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Operational risk assessment of ballasting and de-ballasting on-board tanker ship under FMECA extended Evidential Reasoning (ER) and Rule-based Bayesian Network (RBN) approach

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ABSTRACT

Ballasting and de-ballasting operations play a critical role in maintaining stability and safety onboard tanker vessels. The process involves considerable risks to human health, the marine environment and property since the failures during the operation may lead to loss of equipment, serious balance defection and related safety problems, and harm to the coastal ecosystems. In this context, this paper aims to fill the gap concerning this problem by analyzing the operational risks of ballasting and de-ballasting performed on tanker ships. It is utilized a robust methodological approach, Failure Mode Effects and Criticality Analysis (FMECA) to provide a detailed insight into operational hazards, and Evidential Reasoning (ER) and Rule-based Bayesian Network (RBN) to tackle with limitations of FMECA by evaluating the hazards' importance degrees. The highest-ranked risks are found as "unsynchronized cargo and ballast operation" with a crisp risk value of 50.59 and "excessive list during cargo operation" with 47.08 crisp risk value, while the least crisp risk valued (21.94) failure is "undetected blockage of air vents". Besides its robust theoretical background, the paper provides valuable insights to tanker officers, shipowners, safety and technical inspectors to minimize risks and enhance safety at the operational level onboard tanker vessels.

1. Introduction

A significant part of the cargo is transported by seaway, with growing cargo volumes and an increasing number of vessels. Ships are loading cargoes every day at different ports around the world, then navigating to the discharge port to perform the operation reversely. During these operations, the stability and buoyancy of the ship must be monitored and ensured, since tons of liquid, solid, or gas substances are transferred from the vessel to shore or vice versa [1]. Ballasting and de-ballasting are performed simultaneously with the cargo operations to achieve optimal balance conditions. Seawater, widely known as ballast water, is taken inside the ship when it is unloading the cargo or is discharged from the vessel during the loading process to support its stability form and maneuverability. It is pumped in the vessel's designated tanks used for holding the ballast water and integrated with specific pipelines and pumping systems [2]. However, many risks have been found due to the discharge of ballast water in particular for the marine environment, over time. The microorganisms or other sea life are easily transferred with the ballast water inside the ships, navigating between different regions' ports [3]. It has been observed and proven that the release of unmanaged ballast waters harms both local marine habitats and human health [4].

The International Maritime Organisation (IMO), the responsible authority for global maritime issues, deals with the problems and risks affecting human life, ship safety, and the marine environment. It produces rules and regulations for commercial cargo ships and inspects their compliance with those requirements periodically. One of the most important rules of IMO is the Ballast Water Management Convention (BWMC) which is adopted in 2004 and entered into force in 2017. It aims to protect the marine environment, therefore introduces requirements for ship ballasting and de-ballasting process. The vessels are required to implement a BWM plan which is prepared according to the ship's design and capacity, keep a ballast water record book, and manage and control the ballast water with specific D-1 and D-2 standards of the convention. While D-1 includes the requirements for the exchange of ballast water, the D-2 standard addresses the criteria

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concerning the viable organisms in the ballast water to avoid the transfer of invasive aquatic species [5]. To meet those criteria, ships must have a type-approved treatment system onboard, such as systems that apply chemical treatment, deoxygenation of water, and treatment with Ultra-violet lights or electro-chlorination, etc. [6]. Also, ships are required to fulfill all maintenance needs and control that equipment to ensure their appropriate and effective operations.

Ballasting and de-ballasting operation of ships is performed using the complex integrated system consisting of sea chests, pipelines, valves, pumping arrangements, stripping ejectors, treatment systems, sensors and alarms to fill, empty and monitor the ballast tanks. The safety and proper implementations of ballasting and de-ballasting are directly linked to the effectiveness of those systems. It is essential and one of the critical operations on-board to ensure the stability and balance of the vessel, since failures during ballasting and de-ballasting may lead to accidents such as foundering or flooding [7,8], therefore loss of lives, ship and the cargo, and also harm the marine environment. Operational risks of the ballasting and de-ballasting process should be evaluated to detect and overcome the deficiencies in the system to implement safe operations and prevent such accidents.

Assessment of risks, the importance of which is increasing in recent years in the maritime industry, aims to find the factors that may cause dangerous situations in a system or operation and reduce the risk to acceptable values. IMO emphasizes the application of Formal Safety Assessment (FSA) for the maritime sector to evaluate the risks. It is a rational, structured, and systematic method that follows the steps of identifying hazards, risk analysis, risk control measures, cost-benefit assessment, and recommendations to create a safer environment [9]. FSA aims to improve the safety of operations to protect human life, property and the marine environment, however, it is not stated by IMO which tools and techniques to be used for the risk analysis. Therefore, different methods have been applied and suggested for various marine fields in literature to enlighten maritime professionals [10–17]. Recently, risk analysis techniques such as Fault Tree Analysis (FTA) [18–20], Event Tree Analysis (ETA) [21,22], Bow-Tie Analysis [23,24], Hazard and Operability study (HAZOP) [25], Failure Modes and Effects Analysis (FMEA) [26–28] is widely cited in maritime literature. These risk analysis techniques have some limitations. Therefore, researchers have integrated techniques such as fuzzy logic, Bayesian network (BN) and Dempster–Shafer (D-S) evidence theory into risk analysis methods to cope with limitations and obtain more accurate results. In this context, there are various risk assessments on subjects such as marine accidents [29–31] shipboard operations [32,33], autonomous ships [34–36], marine environment [37,38], and ship navigation [39–41] in the field of the maritime industry.

Ballasting and de-ballasting operation is an essential and critical operation on-board ships, however, there is a research gap in the literature assessing operational risks. Most of the studies have been conducted about environmental threats to ballast water such as invasive species and pathogens [4,42,43], ballast sampling [44], evaluating ballast water treatment and using treatment systems [5,45–48], risk assessment during ballast tank maintenance [49] or potential risks in ballast water system [28]. Therefore, this paper aims to assess the risks of the ballasting and de-ballasting process by including the potential failures in terms of shipboard operational aspects since those failures may lead to serious accidents, and affect life, property, and the marine environment. In the stage of numerical analysis, FMECA extended ER and RBN approach is implemented. In FMECA, where risk parameters are evaluated by experts, ER is performed to reduce the subjectivity of experts and to combine the assessments of different participants. RBN graphically visualizes the dependency relationships of risk variables and enhances the reasoning and quantification power of FMECA. Thus, this robust combined methodology is attracting attention in the literature, as the ER and RBN help to handle the limitations of FMECA, while the FMECA allows for a detailed hazard assessment.

In this context, the paper presents four sections. This section introduces ballast water and its effects on the environment, international regulations for ballast operation on ships, need and motivation for operational risk assessment of the ballasting and de-ballasting process. Section 2 provides methodological steps and the proposed approach. Section 3 includes the application of risk assessment, and then, discusses the application findings. Finally, Section 4 concludes the paper.

2. Methodology

This section provides detailed information about the theoretical background of the methodologies utilized in the paper.

2.1. Evidential Reasoning

Evidential reasoning (ER) based on Dempster-Shafer's theory is applied to deal with conflict and fusing problems. First introduced in 1994 [50,51], ER has been developed in later times [52]. Afterwards, it is widely used in many different domains of science and engineering [53–58].

Let's assume that L experts perform the evaluation process $e_i(i = 1, 2\ldots, L)$. A set of experts can be defined as $E = \{e_1, e_2, \ldots, e_i \ldots e_L\}$ The relative importance weights of the experts are expressed with the set $w = \{w_1, w_2, \ldots w_i, \ldots w_L\}$. Here w_i represents the weight of the ith (e_i) expert and it is $0 \leq w_i \leq 1$. On the other hand, an expert's collective expression of N different evaluation grades is $H = \{H_1, H_2, \ldots, H_n, \ldots, H_N\}$. In addition, the evaluation made by e_i can be shown mathematically as follows in Eq (1).

$$S(e_i) = \left\{\left(H_n, \beta_{n,\ i}\right),\ n = 1,\ \ldots,\ N\right\}\ i = 1,\ \ldots,\ L \tag{1}$$

Here, $\beta_{n,i}$ indicates the degree of belief assigned to the nth parameter by the ith expert, and $\beta_{n,i} \geq 0$, $\sum_{n=1}^{N} \beta_{n,\ i} \leq 1$. Let β_n be assumed as the degree of belief for which the parameter H_n is evaluated. By performing the evidential reasoning algorithm, the degree of belief of multiple experts can be brought together and $\beta_n(n = 1, \ldots, N)$ can be formed.

$\beta_{n,i}$, which expresses the degree of belief, can be converted into basic probability masses by using Eqs. (2) and (3). $m_{n,i}$ represents the basic probability mass for the H_n parameter of the ith expert. Also, $m_{H,i}$ is the probability mass that remains unassigned for any parameter, considering all the evaluations made by the ith expert for parameter N.

$$m_{n,i} = w_i \beta_{n,\ i} \tag{2}$$

$$m_{H,i} = 1 - \sum_{n=1}^{N} m_{n,i} = 1 - w_i \sum_{n=1}^{N} \beta_{n,\ i} \tag{3}$$

$m_{n,I(i+1)}$ is the fused basic probability mass that takes into account the evaluations made by the i+1 expert according to the relevant parameter. The fusing process can be calculated with the help of the following Eqs. (4) and (5). β_n denotes the normalized degree of belief in the final combined result I.

$$m_{n,I(i+1)} = K_{I(i+1)}\left(m_{n,I(i)} m_{n,(i+1)} + m_{n,I(i)} m_{H,(i+1)} + m_{H,I(i)} m_{n,(i+1)}\right) \tag{4}$$

$$K_{I(i+1)} = \left[1 - \sum_{t=1}^{N} \sum_{j=1,\ j\neq t}^{N} m_{t,\ I(i)} m_{j,\ i+1}\right]^{-1} \quad i = 1, \ldots, L - 1 \tag{5}$$

$$\beta_n = \frac{m_{n,\ I(L)}}{1 - \overline{m}_{H,I(L)}} \tag{6}$$

2.2. FMECA

Failure mode and effect analysis (FMEA) is one of the practical risk assessment tools that focus on analyzing possible failure modes and their effects on equipment and system performance. FMECA is an extension of FMEA where failure modes are prioritized based on risk. The technique was first applied in the aerospace field [59]. Afterwards, it was performed in many industries such as automotive [60], maritime [61], electrical engineering [62], energy [63], nuclear power plant [64], and chemical [65]. In FMECA, failure modes are prioritized by calculating RPNs associated with three risk parameters, occurrence (O), severity (S), and detection (D). The RPN is determined in Eq. (7) as follows.

$$RPN = O \; x \; S \; x \; D \tag{7}$$

The application of FMECA in risk and safety assessment processes has some limitations [66]. The relative weights of the risk parameters are not taken into account. Different combinations of risk parameters can calculate the same RPN value. In the method, which considers three risk factors in terms of safety, the uncertainty and subjectivity of expert judgments are ignored. Therefore, hybrid approaches including methods such as D-S theory [67], fuzzy logic [68], and Bayesian Networks [69] are recommended to improve the performance of FMECA.

2.3. Rule-based Bayesian Network

Rule-based Bayesian Network (RBN) is the approach in which linguistic evaluations are used instead of numerical evaluations. It consists of rules in which causal relationships and influential magnitudes are defined within the network. The antecedent and concluding sections involve linguistic variables [70]. In RBN, where IF-THEN rules are performed, qualitative aspects of fuzzy human information are handled without using exact quantitative values. In the IF part of the rules, p attendance attributes $\{A_{1,} \; A_{2,} \; \ldots, \; A_{p,} \; \}$ are specified, while in the THEN part it is transformed into q $\{C_{1,} \; C_{2,} \; \ldots, \; C_{q,} \; \}$ states with a belief degree $\{B_{1,} \; B_{2,} \; \ldots, B_{q,} \; \}$. The w-th rule, denoted as R_w, can be shown as follows [69–71].

$$R_w \; : IF \; A_1^w and \; A_2^w \; and \ldots and \; A_p^w, \; THEN \left\{ \left(B_1^w, C_1\right), \; \left(B_2^w, C_2\right), \; \ldots, \; \left(B_q^w, C_q\right) \right\}$$

After creating the rules that represent ambiguous information, all of them are combined to form a rule-based set. Thus, the RBN approach can be applied to produce the final result by utilizing Bayes' chain rules.

2.4. Integration of methodologies

This section describes how methods are integrated. Fig. 1 depicts the conceptual framework of methodologies.

Step 1. Determination of failure modes and construction of the Bayesian Network: Failure mode categories are defined in accordance with the subject discussed. Each failure mode category contains failure modes within itself. Then, a Bayesian network is established, where failure modes are at the root nodes, failure mode categories are at the intermediate nodes, and the general risk is at the leaf node [69,72].

Step 2. Expert evaluations: In this step, the O, S, and D parameters of each failure mode in the risk model are assessed by experts according to the linguistic scale in Table 1. Accordingly, experts indicate their degree of belief in each item on the scale. The inputs obtained from different experts for each failure mode are fused with the help of ER. Thus, the nodes expressing the O, S, and D parameters of each failure mode are identified.

Step 3. Derivation of rules: Various rules are derived in the FMECA-based BN after expert assessments are fused. Rules specify degrees of belief of states (very low, low, average, high, very high). First, the rules for root nodes with failure modes are determined. These rules are constituted by considering the evaluations that can be made to the risk parameters (O, S, D). Rules are generated associated with five linguistic variables and a total of 125 (5 × 5 × 5) Bayes rules are obtained [69].

Table 1
The linguistic scale of risk parameters O, S, and D.

Risk Parameter / Scale	1	2	3	4	5
Occurrence (O)	Very Low (VL)	Low (L)	Average (A)	High (H)	Very High (VH)
Severity (S)	Negligible (N)	Marginal (MA)	Moderate (MO)	Critical (CR)	Catastrophic (CA)
No Detection (D)	Highly Unlikely (HU)	Unlikely (U)	Average (A)	Likely (L)	High Likely (HL)

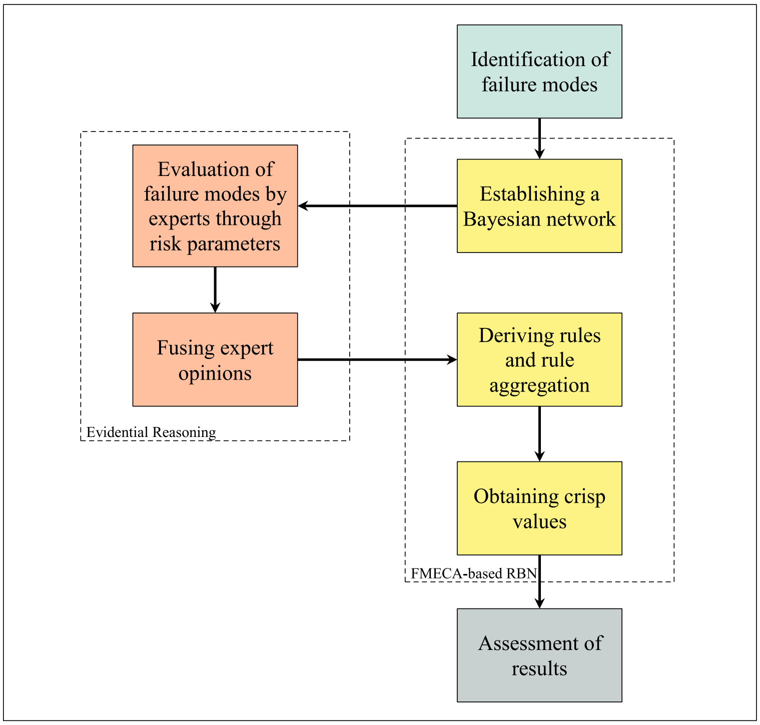

Fig. 1. Conceptual framework of FMECA extended ER and RBN approach.

Some of the rules are shown in Table 2.

For example;

Rule# 1: If occurrence = very low (O1), and severity = negligible (S1), and undetection = very unlikely (D1), THEN {(1, very low (R1)), (0, low (R2)), (0, average (R3)), (0, high (R4)), (0, very high (R5))}

Here, if the condition is O1, S1, D1, the probability of R can be expressed as $p(R|O_1, S_1, D_1) = (1, 0, 0, 0, 0)$.

Similarly, rules are determined for failure mode categories and overall risk. The number of these rules varies according to the number of failure modes and failure mode categories specified in relation to the subject under consideration [71].

Step 4. Rule aggregation: After the expert assessments are fused and the rules are derived, the prior probabilities are combined to obtain a result (i.e. marginal probabilities). The marginal overall probability p (R_h) for failure modes at the root nodes is calculated with the following Eq. (8) [69,72].

$$p\ (R_h) = \sum_{i=1}^{5} \sum_{j=1}^{5} \sum_{k=1}^{5} p(R|O_i,\ S_j,\ D_k)\ p(O_i)\ p(S_j)\ p(D_k) \qquad (h = 1,\ 2,\ 3,\ 4,\ 5) \tag{8}$$

The marginal overall probabilities are also calculated for the failure mode categories in the intermediate node. For this, Eq. (9) is used, which is similar to Eq. (8).

$$p\ (R_h) = \sum_{i=1}^{5} \times \sum_{j=1}^{5} \cdots \sum_{k=1}^{5} p\left(R|R_{X1,i},\ R_{X2,j}, \ldots\ R_{Xm,k}\right)\ p\left(R_{X1,i}\right)\ p\left(R_{X2,j}\right) \ldots\ p\left(R_{Xm,k}\right) \tag{9}$$

Step 5. Converting the results to crisp values with utility functions: In order to prioritize the failures in the constituted risk model, suitable utility values for R_h should be determined. In this context, the linear utility function is applied in Eq. (10) as follows to calculate the crisp values of R.

$$CV = \sum_{z=1}^{5} p(R_h) U_z \tag{10}$$

Here, $p(R_h)$ is the marginal probability and U_z (z = R1, R2, R3, R4, R5) is the utility value identified for R and it is $\{R_1 = 0.2,\ R_2 = 0.4,\ R_3 = 0.6,\ R_4 = 0.8,\ R_5 = 1\}$ can be specified [69, 70,72].

3. Operational risk assessment of ballasting and de-ballasting on-board tanker ship

3.1. Ballasting and de-ballasting operation on-board tanker ship

Ballast water operations are carried out on vessels to ensure their stability and structural balance for buoyancy. It is a simultaneous work which is conducted by ship officers mainly when loading and discharging the cargo, besides, it can be performed for safe navigation such as passage under the bridge, entering canals, etc. The operation requires a structured system onboard whose components are a sea chest, pipelines, pumps, valves, a treatment system, sensors, alarms, and also a remote-control panel in the cargo control room [1]. Fig. 2 illustrates a basic demonstration of the ballast system on-board ship. The system can be also integrated with other critical equipment on tankers such as fixed gas detection systems, tank radar systems, etc. to monitor the atmosphere inside ballast tanks for safety.

Considering the harmful effects of ballast water when discharged in coastal areas, mandatory regulations under BWMC have been introduced to the maritime industry [73]. BWMC addresses the managing procedures of ballast water with two main regulations: D-1 and D-2. The exchange of ballast water is regulated by the D-1 standard and can be performed through the sequential method, the flow-through method, and the dilution method. According to D-1, vessels discharge their ballast water, which is taken from coastal waters, into open seas and deep oceans as the pathogens and organisms will not survive due to differences in temperature, salinity, and other parameters. D-2, on the other hand, is based on the principle of treating the ballast water to be discharged to reduce the aquatic life in it to the determined limit values [74]. Since the limits specified in D-2 are quite low, using a treatment system has become indispensable to achieving compliance. The number of microorganisms and other marine creatures inside the ballast water can be minimized significantly by using different treatment methods such as filtration and separation, electrolytic chlorination, disinfecting chemicals, ultra-violet lights, cavitation/ultrasound, and deoxygenation. Suitable and type-approved technologies are preferred by ship owners and installed on vessels according to ship technical specifications and voyage requirements [75].

3.2. Problem statement

Ballasting and de-ballasting operations are crucial to perform for vessels' structural integrity and stability, in particular when the ship is dealing with cargo loading and discharging operations. It is considered a critical process since the ballast water system is one of the complex systems onboard and requires proper valve and pump management in

Table 2
Bayesian rules generated for root nodes.

Rule Number	If part			Then part				
	O	S	D	R1	R2	R3	R4	R5
1	Very Low (O1)	Negligible (S1)	Highly Unlikely (D1)	1	0	0	0	0
2	Very Low (O1)	Negligible (S1)	Unlikely (D2)	0.67	0.33	0	0	0
3	Very Low (O1)	Negligible (S1)	Average (D3)	0.67	0	0.33	0	0
4	Very Low (O1)	Negligible (S1)	Likely (D4)	0.67	0	0	0.33	0
5	Very Low (O1)	Negligible (S1)	High Likely (D5)	0.67	0	0	0	0.33
…	…	…	…	…	…	…	…	…
61	Average (O3)	Moderate (S3)	Highly Unlikely (D1)	0.33	0	0.67	0	0
62	Average (O3)	Moderate (S3)	Unlikely (D2)	0	0.33	0.67	0	0
63	Average (O3)	Moderate (S3)	Average (D3)	0	0	1	0	0
64	Average (O3)	Moderate (S3)	Likely (D4)	0	0	0.67	0.33	0
65	Average (O3)	Moderate (S3)	High Likely (D5)	0	0	0.67	0	0.33
…	…	…	…	…	…	…	…	…
121	Very High (O5)	Catastrophic (D5)	Highly Unlikely (D1)	0.33	0	0	0	0.67
122	Very High (O5)	Catastrophic (D5)	Unlikely (D2)	0	0.33	0	0	0.67
123	Very High (O5)	Catastrophic (D5)	Average (D3)	0	0	0.33	0	0.67
124	Very High (O5)	Catastrophic (D5)	Likely (D4)	0	0	0	0.33	0.67
125	Very High (O5)	Catastrophic (D5)	High Likely (D5)	0	0	0	0	1

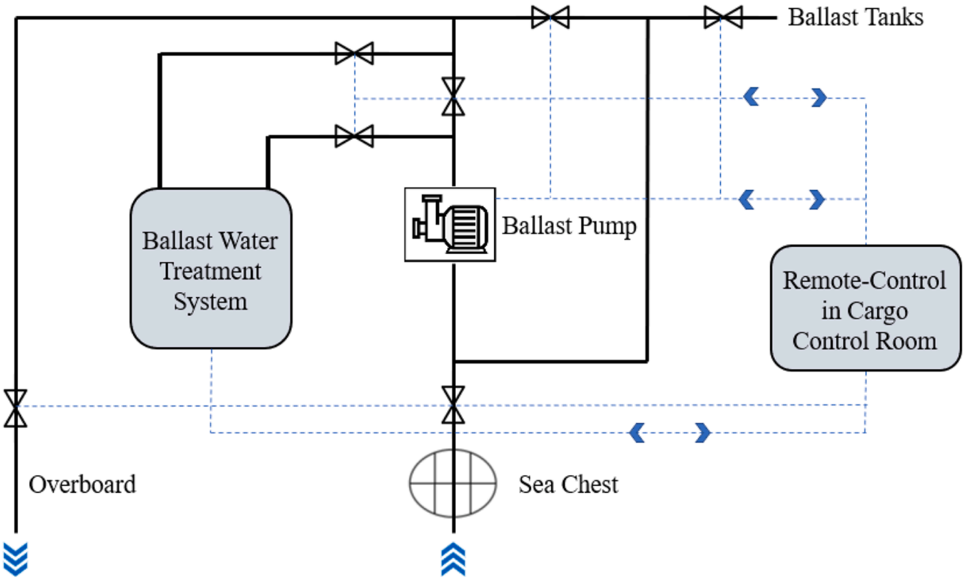

Fig. 2. Basic demonstration of ballast system on ship

Table 3
Failure modes, effects, and consequences of ballasting and de-ballasting operation.

Failure Mode Category	Failure Nr.	Failure Modes	Failure Effects	Consequences
C1. Equipment or structure failure risks	FM 1.1	Failure in tank radar system	Leads to using erroneous sounding values for stability/stowage calculation	• Stability problems due to incorrect filling level of ballast tanks
	FM 1.2	VRCS (Valve Remote Control System) valve leaks	Causes hydraulic oil leakage into ballast tanks	•Inefficient operation •Delay in ports due to extended operational time • Oil spill in case of de-ballasting
	FM 1.3	Ballast water contaminated with cargo	Pollutant effect when overboard	• Environmental pollution
	FM 1.4	Undetected blockage of air vents	Increases the pressure or vacuum inside the ballast tank	• Structural damage of the tank
C2. Operational failure risks	FM 2.1	Dry running the ballast pump	Defects the mechanical seal of the pump	• Damage to the ballast pump
	FM 2.2	Incorrect valve management	Ballast water may not be controlled as required	• Inefficient operation • Time loss
	FM 2.3	Improper management of fixed gas detection system	Sea water fills into the fixed gas detection pipes, clogges the solenoid valves and filters	• Deficiency of fixed gas detection system • Inability to monitor atmosphere inside tanks
C3. Terminal operation & stability failure risks	FM 3.1	Unsynchronized cargo and ballast operation	Increases stress on the ship's body	• Structural damage • Stability defects
	FM 3.2	Excessive list during cargo operation	Loads up stress on terminal's manifold arm and mooring lines	• Damage to terminal's manifold arm • Mooring line break • Property and time loss
	FM 3.3	Excessive cargo loading rate	Increases the pressure on ballast water lines	• Pipeline damage
	FM 3.4	Tanks over flowing when at the terminal	Traces of oil on deck if present could be overboarded	• Oil spill • Commercial loss
C4. Navigation & stability failure risks	FM 4.1	Excessive list or trim at voyage	Creates forces that cause the listing or trimming of the ship	• Stability problems • Foundering • Flooding
	FM 4.2	Excessive trim by the stern	Limiting vessel's bridge visibility for effective watchkeeping	• Loss of bridge visibility • Dangerous navigation
	FM 4.3	Insufficient draft	Decreases the performance of the ship's propeller and bow thruster	• Loss of maneuverability
C5. Regional condition risks	FM 5.1	Ballasting in muddy areas	Muddy ballast water may clog filters of BWTS, also, sediments may accumulate at the bottom	• Mechanical defect in BWTS • Sediments inside ballast tanks after de-ballasting
	FM 5.2	Transferring harmful organisms	Certain aquatic species invade coastal habitats	• Harm to marine environment and public health
C6. BWTS risks	FM 6.1	Overriding temperature and pressure sensors in BWTSs	Internal temperature and pressure of the unit may be increased	• Structural damage to BWTS and other machinery • Personal injury
	FM 6.2	Failure in the TRO (total residual oxidant) sensors in BWTSs	Causes inaccurate treatment process	• Environmental violation
	FM 6.3	Unsafe storage or handling of chemical disinfectants used in BWTSs	Chemical disinfectants such as sodium hypochlorite and hydrogen peroxide have damaging effects on tissue	• Chemical burns

addition to continuous stability control. Failures during the process may lead to serious consequences such as structural damages, stability problems, and loss of maneuverability, which may lead to more catastrophic events like foundering, capsizing, and total loss [7,8,52,53]. Moreover, ships must comply with the environmental rules of IMO by managing the ballast water through defined appropriate methods to prevent the transfer of harmful organisms. These requirements bring new risks for vessels during both exchange and treatment processes, such as increased stress on the ship's body, excessive listing, failures in treatment units, and sensor failures. As a consequence of those failures, the ship's stability may defect and equipment may be damaged. Also, ballast water may not be managed properly and jeopardize marine habitats due to living invasive species. Ballast water operations are frequently performed on vessels; however, they can be extremely dangerous considering various technical, operational, and environmental aspects. It has been a serious issue for the maritime industry to handle the operational risks of ballast water operations. To support safety solutions, this paper aims to assess the operational risks of the ballasting and de-ballasting process comprehensively.

3.3. Numerical analysis

In this section, risk assessment is performed for ballasting and de-ballasting operation on-board tanker ships using a combination of ER, FMECA, and RBN methods.

Step 1. Determination of failure modes and construction of the Bayesian Network: Failures during the operation are identified and analyzed in a framework with their effects and potential consequences. Table 3 shows failure modes, effects, and consequences in the course of ballasting and de-ballasting on ships [7,8,76–78]. Then a Bayesian network is constructed, including failure modes, failure mode categories, and overall risk. The Bayesian network created by using the GeNIe software is shown in Fig. 3.

Step 2. Expert evaluations: The risk parameters (O, S, D) of the failure modes of the ballasting and de-ballasting operation are evaluated by maritime experts. Seven experts participated in the paper. Experts consist of people with extensive knowledge and experience who have worked on tanker ships. Table 4 shows the marine expert profile. Inputs from each expert are aggregated through ER, thus determining the degree of belief in the risk parameters of each failure mode. As an illustrative example, Table 5 contains expert judgments and aggregated results for FM 3.1 (Unsynchronized cargo and ballast operation), which is in the terminal operation & stability failure risks category (C3). Similar evaluations are performed for all other failure modes.

In this context, as seen in Fig. 4, The degrees of belief obtained from the ER form the inputs of the Bayesian network in the paper where the risk assessment was conducted with the GeNIe software. For instance, for FM 3.1 (Unsynchronized cargo and ballast operation), the belief degrees of the occurrence parameter obtained by combining expert judgments are 11% Very high, 24% High, 38% Average, 26% Low, and 1% Very low. Similarly, the belief degrees of the severity parameter are 14% Catastrophic, 37% Critical, 35% Moderate, and 14% Marginal. And the degrees of belief for the no detection parameter are 23% Highly likely, 37% Likely, 23% Average, 15% Unlikely, and 3% Highly unlikely.

Step 3. Derivation of rules: Rules are defined for the analysis process. Rules are created for both failure modes, failure mode categories, and overall risk. Table 2 has 125 rules derived for failure modes. Similarly, rules are defined for failure mode categories and overall risk. For example; the first category, which covers equipment or structure failure risks, includes four failure modes. Likewise, there are four failure modes in the third category, which covers terminal operation failure risks. Therefore, there are (5 × 5 × 5 × 5) 625 rules for the first and third categories. There are 125 rules for the rest of the categories because it consists of three failure modes.

Step 4. Rule aggregation: The rule aggregation step is performed using the Bayesian mechanism. In this context, marginal overall probabilities are determined. For the calculation of marginal overall probabilities, belief degrees of O, S, and D parameters obtained by combining expert opinions and established rules are used. The marginal overall probability is calculated for all nodes in the BN. As illustrated in Fig. 4, four root risks are identified in category C3. Arrows in parameters O, S, and D indicate each root risk. In addition, each root risk is associated

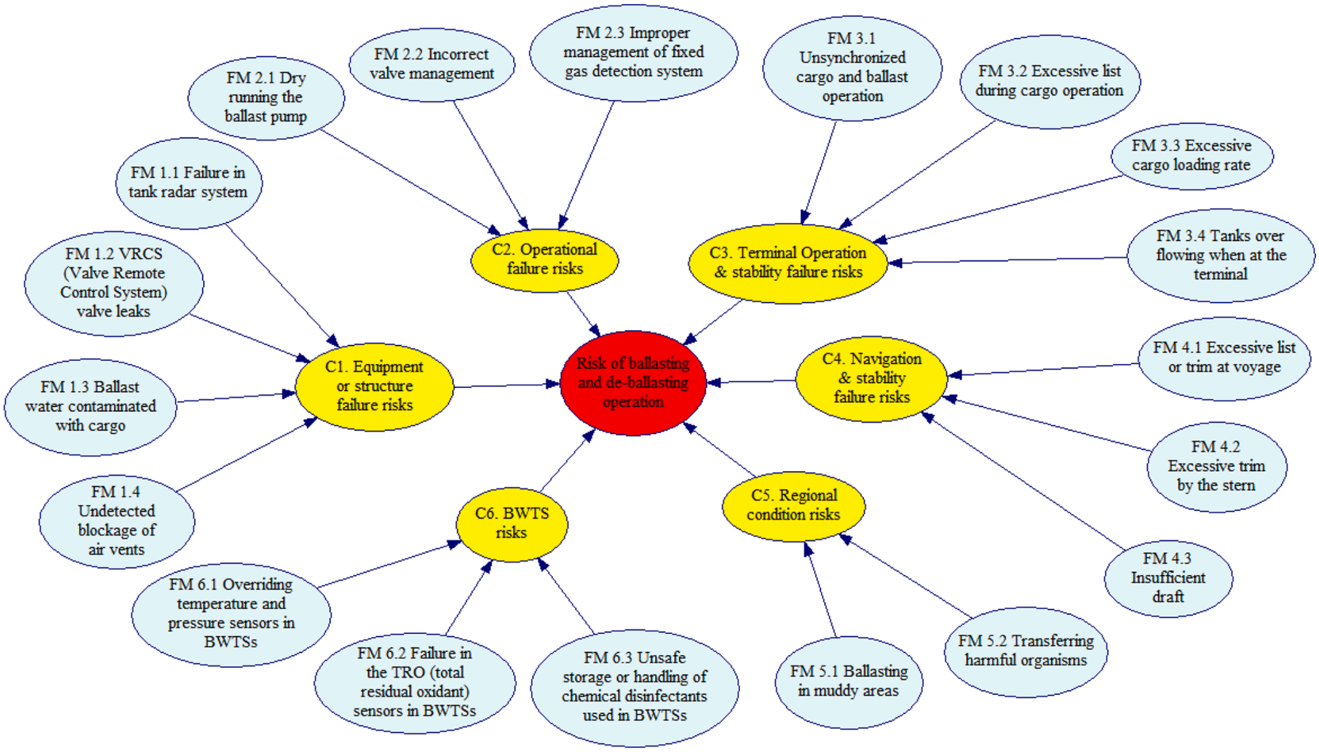

Fig. 3. Bayesian network diagram for risk of ballasting and de-ballasting operation on-board tanker ship.

Table 4
Information concerning maritime experts.

Expert	Position	Education	Job Experience	Knowledge
1	Oceangoing Chief Officer	BSc.	7 years	This expert had worked on tankers that give service at various sea areas, and is actively work onboard. He is familiar with the ballast operations since he executes the process as the main responsible personnel.
2	Oceangoing Master	BSc.	10+ years	This participant commands on tanker ships including new built vessels. He has significant experience about ballasting and de-ballasting, inspects and approves his chief officers. He also helped while establishing the failure modes in the paper.
3	Oceangoing Chief Engineer	MSc.	10 years	This participant had worked on many tanker vessels that give international service. He is familiar with the ballast water treatment systems and their failures. He also supported the study while preparing the failure modes in the paper.
4	Academician	MSc.	5 years	This expert works at a maritime university and research concerning ship operations including ballasting and de-ballasting. She is also a former oceangoing watchkeeping officer who has experienced such processes by assisting the chief officer.
5	Company Technical Inspector	BSc.	10+ years	This expert monitors the technical condition of ships in the company's fleet, also visit the vessels periodically for technical inspections. Prior to his shore career, he had worked as a chief engineer on tankers.
6	Academician	MSc.	9 years	This participant is a former chief officer of international tanker vessels. He has significant experience in the ballast and cargo operations. He currently works and research at a maritime university.
7	Safety Superintendent	BSc.	8 years	This expert is former oceangoing master who has experience and knowledge about ship operations including ballasting and de-ballasting. He monitors the vessels' safety including cargo-ballast process, and also is a professional in the company that the ship personnel can consult about the safety issues.

with the terminal operation failure risks category (C3). For example, depending on Table 2 and Eq. (9), the marginal overall probabilities of FM 3.1 is determined as 16% Very high, 33% High, 32% Average, 15% Low, and 4% Very low.

Step 5. Converting the results to crisp values with utility functions: In this step, the crisp values are determined for all root nodes and intermediate nodes of the ballasting and de-ballasting operation with the help of the linear utility function. Fig. 4 shows the crisp values calculated using the linear utility function specified in Eq. (10). Accordingly, the risk is 50.59 for FM 3.1 (Unsynchronized cargo and ballast operation), the risk is 47.08 for FM 3.2 (Excessive list during cargo operation), the risk is 30.21 for FM 3.3 (Excessive cargo loading rate), and the risk is FM 35.52 for 3.4 (Tanks over flowing when at the terminal). The overall risk of the terminal operation failure risks category (C3) is calculated as 40.86.

Due to the space limitation in the study, the detailed assessment of the terminal operation failure risks category (C3) as a sample is presented in Fig. 4. Similarly, risk assessment results for all failure modes and failure mode categories can be obtained and the results are given in Table 6.

Overall, the Bayesian network model in which the risk assessment of the ballasting and de-ballasting operation is performed in the study with six failure mode categories is shown in Fig. 5.

3.4. Findings and discussion

Based on the analysis, the highest risk failure mode (FM) category of ballasting and de-ballasting operation on tanker vessels is found in terminal operation & stability failure risks (C3) with a 40.86 crisp risk value. FM 3.1 "unsynchronized cargo and ballast operation" has a risk level of 50.59. It is followed by FM 3.2 "excessive list during cargo operation" with a risk value of 47.08, and they are considered the most critical failure modes. A tanker, when at the terminal, performs loading or discharge operations of liquid substances. Ballast operations are made simultaneously to keep the vessel in a balanced condition. For a basic example, if the tanker loads the cargo to the number 3 starboard (right side) tank, ballast water in the number 3 starboard ballast tank is to be discharged, and the number 3 port (left side) ballast tank is to be filled. If the balance of changing load can not be synchronously achieved, structural problems such as straining may appear due to the increasing stress on the ship's body. Moreover, serious stability defects may occur that lead to listing the vessel. Excessive listing on the other side of berthing can also create additional tension on the mooring lines and the manifold arm where the cargo flows through. As a result, property and time losses may occur due to mooring line breaks and damage to the manifold's arm. Considering the risk factors O, S and D, the aforementioned failure modes present significant parts of the ballasting and de-ballasting operations. To minimize the risks of FM 3.1, stability monitoring systems may be used. Also, cargo and ballast plans should be prepared according to vessels' pump capacities to provide optimum loading and discharge rates.

The next highest crisp risk value is found at 43.33 for the failure mode of FM 1.2 "VRCS (Valve Remote Control System) valve leaks",

Table 5
Expert evaluation and aggregated results for FM 3.1

		Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Aggregated Results
Occurrence (O)	VL	0.05	0	0	0.05	0	0	0	0.01
	L	0.3	0.2	0.3	0.25	0.3	0.2	0.3	0.26
	A	0.45	0.5	0.3	0.3	0.3	0.4	0.3	0.38
	H	0.2	0.2	0.3	0.3	0.2	0.3	0.2	0.24
	VH	0	0.1	0.1	0.1	0.2	0.1	0.2	0.11
Severity (S)	N	0	0	0	0	0	0	0	0
	MA	0.2	0	0.3	0	0.2	0.15	0.2	0.14
	MO	0.4	0.3	0.3	0.35	0.3	0.35	0.4	0.35
	CR	0.3	0.5	0.3	0.4	0.3	0.4	0.3	0.37
	CA	0.1	0.2	0.1	0.25	0.2	0.1	0.1	0.14
Detection (D)	HU	0	0	0.2	0	0	0	0	0.03
	U	0	0	0.3	0.1	0.2	0.3	0.2	0.15
	A	0.1	0	0.3	0.2	0.3	0.3	0.4	0.23
	L	0.6	0.5	0.2	0.35	0.3	0.2	0.3	0.37
	HL	0.3	0.5	0	0.35	0.2	0.2	0.1	0.23

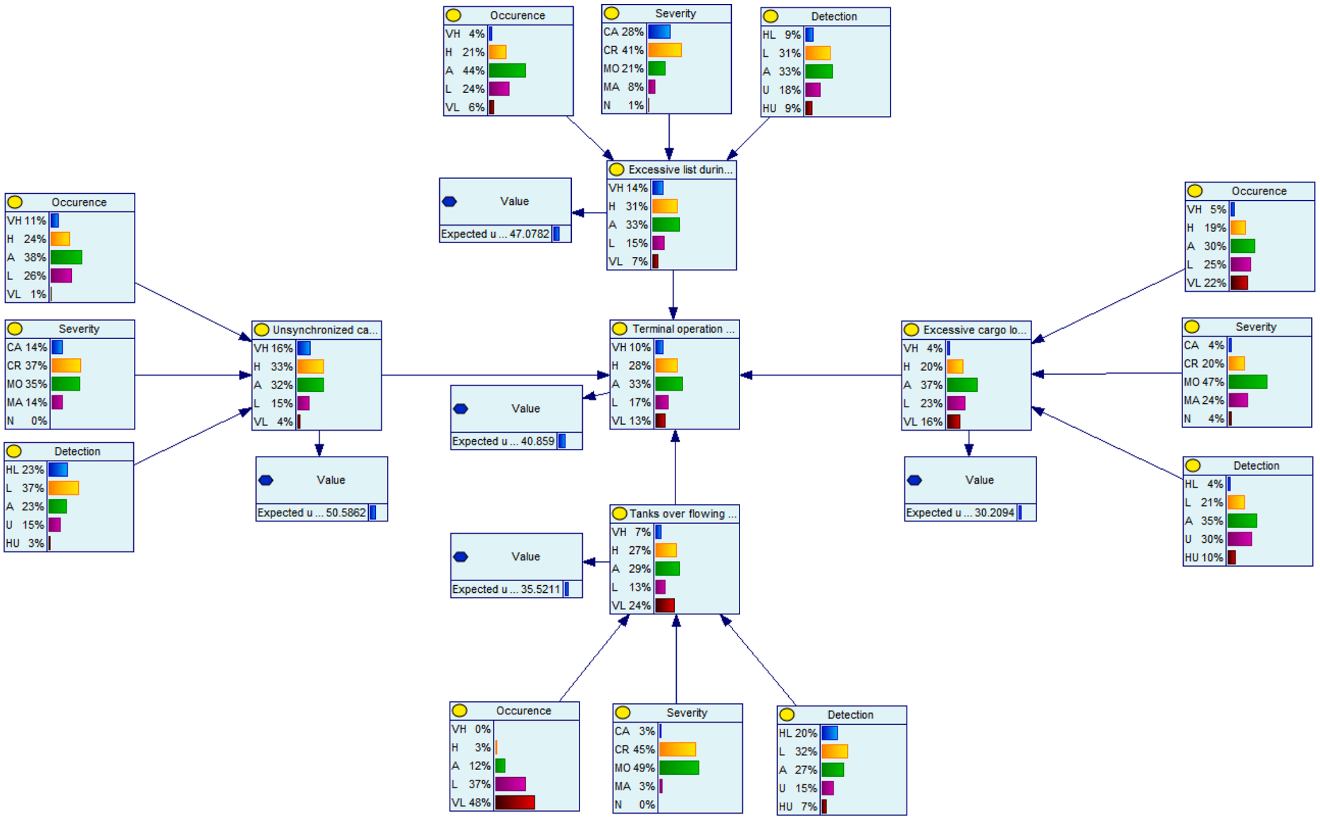

Fig. 4. Risk assessment result of terminal operation & stability failure risks category.

which is classified under equipment or structure failure risks (C1). FM 1.2 is the third most dangerous failure since it has an environmental dimension. The VRCS is a practical system that allows ship officers to control the valves from the cargo control room remotely [79]. Hydraulic oil moves in VRCS pipelines by commanding the actuators and solenoids, which help open or close the valves of ballast tanks. Defects in this system may lead to oil leakage into the ballast tanks, and therefore into the sea when the ballast water is discharged. The mechanical parts of the system should be controlled and renewed at planned times. Besides, alarms of VRCS oil tank, in particular, the low-level alarm should be strictly considered since it means the oil in the pipes leaked into the ballast tank.

FM 2.2 “incorrect valve management” is another significant failure mode which is classified under the operational failure risks category (C2). It is the fourth-highly ranked failure mode with a crisp risk value of 38.48. Ballast water operation is performed from the cargo control room by a remote system that commands valves of the sea chest, ballast lines and ballast pumps. On tankers, management of valves may be complicated when handling multiple grades of cargoes simultaneously since ballast operation is made with a parallel process. It is probable to arrange the valves incorrectly and that may lead to time loss and inefficient ballasting or de-ballasting operations [80]. To prevent incorrect actions, efficient training should be provided for cargo officers.

FM 4.1 “excessive list or trim at voyage” under navigation & stability failure risks (C4) is another substantial failure mode. The crisp risk value is found at 37.94 in numerical analysis. Tankers may perform ballast operations in the open sea, particularly for a ship-to-ship cargo operation, or due to adverse sea conditions. Excessive list or trim may defect a ship’s stability, specifically in heavy weather, further leading to flooding and foundering, which are more catastrophic consequences [7,77]. All

Table 6
Risk assessment results for failure modes and failure mode categories

Failure Mode Category	Crisp Risk Value	Failure Mode	Crisp Risk Value
C1 Equipment or structure failure risks	32.85	FM 1.1 Failure in tank radar system	35.66
		FM 1.2 VRCS (Valve Remote Control System) valve leaks	43.33
		FM 1.3 Ballast water contaminated with cargo	30.47
		FM 1.4 Undetected blockage of air vents	21.94
C2 Operational failure risks	33.03	FM 2.1 Dry running the ballast pump	36.79
		FM 2.2 Incorrect valve management	38.48
		FM 2.3 Improper management of fixed gas detection system	24.35
C3 Terminal operation & stability failure risks	40.86	FM 3.1 Unsynchronized cargo and ballast operation	50.59
		FM 3.2 Excessive list during cargo operation	47.08
		FM 3.3 Excessive cargo loading rate	30.21
		FM 3.4 Tanks over flowing when at the terminal	35.52
C4 Navigation & stability failure risks	34.82	FM 4.1 Excessive list or trim at voyage	37.94
		FM 4.2 Excessive trim by the stern	33.65
		FM 4.3 Insufficient draft	33.20
C5 Regional condition risks	31.43	FM 5.1 Ballasting in muddy areas	35.72
		FM 5.2 Transferring harmful organisms	27.14
C6 BWTS risks	30.23	FM 6.1 Overriding temperature and pressure sensors in BWTSs	31.10
		FM 6.2 Failure in the TRO (total residual oxidant) sensors in BWTSs	26.54
		FM 6.3 Unsafe storage or handling of chemical disinfectants used in BWTSs	33.28

kinds of ballast operation which is carried out to adapt the ship to the dynamic conditions should be approved by the ship's master. Moreover, additional visual control from the bridge will help to ensure the balance of the vessel.

FM 2.1 "dry running the ballast pump" is also one of the critical failure modes of C2 with a crisp risk value of 36.79. A ballast water pump has both electrical and mechanical components which allow the intake or discharge of seawater. Running the pump without seawater can defect the mechanical seal of the pump in a short period of time [81]. It is significant to consider the noise and the vibration spreading from the pump since it may be a strong indicator of upcoming defection.

Under regional condition risks (C5), FM 5.1 "ballasting in muddy areas" is among the significant failure modes with a crisp value of 35.72. In such areas, filters of BWTS can be clogged in a short period of time. If the system has no robust filters, it should not be activated as much as possible to prevent its breakdowns. Accordingly, ballast operations should be performed according to D-1 standards, since fulfilling the D-1 requirements is sufficient to minimize harmful organisms in ballast water [5,73]. Besides, FM. 5.1 may cause the bottom of ballast tanks to be filled with sediments, whose discharge is another challenging process [82]. Inspection after the first de-ballasting could help detect any sediment accumulation and take action for handling solutions [58].

FM 1.1 "failure in-tank radar system" has a 35.66 crisp risk value and poses potential hazards under C1. A tank radar system, a type of gauging system, is one of the most significant monitoring arrangements on tanker vessels [37]. It displays the volume, sounding, ullage and temperature measurements of cargo tanks. The system can also be integrated with ballast tanks to easily and quickly control cargo and ballast operations. In case of a failure of this structure, erroneous sounding values may be displayed, leading to inaccurate stability calculations. On tankers, it is expected the system generally works in good condition. Therefore, the O parameter is evaluated lower than other high-risk failure modes. However, due to its severity, FM 1.1 is involved in important failure modes. The system should be type approved in terms of its various design properties and controlled according to the planned maintenance program. Furthermore, comparing the system with manual gauging would be helpful to ensure its accuracy. On the other hand, Table 7 shows control actions for highly ranked failure modes in terms of crisp risk values.

In addition to the failure modes and actions in Table 7, it would be useful to mention BWTS risks (C6) during ballasting and de-ballasting operations. The highest crisp risk value is 33.28 for FM 6.3 "unsafe storage or handling of chemical disinfectants used in BWTSs". The BWTSs provide vessels with different treatment methods according to owners' specific requirements. One of the frequently used methods is chemical disinfection. It aims to remove the living organisms in ballast water loaded on the ship via chemical substances such as sodium hypochlorite and hydrogen peroxide. However, handling these materials can be dangerous for human health; unsafe practices may lead to severe chemical burns [83]. It is important to consider material safety data sheets and to use protective equipment before handling such chemicals.

4. Conclusion

Risk assessment is essential to improve safety and minimize hazards for sustainable maritime transportation, in particular for tanker vessels. Tankers can carry and handle different types of dangerous liquids in large quantities; therefore, complex and critical works are carried out onboard, including cargo and ballast operations. This paper focuses on ballasting and de-ballasting, which is a fundamental process to maintain the vessel's stability. Besides, it should be performed only by meeting the requirements of international regulations concerning ballast water management, aiming to minimize the harmful aquatic organisms. The process involves considerable risks, specifically when conducted with parallel cargo operations. Failures may lead to unfortunate events such as stability defects, structural damage, and capsizing. However, the literature is still scarce, particularly on operational aspects and risks of ballasting and de-ballasting. This paper intends to highlight this gap and present a comprehensive risk assessment.

As stated by IMO, it is optional for shipping companies which risk analysis methods to be used, as long as it helps to enhance safety onboard. Therefore, the paper utilizes a robust risk assessment technique which integrates FMECA with Evidential Reasoning (ER) and Rule-based Bayesian Network (RBN) to quantify the risk levels of the determined hazard. Whilst the FMECA performs an extensive hazards analysis, the ER is capable of providing a smart solution for the degree of belief distribution in expert judgement. The RBN is tackling with limitations of conventional FMEA.

The paper identifies nineteen failure modes for ballasting-deballasting operation onboard tankers under six main categories. The data derivation was provided based on expert judgements. Given the findings, "unsynchronized cargo and ballast operation" with a crisp risk value of 50.59 and "excessive list during cargo operation" with a 47.08 crisp risk value represents the highest operational overall risk of ballasting-deballasting operation. In addition, control actions are recommended to minimize risks.

The paper also has some limitations which are needed to be improved. The number of experts can be considered a limitation of the research. All respondents are experienced in the subject and related marine operations; however, both numbers and qualifications can be improved in further studies. The other limitation is failure mapping. The authors evaluated ballasting and de-ballasting operation deeply and presented the most potential failures in the study, which were formed with the help of experts. More detailed research can be conducted in

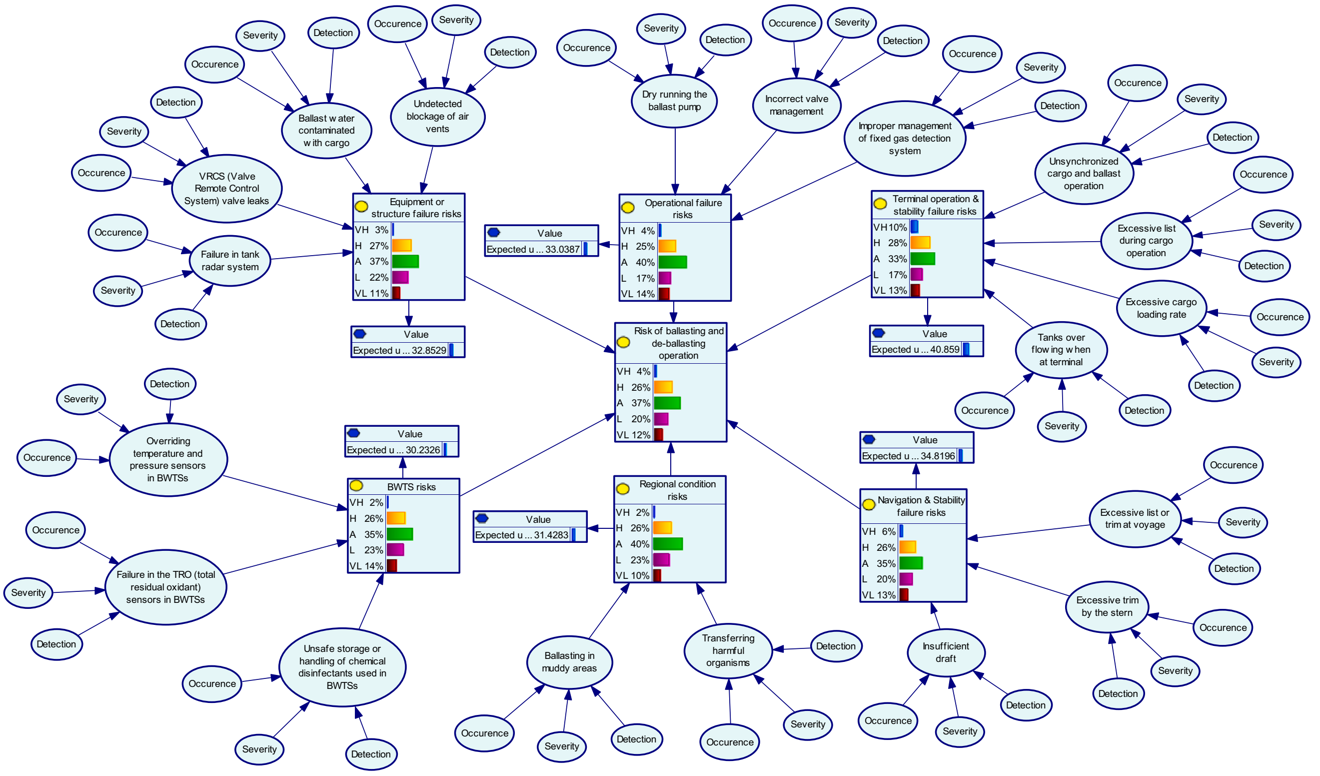

Fig. 5. Bayesian network model of risk assessment of ballasting and de-ballasting operation.

Table 7
Control actions for failure modes.

Failure mode	Control action
3.1	• Follow the stress on the ship's body through a monitoring system • Implement cargo and ballast plan which is prepared considering the tanker's pump capacities, including defined loading and discharge rates
3.2	• Follow the listing degree of the ship during ballast operation • Increase visual watch on the manifold area • Check the tightness of mooring lines regularly
1.2	• Provide maintenance and control for VRCS, including renewing the seals • Monitor alarms of VRCS, in particular, low-level alarm of VRCS oil tank • Visual control from ballast tank observation holes to check the existence of oil
2.2	• Provide training for officers about valve system • Distribution of responsibilities optimally during cargo and ballast operation • Use additional visual marks for remote control valves, in particular for inexperienced crew
4.1	• Plan ballasting and de-ballasting operation with master's approval • Inform bridge personnel during ballast operation for additional visual control of the ship's listing
2.1	• Ensure that the ballast system is ready to run, including the condition of the valves • Follow the noise and vibration effects of ballast water pumps
5.1	• Perform ballast operations according to D-1 standards as possible • Inspect ballast tanks after first de-ballasting
1.1	• Use approved tank radar systems in terms of design properties • Compare the system with manual gauging regularly • Carry out planned maintenance of the tank radar system without deferring

further studies, particularly about ballast water treatment systems.

In conclusion, the study's findings would contribute to tanker shipowners, operators, safety inspectors and health, safety & quality managers for their efforts to improve safety and prevent risks at the operational level during ballasting de-ballasting operation.

CRediT authorship contribution statement

Gizem Elidolu: Writing – original draft, Formal analysis, Visualization. **Sukru Ilke Sezer:** Methodology, Formal analysis, Writing – original draft, Visualization. **Emre Akyuz:** Writing – original draft, Writing – review & editing, Conceptualization, Supervision. **Ozcan Arslan:** Writing – review & editing. **Yasin Arslanoglu:** Writing – review & editing.

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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