	4.37	8.77	54.88	5.99	14
FM11	1.64	9.17	4.86	73.19	5.92	15
FM01	7.87	3.87	6.90	210.13	5.61	16
FM12	3.52	8.16	3.44	98.78	5.40	17
FM21	1.43	9.17	3.52	46.18	5.39	18
FM15	2.55	5.35	3.44	46.90	5.29	19
FM02	1.43	6.49	4.13	38.35	5.02	20
FM07	2.55	4.13	2.61	27.44	4.92	21
FM13	5.30	8.34	2.35	104.04	4.54	22
FM22	1.15	8.96	1.52	15.59	4.50	23
FM16	1.52	6.35	1.89	18.16	4.31	24
FM20	1.15	7.97	1.52	13.89	3.97	25
FM26	2.35	2.83	4.79	31.83	3.93	26
FM24	1.52	3.90	1.74	10.29	3.74	27

Figure 6. *Traditional and Fuzzy RPN outputs of the study*

RPN: Risk priority number

FRPN of 6.92. In this failure scenario, the inputs for GM O, GM S, and GM D are all above-average. Inadequate communication within the ship or between the ship and the barge or shore facility during bunkering can lead to numerous errors. To mitigate this risk, it is advisable to enhance communication proficiency, provide modern technology that facilitates uninterrupted communication, or employ efficient foreign language capabilities.

Equally significant, FM09 (6.70), identified as "non-operational bunker level monitoring systems", was ranked as the fourth most critical failure mode. The primary factor contributing to its risk is difficulty in D. Before, during, and after fuel bunkering, monitoring systems measure tank levels, thereby aiding in managing the entire process. Malfunctioning monitoring systems can cause users to mislead, resulting in incorrect fuel calculations within the tank and undesirable situations, such as fuel overflow.

FM05, with an FRPN of 6.62, represents "inadequate planning and lack of pre-bunkering meetings" and is the fifth most critical failure mode. This mode has average GM values for O (GM O) and S (GM S). Bunkering is a multifaceted operation that requires coordinated and preplanned teamwork among various ship personnel, including the chief engineer, third engineer, donkeyman, fitter, and oiler. Effective planning before operation, clearly assigning each crew member's duties, and scheduling necessary checks are crucial.

The lowest priority with an FRPN value of 3.74 is FM24, "absence of material safety data sheets for bunker fuel." This indicates a relatively lower risk than other identified failure modes.

When examining the results of other studies that have conducted risk analyses on bunkering operations, Kamal and Kutay [5] approached the issue from an environmental perspective. They identified major pollution-related factors as overflow, operational causes, and crew-related causes. Similarly, Akyuz et al. [4] investigated bunkering risks with a focus on human factors. Their findings indicate that both pre-and during-bunkering operations exhibit relatively high human error probabilities (HEPs). Specific subtasks contributing to these high HEPs include low pumping at the beginning of the operation, continuous monitoring of the bunkering process, and issues such as plugged deck scuppers. On the other hand, Çiçek and Topcu. [39] highlighted failures such as inadequate control of checklists, system calibration issues, gauge errors, non-compliance with the fuel bunkering plan, and communication deficiencies as unacceptable risk levels. Furthermore, Doganay et al. [40] identified periodic inspections of level sensors in fuel tanks and pre-operation sounding measurements as critical factors. These steps ensure accurate monitoring and prevent operational risks. Many of the high-risk findings identified in previous studies were similarly ranked among the highest FRPN values in this research, underscoring the consistency and corroborative nature of this study with prior investigations. Additionally, while the majority of literature predominantly focuses on human error, this study broadens the analytical framework by incorporating the technical failures associated with contemporary technological components, such as machinery and software. By addressing these technical dimensions, this study offers a comprehensive analysis of risk factors in bunkering operations, thus contributing to a deeper understanding of the multifaceted nature of operational risks.

6. Conclusion

Ships require a continuous supply of fuel to maintain their commercial functions, which necessitates frequent execution of ship bunkering operations. Despite the critical nature of these operations for the sustenance of maritime activities, they inherently encompass a multitude of risks. The ramifications of such risks are considerable, posing severe threats to cargo integrity, human safety, and environmental preservation. Consequently, a thorough examination and identification of these hazards are imperative to prevent accidents associated with bunkering activities. This study, therefore, undertakes a comprehensive risk analysis of ship bunkering operations, motivated by the objective of enhancing safety protocols and mitigating potential hazards.

The findings quantitatively reveal the risks associated with bunkering operations. The analysis identified the most hazardous failure modes as lack of proper control mechanisms (7.04), incorrect valve operations (6.93), and ineffective communication between the ship crew and the shore or barge personnel (6.92).

The findings of this study hold significant implications for regulatory compliance, particularly concerning international maritime safety and environmental standards, such as those outlined by the IMO and The International Convention for the Prevention of Pollution from Ships. The prioritization of critical failure modes, such as improper valve operations and ineffective communication, can directly inform the design of regulatory protocols and ship-specific safety procedures. By integrating advanced risk assessment methodologies like FFMEA, shipping companies and regulatory bodies can proactively address operational risks, ensure adherence to environmental standards, and minimize the likelihood of non-compliances. Furthermore, these results offer practical insights for the development of training modules and operational checklists to enhance crew preparedness and system reliability. Ship bunkering operations exert significant environmental repercussions globally. Therefore, implementing a comprehensive risk assessment in this area is essential for mitigating the incidence of such accidents. The findings of this study have provided maritime stakeholders with a detailed quantitative risk ranking specific to bunkering operations. An accurate understanding of these risks, coupled with the implementation of proactive measures, will effectively mitigate or minimize the consequences of potential accidents.

The primary limitation of this research is the unavailability of professionals with over 15 years of ship experience, particularly those who have supervised numerous bunkering operations as chief engineers. Consequently, the study relied on input from five marine experts for analysis. While their expertise significantly contributed to the reliability of the findings, the inclusion of a more diverse panel of experts could enhance the robustness of future analyses. Expanding expert selection to include regulatory officials, port authorities and academic researchers would provide a broader spectrum of operational insights and regional variations, improving the generalizability and applicability of the risk assessment framework. Future studies should also explore hybrid risk analysis methods tailored to alternative fuels, such as methanol and ammonia, to address both emerging risks and evolving regulatory requirements in maritime operations.

Ethics

Ethics Committee Approval: The study was approved by the Bandırma University Onyedi Eylül University Science and Engineering Ethics Committee (approval no.: 2024/01, date: 11.11.2024).

Footnotes

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