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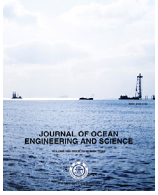

Research Paper

# D-S evidence based FMECA approach to assess potential risks in ballast water system (BWS) on-board tanker ship

Sukru Ilke Sezer[a,c,*], Bulut Ozan Ceylan[b,c], Emre Akyuz[c], Ozcan Arslan[c]

[a] *Department of Maritime Transportation and Management Engineering, Iskenderun Technical University, Iskenderun, 31200, Hatay, Turkey*
[b] *Department of Marine Engineering, Bandirma Onyedi Eylül University, Bandirma, 10200, Balikesir, Turkey*
[c] *Department of Maritime Transportation and Management Engineering, Istanbul Technical University, Tuzla, 34940, Istanbul, Turkey*

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ABSTRACT

Ballast water is essential for cargo ships since it stabilizes vessels at sea. Most ships are equipped with a ballast water system (BWS) to maintain safe operating conditions. This paper attempts to perform a risk assessment for the BWS on-board tanker ship as it poses a major threat to the operational safety of the ship, marine environment, and cargo. To achieve this purpose, the paper utilizes a robust methodology integrating D-S evidence (Dempster-Shafer) theory and FMECA (Failure mode effects and criticality analysis). In the methodology, while the D-S evidence theory introduces a proper mathematical framework to handle epistemic uncertainty in the assessment of risk parameters and to prioritize failure modes as intended, the FMECA is capable of evaluating system potential failures and their causes. Hence, the risk priority number (RPN) can be calculated to assess potential hazards and their consequences in BWS on-board ships. Besides its theoretical insight, the paper contributes to marine safety inspectors, safety researchers, and HSEQ (Health, Safety, Environment, and Quality) managers to identify potential hazards, effects, and consequences in case of BWS failures on-board tanker ships.

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## 1. Introduction

Shipping is regarded as the main element of global trade [65]. Although maritime transportation is exceedingly preferred, this sector contains various challenges and risks [40]. Therefore, safety is a great concern for maritime professionals due to the nature of their work [19]. According to the current studies, it is clear that the concept of risk in the maritime industry is a popular topic. Abdussamie et al. [1] conduct Liquefied Natural Gas (LNG) and Floating LNG (FLNG) vessels risk assessment during maneuvering in the open sea. Cheliyan and Bhattacharyya [24] handled the sub-sea production system's oil and gas leakage risks. Mehrafrooz et al. [53] performed consequence-based risk analysis in subsea pipelines. Prabowo et al. [54] carried out a thin-walled double bottom tanker risk assessment about grounding damage. Fam et al. [31] performed a human risk assessment in offshore activities. Cao et al. [16] studied gas leakage of LNG-powered ship risk analysis. Fan et al. [32] carried out Liquified natural gas (LNG) bunkering simultaneous operations (SIMOPs) risk assessment. According to related studies, most of the shipboard operations contain potential hazards and their consequences may become fatal. Additionally, the human factor is one of the significant causes of maritime accidents in the last decades [17,50]. As a result, safety has always been a focus in the marine field. The IMO (International Maritime Organisation), the regulatory body of maritime affairs, introduced numerous codes and conventions such as SOLAS (Safety of Life at Sea), STCW (International Convention on Standards of Training, Certification and Watchkeeping for Seafarers), ISM (International Safety Management) Code, etc. to enhance safety and minimize risks in maritime transportation [8]. At this point, risk assessment is the most critical issue in maritime transportation to improve safety at sea [41,66]. The ISM Code and FSA (Formal safety assessment) address risk within the safety management objectives including establishing control actions against all identified risks [36]. However, they have not prescribed any particular risk assessment techniques that can be used across the maritime domain. To remedy this gap, maritime safety researchers have been proposing some risk assessment methods in line with ISM Code and FSA. Proactive approaches play a key role in reducing and preventing the risks at sea. The most preferred risk assessment methods in maritime transportation are FTA (Fault Tree Analysis), HAZOP (Hazard and Operability Study), bow-tie analysis,

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[*] Corresponding author.
*E-mail address:* ilkesezer@gmail.com (S.I. Sezer).

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ETA (Event Tree Analysis), FMEA (Failure Mode and Effect Analysis), Fine-Kinney, etc. There are many practices of those methods that have been successfully applied in maritime such as shipboard operations [4,6,44,46,60], ship collision or grounding [9,21,30,59], oil spill/response [10,38,48] cyber security [14,23,62], etc. In recent years, Bayesian Network (BN) approach has become one of the greatest concerns in terms of maritime risk assessment. A wide range of good research papers have been published and cited on different topics in maritime [9,29,31,32,51].

As a semi-quantitative risk assessment tool, FMEA has been extensively used in the maritime domain since it provides a practical solution. There are numerous research papers presented to achieve and retain a high level of safety at sea under the FMEA approach [3,13,72,73]. Although FMEA presents a practical solution, it suffers major limitations such as different ratings may produce the same value. To overcome this drawback, different perspectives have been proposed along with FMEA [33,74]. On the other hand, uncertainties arising from expert judgments in FMEA are very important in terms of risk assessment. There are two types of uncertainty in the literature. These are the aleatory uncertainty and the epistemic uncertainty. Aleatory uncertainty is the uncertainty originating from the internal variability of the process, which cannot be decreased by further evaluation. Epistemic uncertainty arises from insufficient knowledge about the parameters affecting the process or from subjectivity [35]. Epistemic uncertainty can be handled using different methodologies. D-S evidence theory copes with epistemic uncertainty when there is insufficient or subjective information to make evaluations about the process [26,27]. Thus, it can deal with weak knowledge without needing complete knowledge of the process. In this context, this paper aims to propose D-S evidence-based FMECA approach to minimize the limitation of the traditional FMEA approach since D-S evidence provides a proper mathematical framework to tackle the epistemic uncertainty in the assessment of risk parameters.

Since there is a lack of study in the literature to address the abovementioned constraint, this work contributes to the body of knowledge by addressing epistemic uncertainty. Furthermore, the ballast system is a critical ship component that involves significant risks. However, in the literature review, no comprehensive study has been found that makes risk analysis in the ballast system with an improved FMECA approach. In view of the above, the paper is organized as follows. This section gives the motivation of the research, the scope of the paper, and a basic literature review about maritime risk assessment. Section 2 introduces methods including the integration of methodologies. Section 3 demonstrates how the proposed method can be applied to the maritime industry. Section 4 concludes the research as well as proposes further studies. In this context, the next section introduces methodologies.

## 2. Material & methods

This paper presents a hybrid approach integrating FMECA and D-S evidence techniques to conduct a risk assessment for the maritime industry. The methods are described as follows.

### 2.1. FMECA (Failure Mode, Effects and Criticality Analysis)

The FMECA is a tailored version of FMEA. It is designed to capture potential failure modes and to determine the risk associated with those failures. The method subsequently helps to prioritize them and suggests corrective actions for the most critical issues. The RPN (Risk priority number) is the critical component of FMECA to calculate and rank the risks [2]. The criticality analysis, an extended version of FMEA is used to chart the probability of failure modes against the severity of their consequences [42]. During the assessment of each failure mode, the method can give a chance to measure their criticality, enabling their prioritization and subsequent identification of appropriate mitigation measures [56]. The criticality assessment has been widely carried out by either: i.) calculating an RPN or ii.) calculating an item criticality number [15].

In this method, experts are asked to score for the O (Occurrence), S (Severity), and D (Detection) inputs, and these 3 inputs are multiplied mathematically to obtain the risk priority number (RPN) value [58]. This calculation is shown in Equation (1):

$$RPN = O \times S \times D \tag{1}$$

According to the equation expressed above, each of the inputs O, S, and D has an equal effect on the RPN value. Since it offers a simple mathematical calculation, the RPN formula is seen as a practical way in risk assessment applications [68]. Although this method is useful, it has some shortcomings in risk scoring and uncertainty [7]. According to the FMECA, experts are asked to score for the O, S, and D inputs of each failure mode, but since human judgments are subjective and uncertain, it is very difficult for experts to rate risk parameters with precise numerical values. For this reason, the interval-valued rating is needed to better convey the knowledge of the experts on the relevant subject. On the other hand, while FMEA is a viable solution, it has other drawbacks, such as the found that various ratings can produce the same number [22]. Distinct O, S, and D scores might generate an equal RPN value. For instance, calculations of 6, 5, 2, and 10, 2, 3, have the same risk number of 60. While these two scenarios have different risks. This may lead to inadequate risk assessment of the system and waste of resources.

### 2.2. D-S evidence theory

Evidence theory, which was first put forward by Dempster [28], was theorized by Shafer for the discovery of epistemic uncertainty and was exhibited as an effective mathematical framework [57]. D-S evidence theory is commonly used in the process of combining data [37,52] and the decision-making process [34].

According to D-S evidence theory, the set of propositions called frame of discernment (FOD) is denoted as Θ. It also includes exhaustive and mutually exclusive circumstances. FOD is expressed in Eq. (2), where H shows the propositions.

$$\Theta = \{H_1,\ H_2, \ldots,\ H_n\} \tag{2}$$

On the other hand, $2^{\Theta}$ denotes the power set, which specifies the cardinality of FOD and comprises all possible subsets, including the empty set ∅, and is defined in Eq. (3).

$$2^{\Theta} = \{\phi,\ \{H_1\}, \{H_2\}, \ldots\ \{H_n\},\ \{H_1 \cup H_2\}, \ldots, \{H_1 \cup H_2 \cup \ldots H_i\}, \ldots\ \{H_1 \cup H_2 \cup \ldots H_n\}\} \tag{3}$$

Where $A$ is any subset of the power set, the basic probability assignment (BPA) is the expression that shows the relationship of the power set to $A$ and indicates the belief assigned to $A$. The requirements for BPA, which is indicated by the mass function ($m$) and assigned a value in the range of [0,1], are as follows:

$$m(\emptyset) = 0 \tag{4}$$

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

The $A$ that satisfies the the Eqs. (4, 5) conditions is called the focal element.

According to the theory, given a set A in the sample space, there are two measures called Belief *(Bel)* and Plausibility *(Pl)* associated with each mass function. These are expressed in Eq. (6) and Eq. (7).

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

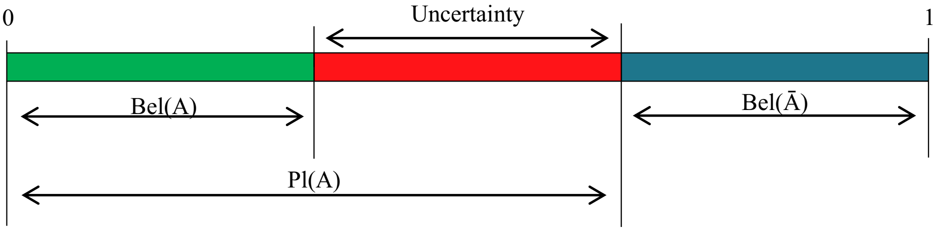


**Fig. 1.** Belief and plausibility functions.

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

Belief function *Bel(A)* shows the degree of confidence in proposition *A*. It is calculated by a sum of all the BPAs of *B*, which are the appropriate subsets of the set *A* of interest. The likelihood function *Pl(A)* defines the measure of uncertainty that seems possible for *A*. The plausibility of *A* is determined by the sum of all the BPAs of subsets *B* that intersect with *A*. In the light of all this, it can be concluded that $Pl(A) \geq Bel(A)$ and that $[Bel(A),\ Pl(A)]$ represents an indefinite range. In addition, *Bel(A)* and *Pl(A)* can be defined as the lower and upper limits of the probability.

The connection of belief and plausibility measures with each other is shown in Fig. 1. On the other hand, the mathematical representation of the relationship is as in the following axiom:

$$Pl(A) = \left[1 - Bel\left(\bar{A}\right)\right] \tag{8}$$

According to Eq. (8), $\bar{A}$ specifies the complement of *A*.

D-S evidence theory allows combining data obtained from different and independent sources. The first rule defined for the fusion process is the Dempster rule. According to this rule, the equations used to combine more than one mass function from the same FOD are as follows.

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

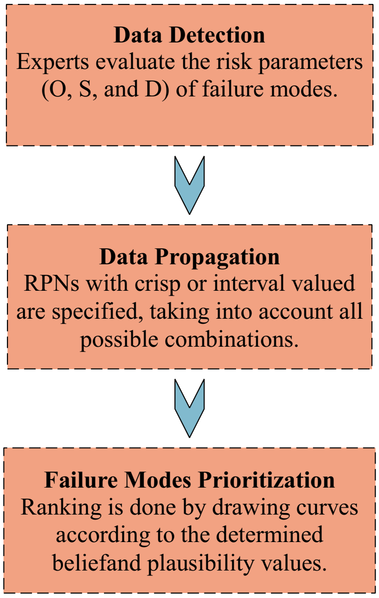
$$k = \sum_{B\cap C=\emptyset} m_1(B)m_2(C) \tag{10}$$

In Eqs. (9)-(10), $m_1(B)$ and $m_2(C)$ are two independent sources defined on $\Theta$. $k$ represents the conflict between $m_1(B)$ ve $m_2(C)$ and is called the conflict coefficient.

### 2.3. D-S evidence based FMECA approach

The D-S evidence theory is applied in many fields to overcome the epistemic uncertainty problem, according to the study's review of related literature [55,70,75]. Some of the papers use D-S evidence and FMECA together for data analysis. In these papers, the appropriate aggregation rule is generally applied [25,69]. However, applying the aggregation rule to each risk parameter of failure modes is a bit of a stretch [18]. In addition, it can be seen that there are failure modes with the same RPN value in studies where the aggregation rule is applied [61,71]. Through the method used in the paper, failure modes can be prioritized in accordance with their purpose without applying the aggregation rule by using interval-valued judgments. The D-S evidence based FMECA approach is applied using Belief and Plausibility distributions. The approach consists of three steps as shown in Fig. 2.

**Step 1. Data detection:** Traditional FMECA has some restrictions on risk scoring and uncertainty [3]. Because human judgments are subjective and uncertain, it is very tough for experts to rank O (occurrence), S (severity), and D (detection) risk parameters with precise numerical values. In this context, experts prefer to make an interval-valued rating in order to better convey their knowledge on the relevant subject. Therefore, in the study, the evaluation of the three risk parameters O, S, and D for each failure mode is done by N experts in a crisp or interval-valued manner. Input data is obtained with the help of a ten-point scale using the International Standard IEC (International Electrotechnical Commission) 60812. This means in terms of D-S evidence that a FOD overlapping with the separate interval [1,10] is identified for whole the three uncertain risk parameters. BPA, that is, the weight of the evidence, $m_{i,r,f}(X)$, which emerged as a result of the responses of the ith expert (i=1,…,N) to the $r_{th}$ risk factor (r=O,S,D) of the f failure mode is calculated as 1/N. Where $X \subseteq 2^{\Theta}$. The total evidence for the $r_{th}$ risk factor of the f failure mode is evenly distributed among the N experts. In this way, Eq. (5) is achieved and the total evidence is 1 [12,18,43].



**Data Detection**
Experts evaluate the risk parameters (O, S, and D) of failure modes.

**Data Propagation**
RPNs with crisp or interval valued are specified, taking into account all possible combinations.

**Failure Modes Prioritization**
Ranking is done by drawing curves according to the determined beliefand plausibility values.

**Fig. 2.** Follow-diagram of the D-S evidence based FMECA approach.

**Step 2. Data propagation:** After each risk factor r of failure mode f is evaluated with as crisp or interval-valued judgments as of the number of experts N, the first step is completed. The RPNs obtained by multiplying the O, S, and D parameters without any fusion process are determined and all possible z (z=1,…Z) combinations related to the failure mode f are considered. The number of combinations for each failure mode f is $N^3$, and the relevant RPN is shown as $RPN_{f,z}$. Considering that interval-valued judgments can be used, BPA, i.e. $m(RPN_{f,z})$, which is the measure corresponding to the failure mode f is calculated as the Cartesian product of the values assigned by the experts in the combination z.

**Step 3. Failure modes prioritization:** After obtaining $N^3$ RPNs for each failure mode, the prioritization of failure modes stage is started. At this stage, a comparison of $RPN_f$, the RPN of failure

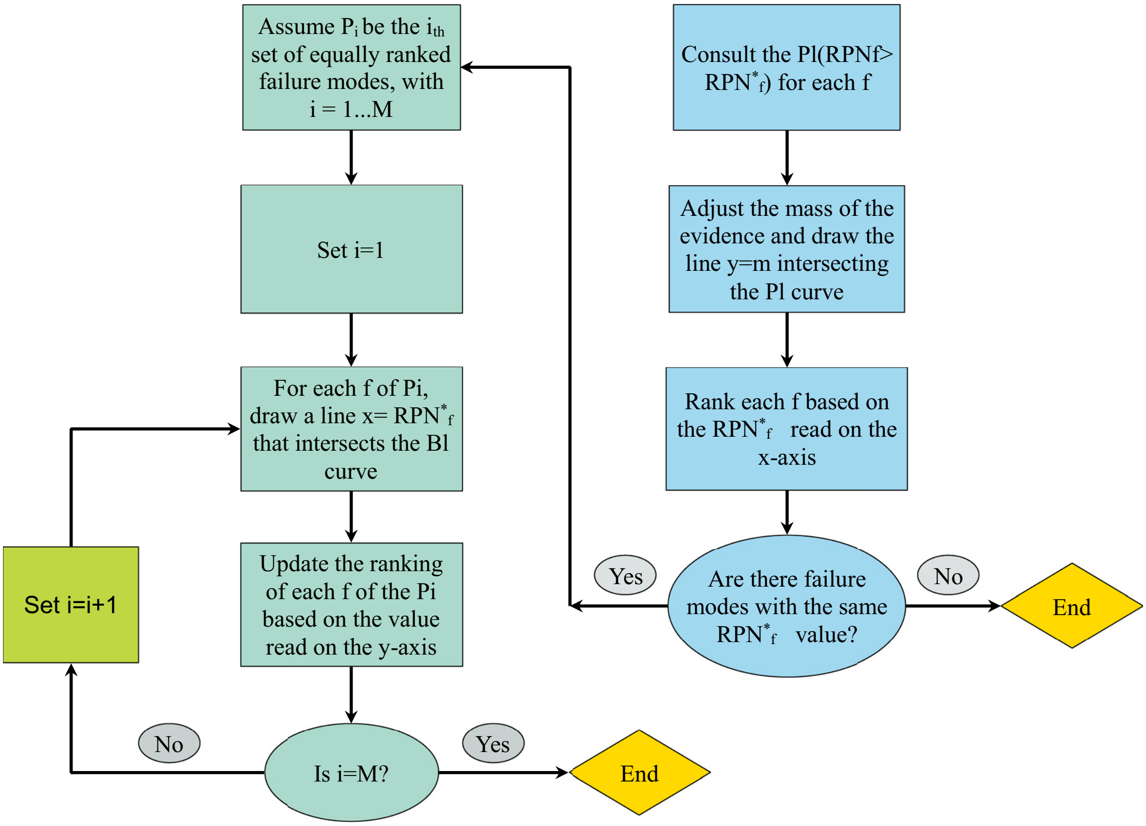


**Fig. 3.** Follow-diagram of the prioritiztion process.

mode f, with the generic threshold value RPN$^*_f$ is made in order to make the existing data more functional. During the comparison process, the axiom $\bar{E} = \{RPN_f > RPN^*_f\}$ is considered. An increase in the RPN value means that the seriousness of the failure mode is greater. Therefore, the evidence supporting the $\bar{E}$ event is analyzed. Then, for each failure mode f, the belief and plausibility distributions of the $\bar{E}$ event is plotted in accordance with the N$^3$ RPNs obtained.

For the plotting process, the upper and lower bounds of each interval value RPN$_{f,z}$ are arranged in ascending order. If any RPN$_{f,z}$ has a crisp value, it is continued by assigning the same value to the lower and upper bounds.

The belief of the complementary event, $E = \{RPN_f \le RPN^*_f\}$, is determined by the sum of the belief masses of all RPN$_{f,z}$ intervals within the interval $[0,\ RPN^*_f]$, and it is expressed by Eq. (11).

$$Bel(E) = Bel\left(RPN_f \le RPN^*_f\right) = \sum_{RPN_{f,z} \subset \left[0, RPN^*_f\right]} m\left(RPN_{f,z}\right) \tag{11}$$

The Plausibility of the event $E = \{RPN_f \le RPN^*_f\}$ is determined by the sum of the belief masses of the RPN$_{f,z}$ intervals that intersect with $[0,\ RPN^*_f]$, and it is expressed as in Eq. (12).

$$Pl(E) = Pl\left(RPN_f \le RPN^*_f\right) = \sum_{RPN_{f,z} \cap \left[0, RPN^*_f\right] \ne \emptyset} m\left(RPN_{f,z}\right) \tag{12}$$

For this reason, the Belief and Plausibility distributions of the $\bar{E}$ event is given in Eq. (13-14):

$$Bel\left(\bar{E}\right) = Bel\left(RPN_f > RPN^*_f\right) = 1 - Pl\left(RPN_f \le RPN^*_f\right) \tag{13}$$

$$Pl\left(\bar{E}\right) = Pl\left(RPN_f > RPN^*_f\right) = 1 - Bel\left(RPN_f \le RPN^*_f\right) \tag{14}$$

The higher the RPN, the more severe the failure mode, so Eq. (14) is benefited first by prioritizing the failure mode. For this, assuming that the credibility mass is m, the line y=m is drawn. The intersection point of the mentioned line with $Pl(\bar{E})$ gives the value of RPN$^*_f$ for each failure mode f. All failure modes are sorted in descending order from most serious to least serious. If different failure modes have the same RPN value and are in the same order, the value at the intersection of the x= RPN$^*_f$ line and the belief curve is taken into account. Failure modes are ranked according to decreasing belief value. The flow diagram of the prioritization process is given in Fig. 3 [18].

As a result, the FMECA method, which was explained in detail in the previous section, needs to be developed to eliminate its deficiencies. The D-S evidence based FMECA approach can solve the drawbacks of FMECA that different O, S, and D scores can generate the same RPN value. In addition, the method eliminates epistemic uncertainty in the assessment of risk parameters by providing the opportunity to provide interval-valued ratings to the experts.

## 3. Risk assessment for ballast water system on-board tanker ship

In this section, the D-S evidence based FMECA approach is applied to assess potential risks in ballast water system (BWS) onboard ship.

### 3.1. Ballast water system on-board tanker ship

Considering the nature of the shipping, ballast water is essential for safe ship operations due to stability requirements [47]. Ships pump in the seawater while the cargo unloading operation and discharge this seawater to the loading port for buoyancy. With the help of this process, ballast water exchange increases the ship's

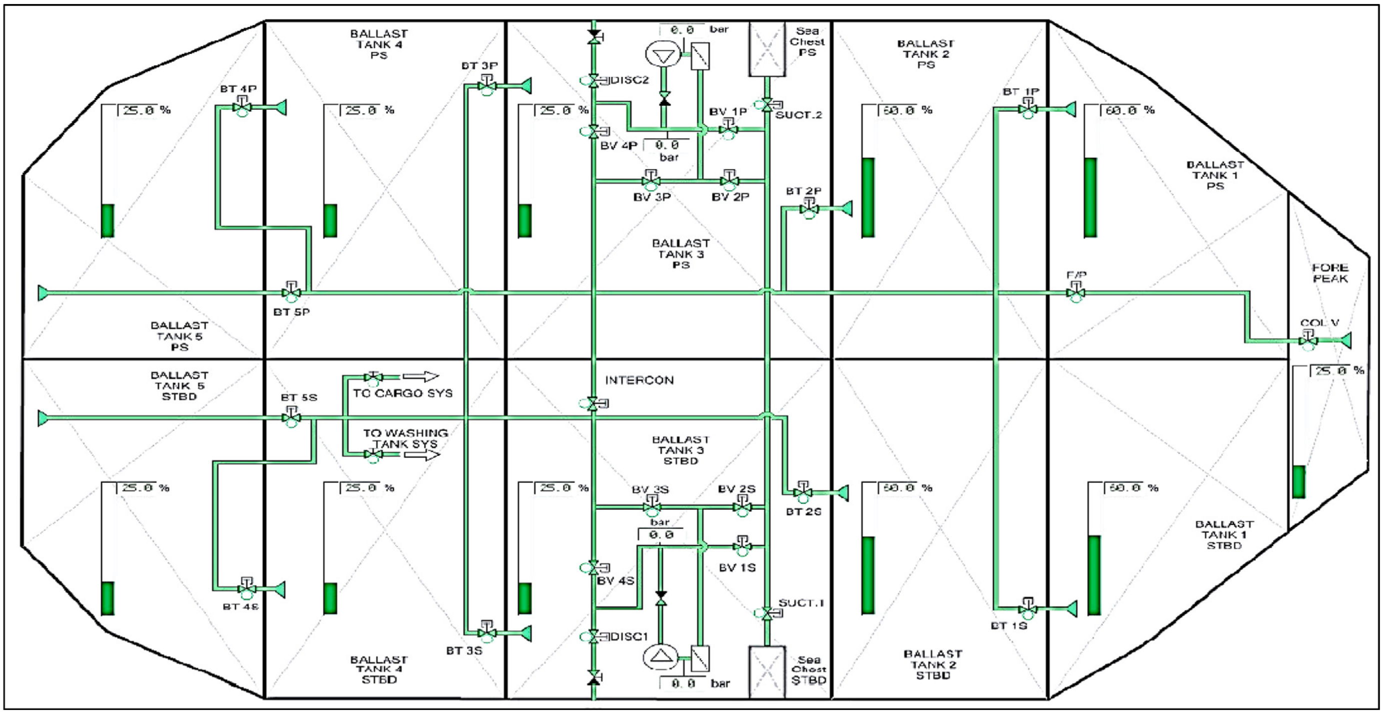


**Fig. 4.** Demonstration of the ballast water system on-board tanker ship.

stability, reduces stress on the ship's hull, and improves its propulsion of the ship [3,63]. Specifically, considering a tanker ship, it is necessary to immediately load the ballast into the ballast tanks during the cargo discharge, as well as quickly ballast discharge with the cargo loading operations. In this respect, BWS in tanker ships is capable of changing the quantity of ballast at any time to adjust the ship's list depending on the loading/unloading steps or the cargo plan. Therefore, it can be operated more frequently during any loading/unloading operation compared to other ship types. Additionally, tanker ships have a deeper draft compared to other ships due to the liquid cargo. For this reason, ballast operations are more critical on this type of ship. Although the ballast system helps to increase the safe navigation of the ship, it contains potential hazards such as leakage, contamination, etc. Therefore, a comprehensive risk assessment is required to minimize potential hazards and their consequences. In the paper, a 60k deadweight product tanker is selected which is equipped with a MAN B&W 6S50MC-C type BWS. It is a common type of BWS in tanker ships. As seen in Fig. 4, sea chests supply seawater to the pumps, the seawater pumps pressurized the water and pumped the ballast tanks with the help of the system valves. According to the ship and its cargo type, valves varied as manually or remote-controlled. In this study, both of them are examined. In addition, the Ballast Water Treatment System (BWTS) integrated BWS is demonstrated since the BWTS is mandatory for ships.

### 3.2. Empirical risk assessment

In the view of the proposed D-S evidence theory-based FMECA approach, a comprehensive risk assessment is performed. In the application stage, four experts (N=4) with extensive knowledge and experience in BWS were selected. The expert group consists of academicians who have worked as marine engineers on board and are currently researching marine engineering safety. There are 20 failure modes (illustrated in Table 1), which are created as a result of the FMECA analysis carried out regarding BWS. The failure modes, causes, and their effects were obtained in the view of the group of experts as well as Class guidance/circulars. According to Table 1, the failure causes and the failure effects of each failure mode that is likely to occur in components are included.

Furthermore, Table 2 shows the experts' assessments for each failure mode. For the assessment process, the ten-point numerical scales of the risk parameters O, S, and D are considered. When assessing the parameters, experts indicate their judgments by crisp or interval values.

Since four experts are involved in the assessment of each failure mode, the BPA for each expert judgment of each failure mode is 1/4. In addition, the RPN values of each failure mode are determined without applying any combining rule. All possible combinations are considered when determining the RPN value. Since there are four experts in the study, $4^3$, i.e. 64 combinations are detected. Each combination provides a crisp or interval RPN value with a BPA equal to 1/64. Table 3 shows 64 combinations for failure mode 4.2. Belief and plausibility curves are drawn according to the 64 combinations obtained. Exemplarily, the belief and plausibility curves of 4.2, the most critical failure mode, are illustrated in Fig. 5.

The mass of evidence m is adjusted to 0.9 for each failure mode [18,43]. $RPN^*_f$, the threshold value of the failure mode f, is determined by the intersection between $Pl(RPN_f > RPN^*_f)$ and the y=0.9 line. $RPN^*_f$ values of all failure modes are determined and ranking according to values is obtained. The relevant ranking is presented in Table 4. It is understood from Table 4 that failure mode 4.2 is the most critical. On the other hand, it is seen that there are failure modes with the same $RPN^*_f$ value.

For fault modes with the same $RPN^*_f$ value, a line is drawn from the point $x = RPN^*_f$ parallel to the y-axis. The point where the line intersects with the belief curve gives the belief value of the event $(RPN_f > RPN^*_f)$. For example, according to Table 4, failure modes 6.2 and 7.1 have the same $RPN^*_f = 216$. Figs. 6 and 7 show the belief and plausibility curves of the failure modes to distinguish the difference between the related modes. To determine the criticality between failure modes, the line x=216 is drawn. The

**Table 1**
FMECA analysis of the system.

| Component | Failure mode | Failure cause | Failure effect |
|---|---|---|---|
| C1. Sea Chest | FM1.1. Sea chest blockage | Large size pollutants | Supply line water flow stoppage |
| | FM1.2. Sea chest filter contamination | Small particle size impurities | Decreasing seawater supply line water flow |
| | FM1.3. Seawater leakage | Improper maintenance, corroded or cracked material, out of order alarm system, insufficient control | Seawater leakage, stoppage of engine operations, loss of propulsion power, flooding, stranding, foundering |
| C2. SW Pump Inlet Filter | FM2.1. Filter contamination | Small particle size impurities | Seawater supply line water flow deceasing |
| C3. SW Pump | FM3.1. Low discharge flow | Low inlet water flow, clogged parts, damaging or wearing pump parts | Decreasing supply line water flow |
| | FM3.2. Pump blockage | Clogged parts, damaged parts | Stoppage of supply line water flow, extra maintenance costs |
| | FM3.3. Leakage | Improper maintenance, deformed or cracked materials | Seawater leakage |
| | FM3.4. High power consumption | Improper maintenance, clogging parts, high pump speed | High generator load, high fuel consumption |
| C4. Valves | FM4.1. Leakage | Corroded or cracked materials, insufficient control | Seawater leakage in the area |
| | FM4.2. Improper valve operations | Lack of occupational knowledge and experience, improper familiarization, insufficient control, deficient procedures | Improper ballasting and de-ballasting operations, losing vessel's stability, flooding, grounding |
| | FM4.3. Stuck valves | Improper maintenance, corroded-deformed material, insufficient control | Extra maintenance costs, delayed ballasting and de-ballasting operations |
| | FM4.4. Remote control failure | Improper maintenance, insufficient hydraulic oil, deficient control-feedback signal, insufficient control | Extra maintenance costs, delaying ballasting and de-ballasting operations |
| C5. Tanks | FM5.1. Excessive or inadequate filling | Human fault, false level alarms | Improper ballasting and de-ballasting operations, losing vessel's stability |
| C6. Level Indicators | FM6.1. Level control failure | Improper maintenance, insufficient control, deficient procedures | Improper ballasting and de-ballasting operations, losing vessel's stability |
| | FM6.2. Calibration fault | Insufficient control, deficient procedures | Improper ballasting and de-ballasting operations, losing vessel's stability |
| C7. Safety System | FM7.1. False level alarms | Insufficient control, deficient procedures | Improper ballasting and de-ballasting operations, losing vessel's stability |
| | FM7.2. Out of order alarm system | Human fault, insufficient control, deficient procedures | Improper ballasting and de-ballasting operations, losing vessel's stability |
| C8. Pipeline | FM8.1. Leakage | Corroded or cracked materials | Seawater leakage |
| C9. BWTS | FM9.1. Out of order BWTS | Human error, improper maintenance, insufficient control, | Untreated ballast water |
| | FM9.2. Inadequate treatment | Deficient BWTS components, improper maintenance | Low treatment capacity |

**Table 2**
Experts assessment.

| Failure Mode | Expert 1 | | | Expert 2 | | | Expert 3 | | | Expert 4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Occurrence | Severity | Detection | Occurrence | Severity | Detection | Occurrence | Severity | Detection | Occurrence | Severity | Detection |
| 1.1 | [4,6] | [6,6] | [2,3] | [4,4] | [5,6] | [2,3] | [4,5] | [4,6] | [2,3] | [4,5] | [4,5] | [3,4] |
| 1.2 | [7,8] | [2,5] | [2,3] | [7,8] | [4,5] | [3,4] | [7,7] | [5,5] | [4,4] | [7,8] | [3,4] | [3,4] |
| 1.3 | [2,4] | [8,8] | [4,5] | [2,3] | [7,8] | [5,5] | [2,3] | [8,9] | [4,5] | [2,2] | [7,8] | [4,5] |
| 2.1 | [5,6] | [5,6] | [4,5] | [3,4] | [5,5] | [6,7] | [5,6] | [5,5] | [5,6] | [5,5] | [5,6] | [6,6] |
| 3.1 | [6,7] | [2,3] | [4,5] | [7,8] | [3,3] | [4,5] | [7,8] | [3,4] | [4,5] | [6,7] | [3,4] | [4,5] |
| 3.2 | [3,3] | [4,5] | [2,3] | [2,2] | [3,5] | [4,5] | [3,4] | [3,4] | [3,4] | [3,3] | [3,4] | [3,4] |
| 3.3 | [5,6] | [5,6] | [3,4] | [4,5] | [6,6] | [3,4] | [4,5] | [6,7] | [3,3] | [4,5] | [5,6] | [3,4] |
| 3.4 | [4,5] | [2,3] | [7,8] | [4,5] | [4,4] | [7,8] | [5,5] | [2,3] | [7,8] | [4,5] | [2,3] | [8,9] |
| 4.1 | [4,5] | [7,8] | [4,5] | [4,5] | [7,9] | [5,6] | [4,4] | [7,8] | [4,5] | [4,5] | [6,7] | [5,5] |
| 4.2 | [5,6] | [8,9] | [8,9] | [5,6] | [8,8] | [9,9] | [4,5] | [7,9] | [8,9] | [5,6] | [8,8] | [8,9] |
| 4.3 | [6,6] | [7,8] | [7,8] | [5,5] | [6,7] | [6,7] | [5,6] | [5,6] | [7,8] | [5,6] | [6,7] | [7,8] |
| 4.4 | [3,4] | [6,7] | [5,6] | [5,6] | [6,7] | [6,7] | [3,5] | [6,8] | [5,6] | [4,5] | [7,7] | [6,7] |
| 5.1 | [3,4] | [5,6] | [4,5] | [3,3] | [5,6] | [4,5] | [3,4] | [4,6] | [4,5] | [3,4] | [4,5] | [4,5] |
| 6.1 | [4,5] | [7,8] | [5,6] | [5,6] | [7,7] | [7,7] | [5,6] | [7,8] | [5,6] | [6,6] | [7,8] | [6,6] |
| 6.2 | [3,3] | [7,8] | [8,9] | [4,5] | [7,8] | [9,9] | [2,3] | [7,8] | [9,9] | [3,4] | [7,8] | [8,9] |
| 7.1 | [3,5] | [6,7] | [8,9] | [3,4] | [5,7] | [8,9] | [3,4] | [6,7] | [8,9] | [3,4] | [5,6] | [7,9] |
| 7.2 | [3,3] | [8,9] | [7,8] | [2,3] | [8,9] | [8,9] | [2,3] | [8,9] | [8,9] | [2,3] | [7,8] | [6,7] |
| 8.1 | [4,5] | [7,8] | [4,5] | [3,4] | [8,8] | [4,5] | [4,4] | [7,8] | [4,5] | [2,3] | [7,8] | [3,4] |
| 9.1 | [2,3] | [3,4] | [3,4] | [2,2] | [3,4] | [3,4] | [2,3] | [2,4] | [2,3] | [2,3] | [3,4] | [3,5] |
| 9.2 | [3,4] | [7,8] | [3,4] | [3,4] | [7,8] | [3,4] | [3,4] | [7,8] | [3,3] | [2,3] | [5,6] | [2,3] |

**Table 3**
Computed combinations for failure mode 4.2.

| Failure Mode | Combination Number | Occurrence | Severity | Detection | RPN |
|---|---|---|---|---|---|
| 4.2 | 1 | [5,6] | [8,9] | [8,9] | [320,486] |
| | 2 | [5,6] | [8,9] | [9,9] | [360,486] |
| | 3 | [5,6] | [8,9] | [8,9] | [320,486] |
| | 4 | [5,6] | [8,9] | [8,9] | [320,486] |
| | 5 | [5,6] | [8,8] | [8,9] | [320,432] |
| | 6 | [5,6] | [8,8] | [9,9] | [360,432] |
| | 7 | [5,6] | [8,8] | [8,9] | [320,432] |
| | 8 | [5,6] | [8,8] | [8,9] | [320,432] |
| | 9 | [5,6] | [7,9] | [8,9] | [280,486] |
| | 10 | [5,6] | [7,9] | [9,9] | [315,486] |
| | 11 | [5,6] | [7,9] | [8,9] | [280,486] |
| | 12 | [5,6] | [7,9] | [8,9] | [280,486] |
| | 13 | [5,6] | [8,8] | [8,9] | [320,432] |
| | 14 | [5,6] | [8,8] | [9,9] | [360,432] |
| | 15 | [5,6] | [8,8] | [8,9] | [320,432] |
| | 16 | [5,6] | [8,8] | [8,9] | [320,432] |
| | 17 | [5,6] | [8,9] | [8,9] | [320,486] |
| | 18 | [5,6] | [8,9] | [9,9] | [360,486] |
| | 19 | [5,6] | [8,9] | [8,9] | [320,486] |
| | 20 | [5,6] | [8,9] | [8,9] | [320,486] |
| | 21 | [5,6] | [8,8] | [8,9] | [320,432] |
| | 22 | [5,6] | [8,8] | [9,9] | [360,432] |
| | 23 | [5,6] | [8,8] | [8,9] | [320,432] |
| | 24 | [5,6] | [8,8] | [8,9] | [320,432] |
| | 25 | [5,6] | [7,9] | [8,9] | [280,486] |
| | 26 | [5,6] | [7,9] | [9,9] | [315,486] |
| | 27 | [5,6] | [7,9] | [8,9] | [280,486] |
| | 28 | [5,6] | [7,9] | [8,9] | [280,486] |
| | 29 | [5,6] | [8,8] | [8,9] | [320,432] |
| | 30 | [5,6] | [8,8] | [9,9] | [360,432] |
| | 31 | [5,6] | [8,8] | [8,9] | [320,432] |
| | 32 | [5,6] | [8,8] | [8,9] | [320,432] |
| | 33 | [4,5] | [8,9] | [8,9] | [256,405] |
| | 34 | [4,5] | [8,9] | [9,9] | [288,405] |
| | 35 | [4,5] | [8,9] | [8,9] | [256,405] |
| | 36 | [4,5] | [8,9] | [8,9] | [256,405] |
| | 37 | [4,5] | [8,8] | [8,9] | [256,360] |
| | 38 | [4,5] | [8,8] | [9,9] | [288,360] |
| | 39 | [4,5] | [8,8] | [8,9] | [256,360] |
| | 40 | [4,5] | [8,8] | [8,9] | [256,360] |
| | 41 | [4,5] | [7,9] | [8,9] | [224,405] |
| | 42 | [4,5] | [7,9] | [9,9] | [252,405] |
| | 43 | [4,5] | [7,9] | [8,9] | [224,405] |
| | 44 | [4,5] | [7,9] | [8,9] | [224,405] |
| | 45 | [4,5] | [8,8] | [8,9] | [256,360] |
| | 46 | [4,5] | [8,8] | [9,9] | [288,360] |
| | 47 | [4,5] | [8,8] | [8,9] | [256,360] |
| | 48 | [4,5] | [8,8] | [8,9] | [256,360] |
| | 49 | [5,6] | [8,9] | [8,9] | [320,486] |
| | 50 | [5,6] | [8,9] | [9,9] | [360,486] |
| | 51 | [5,6] | [8,9] | [8,9] | [320,486] |
| | 52 | [5,6] | [8,9] | [8,9] | [320,486] |
| | 53 | [5,6] | [8,8] | [8,9] | [320,432] |
| | 54 | [5,6] | [8,8] | [9,9] | [360,432] |
| | 55 | [5,6] | [8,8] | [8,9] | [320,432] |
| | 56 | [5,6] | [8,8] | [8,9] | [320,432] |
| | 57 | [5,6] | [7,9] | [8,9] | [280,486] |
| | 58 | [5,6] | [7,9] | [9,9] | [315,486] |
| | 59 | [5,6] | [7,9] | [8,9] | [280,486] |
| | 60 | [5,6] | [7,9] | [8,9] | [280,486] |
| | 61 | [5,6] | [8,8] | [8,9] | [320,432] |
| | 62 | [5,6] | [8,8] | [9,9] | [360,432] |
| | 63 | [5,6] | [8,8] | [8,9] | [320,432] |
| | 64 | [5,6] | [8,8] | [8,9] | [320,432] |

intersection point of the belief curve and the line is identified. Accordingly, it is defined as $Bel(RPN_{6.2}> 216) = 0.25$ and $Bel(RPN_{7.1}> 216) = 0$. In this case, failure mode 6.2 is more critical than 7.1. The same procedure is applied for all failure modes with equal $RPN^*_f$ values. As a result, the final ranking is shown in Table 5.

### 3.3. Findings and extended discussions

Because of the findings, 9 significant components in BWS and 20 failure modes (FM) were defined by the 4 marine experts to indicate potential risks of the ballast water system. In the analysis,

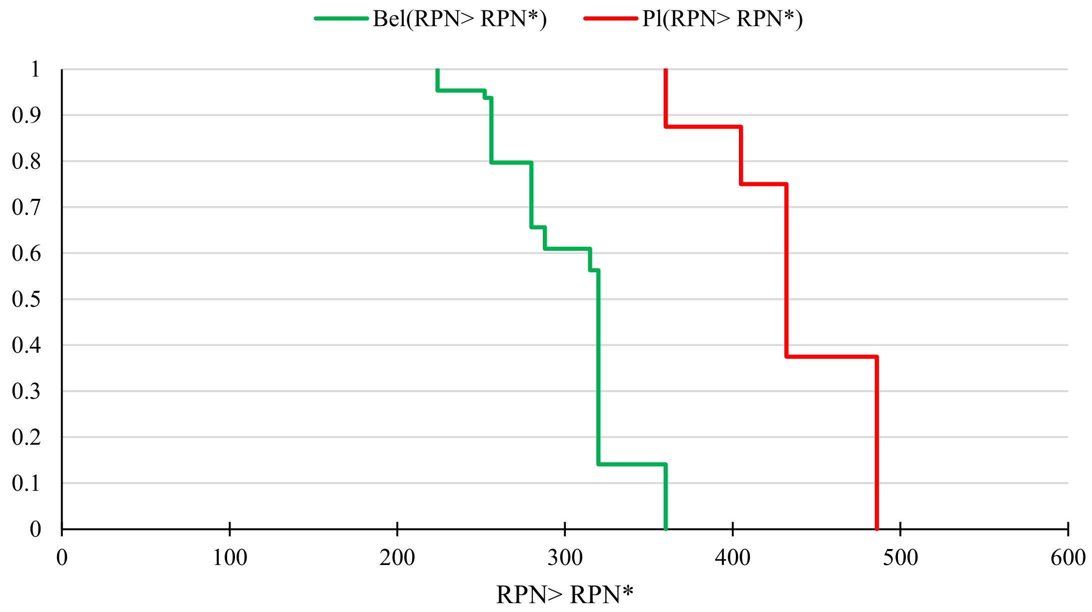


**Fig. 5.** Belief and plausibility curves of failure mode 4.2.

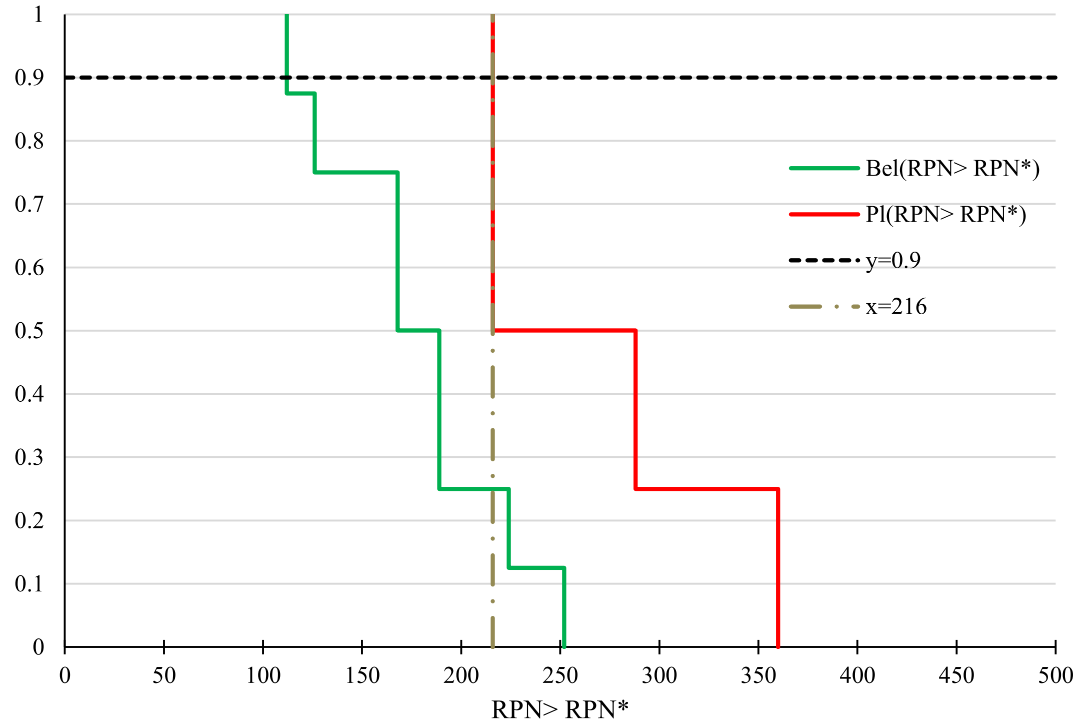


**Fig. 6.** Belief and plausibility curves of failure mode 6.2.

the most important failure modes are found 4.2, 4.3, 6.1, 6.2, and 7.1 accordingly. In the view of Table 5, FM 4.2 (improper valve operations) has the highest RPN value with 360. Because, this failure mode has the potential to cause major problems such as losing the vessel's stability, flooding, and grounding. Faulty operations, which are caused by human error, are frequently detected on ships. Additionally, due to insufficient warning mechanisms, it is extremely difficult to detect faulty valve operation onboard ships. Similarly, FM 4.3 (stuck valves) with a value of 252 is another critical failure mode under the C4 (valves) component as it has the second-highest RPN among the other factors. Detection difficulty is the major threat of this mode. The cause of this failure mode is generally based on human factors such as improper maintenance, insufficient control, etc. Stuck valves can also lead to major problems on ships by causing extra maintenance costs and prolonged ballast operations. FM 6.1 (level control failure) that having the third-highest RPN score is the different important factor of the analysis. Level monitoring of the ballast water tanks is a highly critical system on ships. Since the ballast operations are monitored with the help of this system, a possible failure may lead to improper ballasting/deballasting operations and losing the vessel's stability. Additionally, FM 6.2 (calibration fault) of the level indicators ranks in fourth place among all failure modes. This failure mode has close failure causes with FM 6.1. However, calibration fault, which can only be revealed by periodical onboard tests has a difficult detection process. On the other hand, the FM 7.1 (false level alarms) of

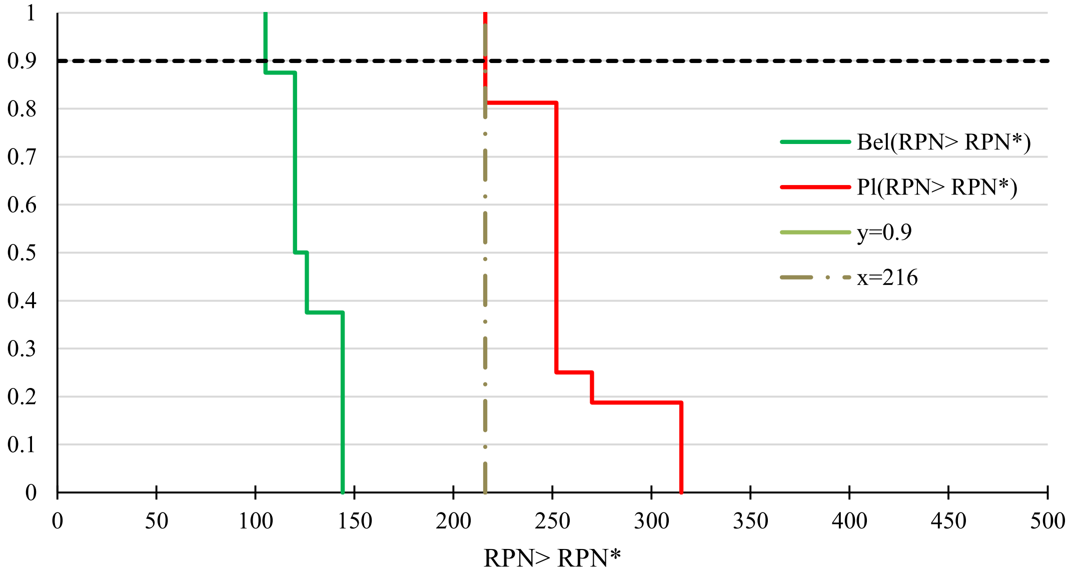


**Fig. 7.** Belief and plausibility curves of failure mode 7.1.

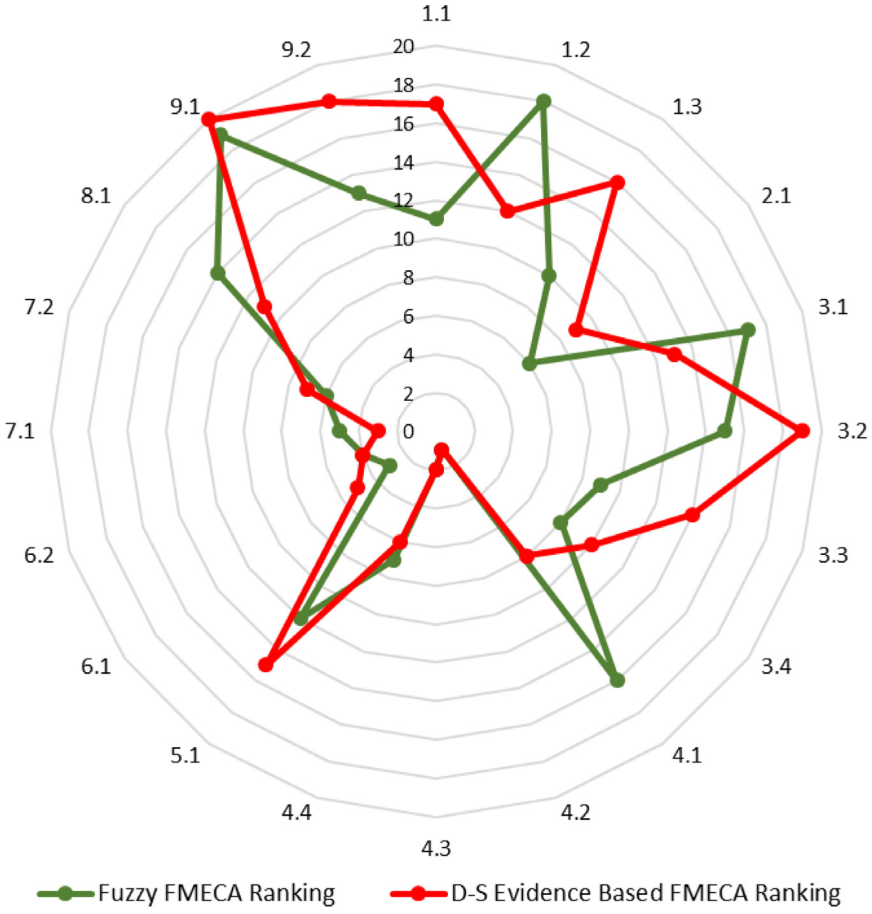


**Fig. 8.** D-S evidence based FMECA and fuzzy FMECA ranking results.

the safety system is another critical factor with the same RPN score of FM 6.2 (216). Safety systems are one of the most important risk-reducing barriers on ships. Misleading safety system alarms such as ballast tank low/high level can cause a losing ship's stability. For this reason, the ship crew must ensure that the safety system is always active and working properly. In this context, other failure modes are ranked by their RPN scores respectively as shown in Table 5. FM 6.2 and FM 7.1 ($RPN^*_{6.2}= RPN^*_{7.1}=216$) have the same priority and ranking score as seen in Table 4. However, FM 6.2 achieved fourth and the FM 7.1 got the fifth final ranking as shown in Table 5. On the other hand, there are other FMs with the same $RPN^*_f$ value in Table 4 ($RPN^*_{2.1}=RPN^*_{3.4}=RPN^*_{8.1}=120$, $RPN^*_{1.2}=RPN^*_{3.1}=105$, etc.). Thanks to the method applied in the paper, in addition to coping with the epistemic uncertainty that

**Table 4**
Ranking of failure modes according to plausibility curves.

| Failure Mode | $RPN^*_f$ | Ranking |
|---|---|---|
| 4.2 | 360 | 1 |
| 4.3 | 252 | 2 |
| 6.1 | 240 | 3 |
| 6.2 | 216 | 4 |
| 7.1 | 216 | 4 |
| 4.4 | 192 | 5 |
| 7.2 | 189 | 6 |
| 4.1 | 160 | 7 |
| 2.1 | 120 | 8 |
| 3.4 | 120 | 8 |
| 8.1 | 120 | 8 |
| 1.2 | 105 | 9 |
| 3.1 | 105 | 9 |
| 3.3 | 90 | 10 |
| 5.1 | 90 | 10 |
| 1.3 | 80 | 11 |
| 1.1 | 72 | 12 |
| 9.2 | 72 | 12 |
| 3.2 | 32 | 13 |
| 9.1 | 32 | 13 |

**Table 5**
Final ranking of failure modes.

| Failure Mode | $RPN^*_f$ | $Bel(RPN_f > RPN^*_f)$ | $Pl(RPN_f > RPN^*_f)$ | Final Ranking |
|---|---|---|---|---|
| 4.2 | 360 | - | - | 1 |
| 4.3 | 252 | - | - | 2 |
| 6.1 | 240 | - | - | 3 |
| 6.2 | 216 | 0.25 | 0.9 | 4 |
| 7.1 | 216 | 0 | 0.9 | 5 |
| 4.4 | 192 | - | - | 6 |
| 7.2 | 189 | - | - | 7 |
| 4.1 | 160 | - | - | 8 |
| 2.1 | 120 | 0.563 | 0.9 | 9 |
| 3.4 | 120 | 0.109 | 0.9 | 10 |
| 8.1 | 120 | 0.094 | 0.9 | 11 |
| 1.2 | 105 | 0.25 | 0.9 | 12 |
| 3.1 | 105 | 0 | 0.9 | 13 |
| 3.3 | 90 | 0.125 | 0.9 | 14 |
| 5.1 | 90 | 0 | 0.9 | 15 |
| 1.3 | 80 | - | - | 16 |
| 1.1 | 72 | 0.125 | 0.9 | 17 |
| 9.2 | 72 | 0 | 0.9 | 18 |
| 3.2 | 32 | 0.297 | 0.9 | 19 |
| 9.1 | 32 | 0 | 0.9 | 20 |

affects input evaluations, FMs with the same $RPN^*_f$ value can be prioritized through belief and plausibility curves as explained in Section 3.2.

As a result, a ship's ballast water system has a significant impact on both ship stability and cargo. Therefore, detecting potential risks associated with the BWS system before an accident occurs is crucial for ship safety. With this study, D-S evidence (Dempster-Shafer) theory and FMECA (Failure mode effects and criticality analysis) were integrated and a risk assessment of the BWS on-board tanker ship was performed and possible failure modes of the ballast water system were detected and ranked. Human factor-based failure modes have a major influence on BWS safety on-board tanker ships, according to the findings. This study contributed to the literature by combining two robust theoretical methods. Besides its theoretical insight, the study helps maritime stakeholders such as safety inspectors, safety researchers, and HSEQ (Health, Safety, Environment, and Quality) managers in identifying potential hazards, effects, and consequences in the occurrence of BWS failures on-board ships.

### *3.4. Comparison with a fuzzy FMECA approach*

In this section, the results of D-S evidence-based FMECA are compared to the fuzzy FMECA methodology to demonstrate the performance of the proposed method. The fuzzy logic system is founded on the concept that some issues do not need a precise or right solution, and can be solved using experience or expert knowledge [22]. Fuzzy FMECA has also grown in popularity as a result of standard FMECA's shortcomings [20]. FFMECA consists of the following steps [45]: define linguistic terms, shape the membership functions, generate the rule base, transform crisp input data to fuzzy values, evaluate the rule base, combine the results of the rules, transform the output data to values that aren't fuzzy. For comparison, the triangular membership function, which is predominantly used in the literature, is preferred. A triangular membership function can be expressed as a triplet A=(l,m,u). l, m and u are crisp numbers and they set a precedent for lower, medium, and upper numbers of a fuzzy (l<m<u) [11,64]. This fuzzy set A in the infinite of discourse X is described by a membership function presented as $\mu$A(x), which can be expressed in the Eq. (15) [39]:

$$\mu A(x) = \begin{cases} 0, & x < l \\ (x-1)/(m-l), & l \le x \le m \\ (u-x)/(u-m), & m \le x \le u \\ 0, & x \ge u \end{cases} \tag{15}$$

In addition to the membership functions, a rule base and an inference engine mechanism are the other main components of this approach. The rule base is a kind of knowledge base determined by experts. An example of an if-then rule structure is demonstrated in Eq (16):

$$Ri : IF\ o\ is\ Oi\ and\ s\ is\ Si\ and\ d\ is\ Di\ THEN\ RPN\ is\ Ri \quad i = 1, 2, \ldots, K \tag{16}$$

where Ri is the rule number; o,s, and d are leading variables; K is the total number of rules $O_i$, $S_i$, $D_i$, and $R_i$ are input fuzzy sets; RPN is the outcome variable. The other fundamental element, the inference engine, is a mechanism that produces outputs based on the interaction of the inputs and the rule base [5].

Matlab R2020b Fuzzy Logic Designer Tool is used in this study. In this program interface, mostly preferred Mamdani is used for aggregating nonlinear factors. Additionally, minimum input and maximum aggregate method inference technique and center of gravity (COG) method for defuzzification are performed. Mathematically, COG can be expressed as in Eq (17):

$$COG = \frac{\int_a^b \boldsymbol{\mu A(X)xdx}}{\int_a^b \boldsymbol{\mu A(X)xdx}} \tag{17}$$

Finally, with the help of the fuzzy FMECA model of the study, fuzzy RPN numbers were calculated. The dataset was collected from four marine experts with sufficient knowledge and experience in maritime safety and tanker ships. With this calculation, fuzzy FMECA risk analysis of BWS on-board tanker ship is demonstrated in Table 6.

In the comparative analysis of BWS failure modes, the D-S evidence based FMECA verifies the results of the fuzzy FMECA method. D-S evidence based FMECA and fuzzy FMECA ranking results are illustrated in Fig. 8. In this figure, each failure mode rankings according to two different approaches were compared. In the light of the findings, there was no variation in the top five significant failure modes. On the other hand, there have been some changes in the rankings of other failure modes.

On the other hand, the fuzzy FMECA approach, which eliminates various shortcomings of traditional FMECA, is a useful and widely used method [49,67]. However, in this method, equal RPN values of different failure modes can be calculated depending on

**Table 6**
Ranking of failure modes according to fuzzy FMECA.

| Failure Mode | Fuzzy RPN | Ranking |
|---|---|---|
| 4.2 | 7.60 | 1 |
| 4.3 | 7.43 | 2 |
| 6.1 | 7.22 | 3 |
| 6.2 | 7.20 | 4 |
| 7.1 | 7.12 | 5 |
| 2.1 | 6.93 | 6 |
| 7.2 | 6.93 | 6 |
| 4.4 | 6.92 | 7 |
| 3.4 | 6.39 | 8 |
| 3.3 | 6.34 | 9 |
| 1.3 | 6.03 | 10 |
| 1.1 | 5.93 | 11 |
| 5.1 | 5.92 | 12 |
| 9.2 | 5.91 | 13 |
| 8.1 | 5.67 | 14 |
| 3.2 | 5.12 | 15 |
| 4.1 | 4.93 | 16 |
| 3.1 | 4.34 | 17 |
| 1.2 | 4.12 | 18 |
| 9.1 | 3.93 | 19 |

the membership functions. According to the fuzzy FMECA results, failure modes 2.1 and 7.2 have the same fuzzy RPN values. In this sense, the D-S evidence based FMECA approach can solve the drawbacks of the fuzzy FMECA that different O, S, and D scores can generate the same RPN value.

## 4. Conclusion

Risk assessment is one of the most important concerns in terms of enhancing the level of safety and minimizing potential hazards in the maritime industry. In this paper, the D-S evidence based FMECA method is utilized for a detailed risk assessment. The method is quite beneficial in the assessment of safety systems where precise and reliable information is not available and can cope with the epistemic uncertainties of expert judgments. In this context, the BWS, which is of great significance for the safety of the ship, the marine environment, and the cargo, is examined. With the proposed method, the marine experts can express the O, S, and D risk parameters with interval-valued judgments and the limitations of the traditional FMECA method can be minimized. Thus, the knowledge of the experts and their interpretations of the relevant subject is handled more accurately. On the other hand, failure modes can be appropriately prioritized through the method.

Potential risks in BWS are evaluated for the application of the utilized methodology. According to the assessments performed by the marine expert group participating in the study, the findings show FM4.2 (improper valve operations) is the most critical failure mode in BWS. In addition, the findings of the research show that all of the 20 detected failure modes differ after the steps of the prioritization procedure are applied.

In conclusion, potential failure modes that can occur in BWS are analyzed and prioritized with an approach that uses D-S evidence theory and FMECA methods in an integrated manner. In this respect, it contributes to risk assessment methods theoretically as well as provides a practical perspective on BWS failures, their effects, and consequences on maritime safety. Due to the lack of data in the maritime industry, O, S, and D input data were obtained from experts who have experience in ballast operations on tanker ships. The results are compared with the fuzzy FMEA approach for validation. The failure mode rankings determined by both methodologies are similar and the findings are consistent. The proposed risk analysis approach can be applied in different industries with a wide variety of risks such as aviation, rail, off-shore, petrochemical, or nuclear power plant, as in maritime.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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