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Assessment of causal mechanism of ship bunkering oil pollution

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ABSTRACT

It is crucial to disclose the causal factors to eliminate the oil spills arising from bunkering operations. To address this phenomenon, this paper presents a novel model for causal mechanism of oil pollution. For this purpose, this research examines the probabilistic relationships among the causal factors which are revealed qualitatively and quantitatively utilizing a Fuzzy-Bayes Network approach. Sensitivity and validation analyses are executed to improve the accuracy of outcomes. Findings of the research indicate that existence of overflow, the existence of operational causes, and crew causes appear as the major contributory factors to account for the occurrence of pollution. Furthermore, it was found that damaged connection hose, existence of over-reliance, and bad flange connection have the least impact to explain the occurrence of oil pollution. P&I Clubs, regulatory authorities, and shipowners can exploit the results of this research to mitigate oil pollution risk stemming from bunkering operation.

1. Introduction

Vessels, which are one of the highest contributors to shipping pollution, can carry a substantial amount of fuel depending on the size of their tanks and spilling this fuel into sea can pose a serious threat to the marine ecosystem (TBMM, 2012; Akyuz et al., 2018; Xu et al., 2021a,b). It is very difficult to clean the bunker fuel spilled into the sea as heavy fuel, called persistent oil, is largely used for bunkers composed of heavier hydrocarbon fractions and they do not dissipate hastily via evaporation (North P&I, 2018; Kamal and Çiloğlu, 2020). It is a laborious process that requires organization, logistics, time, effort, and cleaning costs associated with this process can reach large amounts. (TBMM, 2012). It should be noticed that oil spills from vessels should not be associated only with oil or oil products transported as cargo. Every kind of vessel may be involved in an oil spill incident due to bunker oil that is stored in bunker tanks (Ansell et al., 2001). Furthermore, it is pointed out that the majority of the oil pollution claims are not caused by oil transported as cargo, rather pollution emanating from releasing of bunker fuel are more common (Krata and Jachowski, 2021). Over 80% of the oil spills occurred since 1970 are in small quantity (<7 tonnes), and oil pollution from bunkering operation occupies a noticeable percentage (7%) among them (ITOPF, 2020). According to Gard P&I Club figures, bunker spills are responsible for 18% of all pollution incidents dealt by the Gard claims teams between 2014 and 2018, and the average cost per incident exceeds USD 100.000 (Gard P&I, 2019).

It is specifically indicated that many bunker spills take place during the bunkering process (North P&I, 2018; Akyuz et al., 2018). Bunkering transaction is a critical shipboard operation that is also known as ship-to-ship transfer involving fuel oil, diesel oil, etc. The operation necessitates utmost care for prevention any type of oil spills. It can be carried out either in a berth or at anchorage (Akyuz et al., 2018). Although bunkering procedures and checklists usually include all the essential points and many bunkering operations are executed without problem, very occasionally, some things might go wrong. A loss of confinement due to a tank overflow, leakage from a pipeline or a failure in transfer hose might result in oil spilling overboard and contaminating the marine environment (Nichol, 2018). It is specified that spills into the marine environment concerning bunkering operations persist to happen with worrying regularity (IMCA, 2016; Nichol, 2018; IMCA, 2019; Richter, 2021). Although bunkering operation is a routine practice, it involves high risk. Two main concerns arise due to bunker spills. These are environmental impacts to the marine ecosystem particularly from persistent oils and the risk of crew members and/or shipowners who might face criminal prosecution. Thus, it is crucial to eliminate oil

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pollution stemming from bunkering operations between barge vessel and bunkered vessel.

Considering oil spill studies conducted in the marine environment domain, it is observed that there has been a significant amount of studies that focus on analyzing causal factors or assessing the impacts of the pollution stemming from ship-sourced spills. In this regard, Liu et al. (2016) employed the Bohai Strait of China as the target location and developed a model of three-dimensional oil transportation and transformation utilizing estuary, coast and ocean models to assess the effects of contamination from ship-related oil spills on nearby coastal locations. Furthermore, taking Sanchi tanker vessel collision and explosion accident case into account, Chen et al. (2020) utilize fault tree approach to systematically investigate the factors that contribute to the accident and ranks their statistical weights. Similarly, for prevention of ship collisions and the reduction of potential pollution, Yu et al. (2021) propose some management strategies for maritime authorities by presenting Spatio-temporal associations of endogenous and exogenous factors (e.g. vessel size, flag registry, vessel type, season, etc.) with vessel collisions in coastal waters. On the ground of evolutionary game theory and prospect theory, the behavioral strategies of multiple stakeholders in controlling of pollution caused by inland shipping are evaluated and discussed by Xu et al. (2021a,b) to present a better decision-making mechanism to realize an effective control of pollution stemming from inland shipping.

On the other hand, in the context of bunkering operations, previous studies generally fall within the LNG-bunkering domain (Jeong et al., 2020; Fan et al., 2021). Specifically, in the oil-bunkering scope, it is observed that studies concentrate on management strategies such as competitiveness, bunkering service quality, optimal costs, contracts to diminish fuel-related costs (Acosta et al., 2011; Wang et al., 2014; Pedrielli et al., 2015; Zhen et al., 2016; Sevgili and Zorba, 2018) rather than concentrating on pollution dimension to prevent contamination although few studies focus on bunker spills under vessel accidents, incident case analysis or rupture of a tank (Talley et al., 2012; Krata et al., 2012, 2018). However, there is not any study encountered in the literature that holistically approaches the oil bunkering-induced pollution from an operational perspective.

To remedy this gap, this research exhaustively evaluates the causal mechanism of the oil pollution occurring during bunkering operations qualitatively and quantitatively. Therefore, this paper aims at revealing and modeling the causal factors of oil pollution and analyze relationships among each other probabilistically to eliminate the recurrence of spill and develop preventive policies. To perform this, this paper utilizes the Fuzzy-Bayes Network (FBN) approach which is explained in the next section. The rest of this paper is organized as follows. Stages of the Fuzzy Bayesian method are presented in Section 2. Following that, the identifications of variables, application of the employed approach on the established model, sensitivity analysis, and validity of the constructed model are provided in Section 3. Results of the model, recommendations and implications are provided in Section 4 and finally, the study is outlined and some further suggestions are made in the last section.

2. Methodology

The ultimate goal, bringing bunkering-induced oil spills to zero point, is yet to be attained, therefore studies to prevent these spills from vessels are still topical. Thus, the research questions of this paper are as follows. (1) What are the key factors that lead to bunkering-induced oil pollution? (2) To what extent does the performance of each causal factor contribute to the occurrence of oil pollution during bunkering operations? To find answers to these questions, interviews with industrial experts initially have been executed to elicitate the causal factors qualitatively. Following that, Bayesian inference principle under a fuzzy environment has been utilized for revealing the probabilistic relationships among the factors. This is an initial study in the literature that models and evaluates comprehensively the causal mechanism of the oil pollution occurring during bunkering operations. In line with this, elements of the FBN method are presented in this part. In this regard, a conceptual framework of the approach carried out is provided in Fig. 1.

2.1. Bayes networks (BN)

The BN method is gaining popularity increasingly regarding the modeling of complex problems involving probabilistic reasoning. The BN is a flexible and powerful graphical model that reveals the probabilistic relationships among variables (Khakzad et al., 2011; Chang et al., 2021). This approach is capable of identifying the relationships between variables both qualitatively and quantitatively.

The BN approach is also called a Directed Acyclic Graph (DAG) and the relationships between variables are demonstrated on directed acrylic arrows (Cakir et al., 2021). The graphical representation of the network incorporates nodes that display variables and directed arrows show the probabilistic causal dependence among the variables (Kim and Pearl, 1983). In this approach, relationships among the nodes can be likened to family relationships. In this illustration, if an arrow originates from a node, that node is called a parent node while the node to which arrows are directed is named as a child node. (Jones et al., 2010; Pristrom et al., 2016).

The quantitative component of the BN manages the probability tables of the variables in the network structure. The probability tables incorporate probabilities, conditional probabilities as well as posterior probabilities that are extracted from them. It is noted that if the probability belongs to the root node then it is named as a marginal probability. Theoretically, the Conditional Probability Tables (CPT) and the marginal probability of the root nodes could be formulated by incorporating statistical data, expert experience, or a combination of both. (Weber et al., 2012). The inference principle of the BN approach is based on the Bayes probability theory. In essence, Bayes's theory describes a probability of an event dependent on the prior knowledge of the conditions which may be relevant to that event. Algorithms of the inference are given in the following equations (Mahadevan et al., 2001):

The joint probability distribution of a set of variables U = $\{X_1, X_2 \ldots, X_n\}$ as:

$$\mathrm{P(U)} = \prod_{i=1}^{n} P(X_i \backslash P_a(X_i)) \tag{1}$$

X_i's marginal probability calculation is as in the following.

$P_a(X_i)$ is the parent set of variables

$$X_i \ \mathrm{P}\ (X_i\ ) = \sum_{X_j\ j \neq i} P(U) \tag{2}$$

The BN that utilizes Bayes theorem to estimate posterior probabilities of the events, given new observations, named as evidence (E), in the shape of the occurrence of incidents, near-misses, etc., as provided in Eq. (3) (Zarei et al., 2019).

$$\mathrm{P\ (U \backslash E)} = \frac{P(U,E)}{P(E)} = \frac{P(U,E)}{\sum_U P(U,E)} \tag{3}$$

2.2. Fuzzy Bayesian Network

To obtain significant outcomes from the BN structure, assigning the probabilities of the nodes represented in the network is a crucial Step. In this context, it is pointed out that there many ways to assign the prior and conditional probabilities of the nodes such as statistical data, literature review, etc. If insufficiency or a high level of uncertainty appears in the statistical data or related literature then uncertainty can be eliminated by utilizing fuzzy set theory suggested by Zadeh (1965) through employing linguistical values in the evaluation stages (Ergin and Eker, 2019). The Fuzzy Bayesian Network (FBN) has been developed to capture the probability values of the nodes in the network structure in the case that statistical data is absent or data is insufficient (Yu et al.,

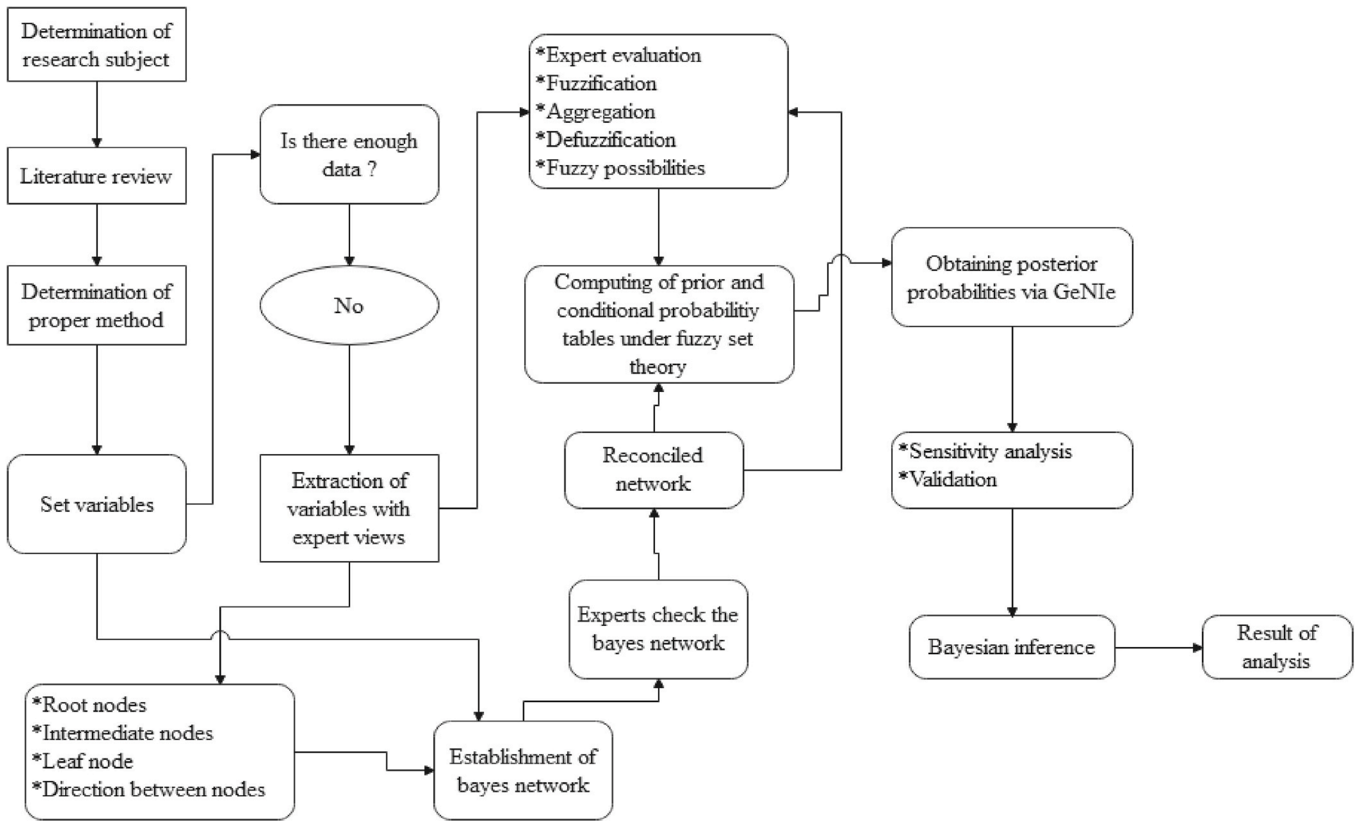

Fig. 1. Research flow chart.

2020). Stages of the adopted methodology are shown as in the following.

2.2.1. *Achieving possibilities from the expert judgment*

In this research, expert assessment has been utilized, and to attain this, a heterogeneous expert group has been elected. Interviewees have been selected from the experts who practiced the bunkering operations onboard vessels several times and have a minimum 10 years of industry experience in total. Each of the experts has occupational experience with varying degrees in the different positions in the industry. These industry experts assess the prior and conditional probabilities of the root and intermediate nodes on the oil pollution arising from bunkering operation. In this stage, a weighting process is applied taking positions, professional experience, and educational backgrounds of the chosen experts into consideration. To show the differences in the evaluation, each professional is appointed different points changing between 0 and 5 (Hsu and Chen, 1996). Based on Equation (4), the weighting points of the experts are computed as in the following (Rajakarunakaran, 2015).

$$\textit{Weighting factor of expert}\ (W_\mu) = \frac{\textit{Weighting score of the expert}}{\textit{Sum of all experts' sweighting scores}} \quad (4)$$

2.2.2. *Fuzzification*

Fuzzy numbers portray the ambiguity in the expert evaluation with the membership function that takes values between 0 and 1. Linguistical variables are utilized to describe uncertain statements in natural languages with definite mathematical terms. There exist several types of membership functions in the literature and a triangular membership function has been employed in this research which is one of the most utilized membership functions (Rajakarunakaran et al., 2015; Kamal et al., 2020). Therefore, this paper employs triangular fuzzy numbers to obtain prior and conditional probability values of root and intermediate nodes, and the membership function of the triangular fuzzy numbers is given in Eq. (5).

$$\mu_{\tilde{A}}(x) = \begin{cases} 0 & x \le a_1 \\ \dfrac{(x-a_1)}{(a_2-a_1)}, & a_1 \le x \le a_2 \\ \dfrac{(a_3-x)}{(a_3-a_2)}, & a_2 \le x \le a_3 \\ 0, & x \ge a_3 \end{cases} \quad (5)$$

In this paper, a linguistic scale comprising seven terms was chosen for expert knowledge elicitation to assess the probability distribution of the ambiguity of the nodes. Linguistic scale and corresponding fuzzy numbers are provided in Table 1. The abbreviations of the linguistical statements are abbreviated as VVH, VH, H SH, M, SL, L, VL and VVL (Senol and Yasli 2021).

2.2.3. *Aggregation of the captured fuzzy possibilities*

Each expert might take different opinions as to the probabilities of the events based on their expertise and occupational experience. Due to

Table 1
A fuzzy linguistic scale.

Measurement Scale	Triangular fuzzy number		
	a_1	a_2	a_3
VVH	0,95	1	1
VH	0,8	0,9	0,99
H	0,65	0,8	0,95
SH	0,5	0,65	0,8
M	0,35	0,5	0,65
SL	0,2	0,35	0,5
L	0,05	0,2	0,35
VL	0,01	0,1	0,2
VVL	0	0	0,05

this, it becomes vital to reach a consensus by considering different expert judgments. In this regard, combining the evaluation of these expert groups, the Similarity Aggregation Method (SAM) proposed by Hsu and Chen (1996) was utilized and provided as follows.

$\widetilde{R1}$, $\widetilde{R2}$: A pair of expert opinions.

$S_{UV}(\widetilde{R1},\widetilde{R2})$: The level of agreement (similarity level) of two different expert judgments.

$S(\widetilde{A}_1,\widetilde{A}_2)$: Degree of similarity between two fuzzy numbers.

$AA(E_u)$: Experts' average agreement.

$RA(E_u)$: Relative degree of agreement of experts.

CC (E_u): Consensus Coefficient degree of the experts.

$\widetilde{R}_{AG}$: The aggregated outcome of the expert decisions.

Step (1) The degree of similarity of a pair of experts' judgment is computed, $S_{UV}(\widetilde{R1},\widetilde{R2})$ of the opinions $\widetilde{R1}$ and $\widetilde{R2}$ of a pair of experts E_U (u = 1 to M).

According to this approach, $\widetilde{A}_1 = (a_{11}, a_{12}, a_{13})$ and $\widetilde{A}_2 = (a_{21}, a_{22}, a_{23})$ are identified as two triangular fuzzy numbers. Then, the similarity degree between two fuzzy numbers can be obtained by the defined similarity function as in Equation (6).

$$S\left(\widetilde{A}_1,\widetilde{A}_2\right) = 1 - \left(1/3\right)\sum_{i=1}^{3}\left|a_{1i} - a_{2i}\right| \tag{6}$$

Step (2) Calculation of Average Agreement (AA) by M experts as follows:

$$AA(E_u) = \frac{1}{M-1}\sum_{\substack{U \neq V \\ V=1}}^{M} S\left(\widetilde{A}_1,\widetilde{A}_2\right) \tag{7}$$

Step (3) The degree of Relative Agreement (RA) is calculated as follows:

$$RA(E_u)\frac{AA(E_U)}{\sum_1^M AA(E_U)} \tag{8}$$

Step (4) Calculation of the Consensus Coefficient (CC) of the experts as in the following:

$$CC(E_U) = \beta.w(E_U) + (1-\beta).RA(E_U) \tag{9}$$

In Eq. (9), β takes a value between 0 and 1 and is attributed as the optimism coefficient in the similarity method. In this method, β ($0 \leq \beta \leq 1$) is the relaxation factor and it reflects the importance of w (E_U) (weight factor of expert u) on RA (E_U). When β takes the value of 0, the weight factor of the expert is ignored as there exists a homogenous distribution between the experts. When β takes the value of 1, the expert has the same CC degree and weight significance. Assignment of an appropriate β value is crucial and in this research, β takes the value of 0.5 (Şakar, 2017).

Step (5) As a last, views of the experts are aggregated via Eq. (10)

$$\widetilde{R}_{AG} = CC(E_1)\times\widetilde{R}_1 + CC(E_2)\times\widetilde{R}_2 + \ldots + CC(E_M)\times\widetilde{R}_M \tag{10}$$

2.2.4. *Defuzzification*

To deduce an inference from the Bayes network, it is necessary to transform the fuzzy numbers into crisp numbers (Peng-Cheng et al., 2012). Fuzzy prior probabilities and conditional probabilities are converted into crisp numbers by carrying out Eq. (12). For the conversion of the fuzzy numbers into crisp numbers, there have been encountered various approaches in the previous studies such as weighted average method, centre of sums, centroid method maximum membership degree, and centre of the largest area (Wang, 1997). In this paper, to minimize knowledge loss and attain more correct analysis, centre of area approach is utilized due to its applicability and simplicity (Şakar and Zorba, 2017). For the conversion of the fuzzy numbers into definite numbers, Eq. (11) and Eq. (12) are provided as in the following.

Defuzzification equation:

$$X^* = \frac{\int \mu_i(x)dx}{\int \mu_i(x)} \tag{11}$$

For a triangular fuzzy number $\widetilde{A} = (a_1, a_2, a_3)$

$$X = \frac{\int_{a_1}^{a_2}\frac{x-a_1}{a_2-a_1}xdx + \int\int_{a_2}^{a_3}\frac{a_3-x}{a_3-a_2}xdx}{\int_{a_1}^{a_2}\frac{x-a_1}{a_2-a_1}dx + \int\int_{a_2}^{a_3}\frac{a_3-x}{a_3-a_2}dx} = \frac{1}{3}(a_1+a_2+a_3) \tag{12}$$

3. The use of fuzzy Bayesian approach on oil pollution of bunkering operation

In this section, the FBN method is employed to model oil pollution incidents occurring during bunkering operations. Before utilizing the approach, it is aimed to identify the causal factors that lead to the pollution during bunkering operation.

3.1. *Definitions of the variables*

Since there has not been come across any study approaching directly the oil pollution incident arising from bunkering operation in the literature, we have attempted at elicitating the root causes through industrial experts qualitatively. To attain expert views, we have carried out semi-structured interviews via face-to-face and telephone conversations. Before performing the interviews, the experts were briefly informed regarding the target of the study, the process of the Bayes networks, and the course of disclosing the probabilities. In this phase, the views of the 12 experts have been achieved. These experts, who have contributed to the identifications of the variables, establishment of the Bayes network, states of the root and intermediate nodes, have been actively involved in the bunkering operations several times throughout their careers and worked in different types of vessels such as tanker, container, RO-RO vessels and bulk carriers. Experts have been working in different segments of the industry in different positions such as chief engineer, first engineer, an academician with a first engineering background, master mariner, technical superintendent, first officer.

The established model has been compromised by experts and eventually 16 root nodes and 6 intermediate nodes, which are indicated to be the contributor to the bunkering operation sourced oil pollution, have been determined. The reconciled variables and relationships between each other can be seen in Fig. 2 and the identifications of the root nodes are presented as in the following.

Fatigue of crew: Crew, who participates in bunkering operation, may be exhausted due to pre-operation workload or long-term channel transition maneuvers. For this reason, problems stemming from the fatigue of crew such as falling asleep, lack of attention etc. during bunkering operation might cause errors.

Incompetent crew: Knowledge of the crew participating in the bunkering operation may be insufficient. Besides, ownerhip management may follow minimum safe manning and this, in turn, might lead to a lack of workforce. Further, a crew member may be attended to the vessel recently or bunkering operation could be the first operation of the crew who has no experience before.

Crew workload: Due to an unforeseen breakdown before or during the bunkering operation, the workload of the personnel participating in the operation may increase and this, in turn, might lead the crew to make a mistake in the bunkering process. Also, during bunkering operation, some engine crew may attend another maintenance or repairing operation that may prevent departure or safety of navigation.

Familiarization: Missing or shortage on giving pre-bunkering

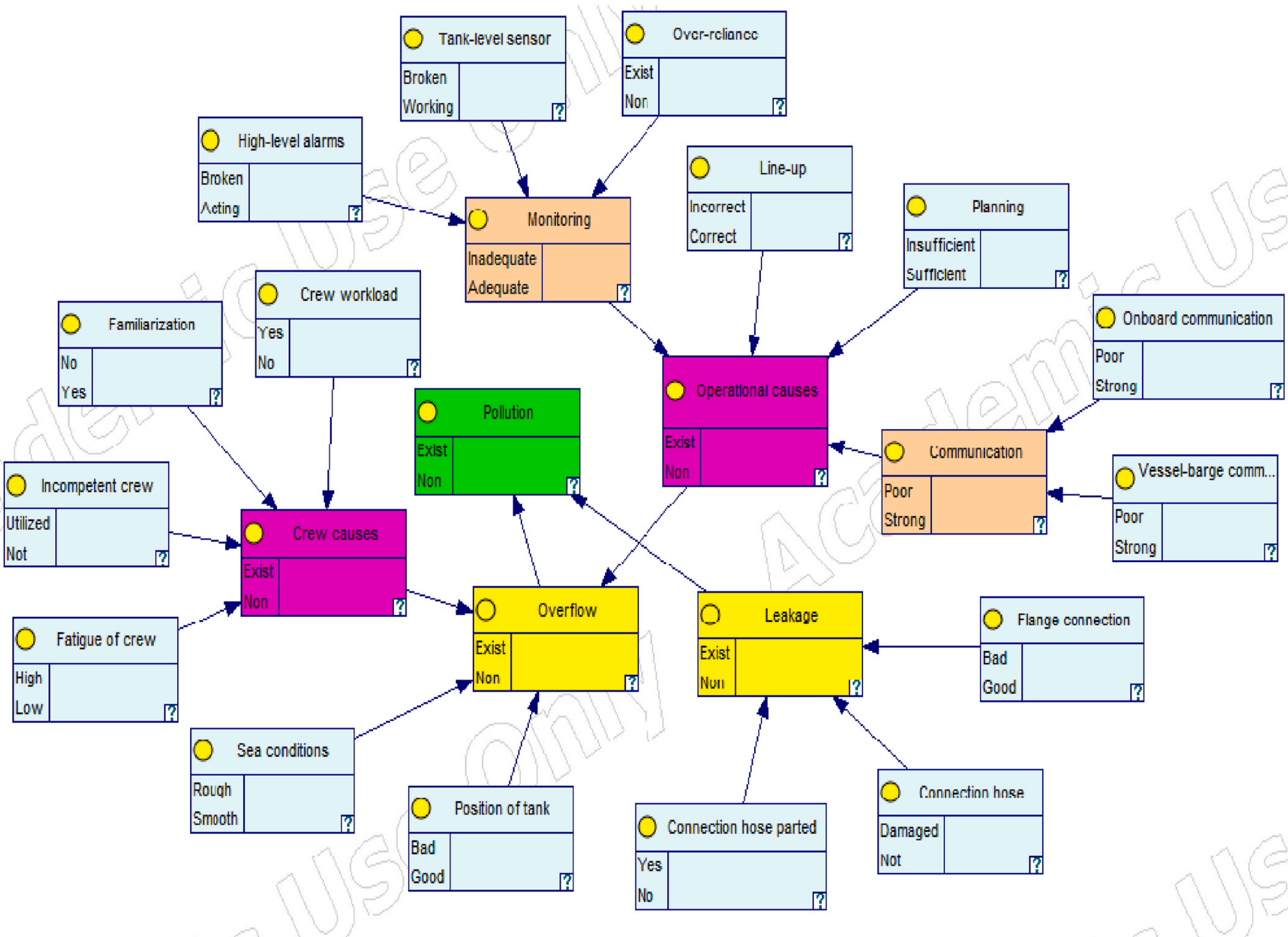

Fig. 2. Causal factors of the oil pollution stemming from bunkering under the FBN method.

information about which officer or crew to carry out the determined duty, planned tanks to be bunkered and the type of the fuel may lead to difficulties. Also, during the bunkering operations that take a long time, the crew might need to be shifted over watches and in that case, short briefing or familiarization should be executed.

High-level alarms: Damaged or not functioning of high-level alarms in fuel storage tanks might cause faulty monitoring.

Tank level sensor: Tank-level sensors that send value to the monitors, in which crew oversee the tanks remotely in the ship's office or the engine control room, may not work properly during bunkering transfer. Also, these sensors not reflecting the instant amount correctly in accordance with the variable trim or heeling of the ship may cause erroneous monitoring.

Over-reliance: Durig bunkering operation, the crew who is ordered to take sounding from the tanks may not exercise due diligence and even may report fictitious sounding value. He may not follow the instructions of the chief engineers and act slowly that in turn may lead to mistakes in monitoring.

Line-up: Before bunkering, the bunkering line may be prepared incorrectly for the planned fuel transfer. Transfer can be started for a filled tank by mistake due to operating of the wrong valve or closed valve can be missed on the line that might lead to overflow on the deck.

Planning: Not to make a bunkering plan before the transfer or to make an inaccurate plan can lead to great faults. A bunkering plan must be prepared before the operation and every amount to be bunkered to the tanks must be calculated meticulously. Furthermore, sounding values can be miscalculated before the transfer, or sounding values during transfer can be confused between the tanks mistakenly.

Onboard communication: Onboard communication within the crew of the bunkered vessel can be done by telephone, radio, or face to face. Especially the communication with the crew on the bunker station can be affected by the weather, the noise of the port operation or cable problems, and misunderstandings in the communication may cause problems.

Vessel-barge communication: Vessel-barge communication is usually carried out face to face or with hand signs. In this regard, some mostly used hand signs must be accepted between the crew of the vessels before the bunkering operation such as start pumping, stop pumping, increase or decrease the rate, etc. There must be on-duty crew on the decks of both ships for communication. This personnel leaving the deck means complete loss of communication. Also, an emergency stop button must be provided by fuel barge to the deck of the bunkered vessel.

Sea Condition: Naturally, bunkering operation should not be performed under heavy weather conditions; however, in practice due to fuel price advantage, an operation may sometimes need to be carried out under rough sea conditions when the ship is in an anchorage area of cheap fuel location. There are also other factors that might force vessels to this situation such as the necessity of delivering cargo on time, the pressure of charterer, etc.

Position of tank: The tank may be fitted in the double bottom, sides of the vessel, or in topsides of the vessel, and this positioning may have a negative effect on bunkering. In the case that especially if the tank capacity is low and the pumping capacity of the barge is very high, then this may cause difficulties during the transfer. However, on some bulk carriers, the fuel storage tanks are fitted in topside tanks under the main deck. The base and the up side of these tanks are built in inclined shape because of the topside tank and the deck chamber structure. This also leads to difficulties during bunkering when the ship is in ballast condition.

***Flange connection*:** A bunkering line flange should be prepared for the connection before bunkering. Not cleaning the flange properly or not renewing the bolts of the bunkering flange may cause leakages. Also using less number of flange bolts, not tightening the bolts properly or not using the right sequence of bolt tightening may cause leakages.

***Connection hose damaged*:** The damaged bunkering hose may lead to leakages and the reasons to account for this is that hose may be damaged during operation by friction or the strength if it is not secured carefully.

***Connection hose ruptured*:** The rupture of the bunkering hose during the operation can cause pollution.

3.2. Construction of prior and conditional probability tables

After constituting the BN graphical network structure and determining the conditions of each node, prior probabilities and conditional probability tables were generated for root and intermediate nodes. To perform this, an excel sheet that includes the identifications of the causal factors, the conditions of each node, and questions to disclose the probabilities, was sent out to the professionals. Linguistic expressions of the fuzzy logic were exploited as given in Table 1. In this phase, an assessment of the probabilities between the nodes was obtained from 5 experts.

Among them, it should be indicated that the technical superintendent had an onboard experience in tanker vessels, the chief engineer in container vessel and bulk carriers, the lecturer in RO-RO and bulk carriers, the first engineer in RO-RO vessels, and the captain in RO-RO, bulk carriers and container vessels. Their industrial experience period both onboard vessel and onshore was provided totally in Table 3. For instance, the superintendent has a 19 years of an industrial experience and 13 years of it was spent onboard vessels and 6 was onshore. Furthermore, the first engineer had a 12 years of experience in total and 4 years of it was spent onboard vessels that make him the expert who has the lowest onboard vessel experience among them. Additionally, the captain holds a PhD from maritime transportation field and currently has been working as an assistant professor in a marine school after serving 7 years onboard vessels. At this stage, it should be indicated that the technical superintendent, currently working in a chemical and oil tanker shipping company, had experienced an oil pollution incident during bunkering operation. Therefore, total weight score that is assigned to this expert is 13 as in Table 3. Since the qualification of each expert does not carry the same weight, a weighting transaction is a necessity to disclose their differences in the assessment operation. Therefore, professional position, experience, and educational degree as weighting criteria for different professionals are taken into account and each criterion is assigned a score between 0 and 5. The details considered for weighting values for the experts are provided in Table 2 and details for experts together with calculations of the weighting process are provided in Table 3 (Rajanakuran et al., 2015).

Table 2
Criteria for weighting.

Constitution	Classification	Score
Professional position (PP)	Technical Superintendent	5
	Chief Engineer	4
	Lecturer	3
	First Engineer	2
	Captain	1
Occupational experince	More than 15 years	5
	11 to 15	4
	6 to 10	3
	3 to 5	2
	Less than 3 years	1
Educational level	PhD	5
	Master	4
	Bachelor	3
	HND	2
	School Level	1

To utilize the data for modeling the BN, GeNle 3.0 academic software package was used. Prior to implementing the GeNIe software, expert expressions, obtained in the linguistic form, were fuzzified through triangular fuzzy members. Subsequently, a similarity aggregation approach that is developed by Hsu and Chen (1996) was utilized to reach a compromise for the opinions of the experts. Since expert statements were obtained on a fuzzy linguistic scale, it is a requirement to transform them into crisp numbers through defuzzification operation by employing the centre of area method as provided in equation (11) and (12). All these computations were executed in an MS Office Excel sheet so that data would be prepared for proceeding with the GeNle. The linguistic assessments and prior probabilities of the root nodes are provided by experts as in Table 4. For the intermediate and leaf nodes, professionals provided fuzzy conditional probabilities as well. Due to limited space, only the CPT of the monitoring node is presented in Table 5, and also posterior probabilities of all nodes are shown in Fig. 3.

3.3. Sensitivity analysis

Sensitivity analysis is of vital importance in probabilistic assessment. It is aimed to illustrate to what extent the performance of each cause arising from bunkering operation has a contribution to the occurrence of pollution (Zhang et al., 2014). Furthermore, it enables the depiction of inconsistencies in the structured model, and variables in the established model are ranked based on their effects on the target node which is pollution in this research (Marcot, 2012). To perform sensitivity analysis, some variables are selected from the different sections of the constructed network and prior probability values of the variables are changed, therefore it becomes possible to monitor the impact of each node on the target node (Kabir et al., 2016). Analysis was executed for all root and intermediate nodes, and outcomes are presented in Table 6 and discussed in the findings section.

3.4. Validity of the model

In the last stage, the constructed model is to be verified. Validity tests are of great importance for the solidity of the results of the BN model. It is observed from the literature that there are various approaches to detect the validity of the established model. According to a widely employed approach which is also exploited in this study, three axioms provided below should be satisfied (Wang et al., 2011; Zhang et al., 2013).

Axiom 1. Carrying out an increase or decrease in the prior probabilities of each parent node to a particular degree must lead to a relative and significant rise or fall in the posterior probabilities of the relative child nodes (Table 7).

Axiom 2. Various rates of increase carried out on the prior probabilities of a parent node must show a consistent impact on the child node (Fig. 4).

Axiom 3. In the case of considering child nodes with more than one parent (assume a and b), the combined impact of parent a and parent b should certainly be stronger than the mere effect of parent a or the mere effect of parent b separately (Table 8).

4. Findings and discussion

In this research, a detailed analysis was performed for the causal factors of pollution stemming from bunkering operations under the FBN method. Variables are constructed by industrial experts, and the occurrence probability of pollution was found as 4% by utilizing the

Table 3
Details of the experts and calculations of the weighting scores.

Expert Level								
expert no	professional position	experience	education level	weighting factor			TW	weighting score
1	Technical Superintendent	19	Bsc	5	5	3	13	0,2280
2	Chief Engineer	17	Bsc	4	5	3	12	0,2105
3	Lecturer	13	Bsc	3	5	3	11	0,1929
4	First Engineer	12	Msc	2	4	4	10	0,1754
5	Captain	18	Phd	1	5	5	11	0,1929

Table 4
Linguistic expert evaluations and fuzzy possibility scores (FPS) for Conditions 1st. of the root nodes.

	Conditions		Expert Evaluations for Conditions 1st.					
Root Nodes	Conditions 1st.	Conditions 2nd.	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Fuzzy Possibility Scores (FPS)
Position of tank	Bad	Good	VVL	L	VL	VL	VL	0.10
Sea conditions	Rough	Smooth	VVL	VL	VVL	VVL	VVL	0.03
Fatigue of personel	High	Low	SL	VL	VL	L	SL	0.22
Incompetent staff	Utilized	Not	L	VL	L	SL	L	0.21
Familiarization	No	Yes	SL	VVL	SL	L	VL	0.21
Staff workload	Yes	No	SL	VL	VL	L	VL	0.17
High-level alarms	Broken	Acting	VVL	VVL	VVL	VVL	VVL	0.02
Tank-level sensor	Broken	Working	VVL	VL	VVL	VVL	VVL	0.03
Over-reliance	Exist	Non	SL	SL	L	VVL	L	0.23
Line-up	Incorrect	Correct	L	VL	L	L	VVL	0.15
Planning	Insufficient	Sufficient	L	VL	L	VVL	L	0.15
Onboard communication	Poor	Strong	L	VL	SL	L	VL	0.19
Vessel-barge communication	Poor	Strong	L	L	VL	VL	L	0.16
Flange connection	Bad	Good	VL	VVL	VL	VL	VL	0.06
Connection hose	Damaged	Not	VL	VVL	VL	VL	L	0.08
Connection hose parted	Yes	No	VVL	VVL	VL	VVL	VVL	0.03

Table 5
Table of the conditional probabilities for monitoring intermediate node.

High-level alarms	broken				Acting			
Tank-level sensor	broken		working		broken		Working	
Over-reliance	exist	non	exist	non	exist	non	exist	Non
Exist	0.941	0.293	0.515	0.026	0.658	0.047	0.11	0.003
Non	0.058	0.706	0.484	0.973	0.341	0.952	0.88	0.996

Bayesian networks (Fig. 3). Taking the sensitivity analysis into account (Table 6), it appears that major contributory causes of pollution are the existence of overflow, the existence of operational causes, crew causes, inadequate monitoring, and bad position of the tank in order. Among them, the existence of overflow has the highest impact on the occurrence of pollution arising from bunkering operation as this node leads to an increase of 91% on the occurrence probability of pollution from 4% to 95%. This outcome is confirmed by Nichol (2018), North P&I (2018) and, Gard P&I (2019) and thus elimination of overflow should carry the highest priority in oil pollution prevention policies. The existence of overflow is followed by operational causes as this node leads to an increase of 15.1% on the occurrence probability of the pollution from 4% to 19.1%. After operational causes, it appears that crew causes, inadequate monitoring, and bad position of tanks have the largest effect on the pollution occurrence probability in order. The node of crew causes leads to an increase of 8.7% on the occurrence probability of pollution from 4% to 12.7%, inadequate monitoring and position of tank 3.7% equally, from 4% to 7.7%. Elaborating on the operational causes, it is found that poor communication and incorrect line-up have the least effect on the pollution probability occurrence in order. The node of poor communication increases the occurrence probability of pollution from 4% to 7.1% and incorrect line-up from 4% to 6.3%.

On the other hand, poor vessel-barge communication, broken high-level alarms, damaged connection hose, existence of over-reliance and bad flange connection appear as the minor causal factors of the pollution. Broken high-level alarms and damaged connection hose show an equal impact to account for the occurrence of pollution probability. These nodes lead to an increase of 0.7% on the pollution probability from 4% to 4.7%. It is found that bad flange connection has the least impact on the pollution occurrence as pollution occurrence probability increase from 4% to 4.5%. Broadly speaking that parents of the leakage node have a minor effect on the occurrence probability of pollution.

Following the sensitivity analysis, axiom tests were carried out for the occurrence probability of the pollution to verify the results. As a consequence of the axiom test 1 (Table 7), considering parent nodes of the operational causes, a relative rise and fall were observed on their child node. In the light of axiom test 2, various rates of fall (3%) were executed on the prior probabilities of the parent nodes of crew causes and therefore a consistent fall was observed on the child node of crew causes (Fig. 4). It is observed that the utilization of the incompetent crew has the largest impact to account for the crew causes. This result is in line with Akyuz et al. (2018) indicating that most of the ship crew has inadequate knowledge in placing deck scupper in position owing to lack of practical training. Moreover, it was found that the combined impact of the parents of overflow appears larger than the mere impact of each parent (Table 8) and the node of operational causes has the largest effect to explain the occurrence probability of the overflow existence and rough sea conditions have the least.

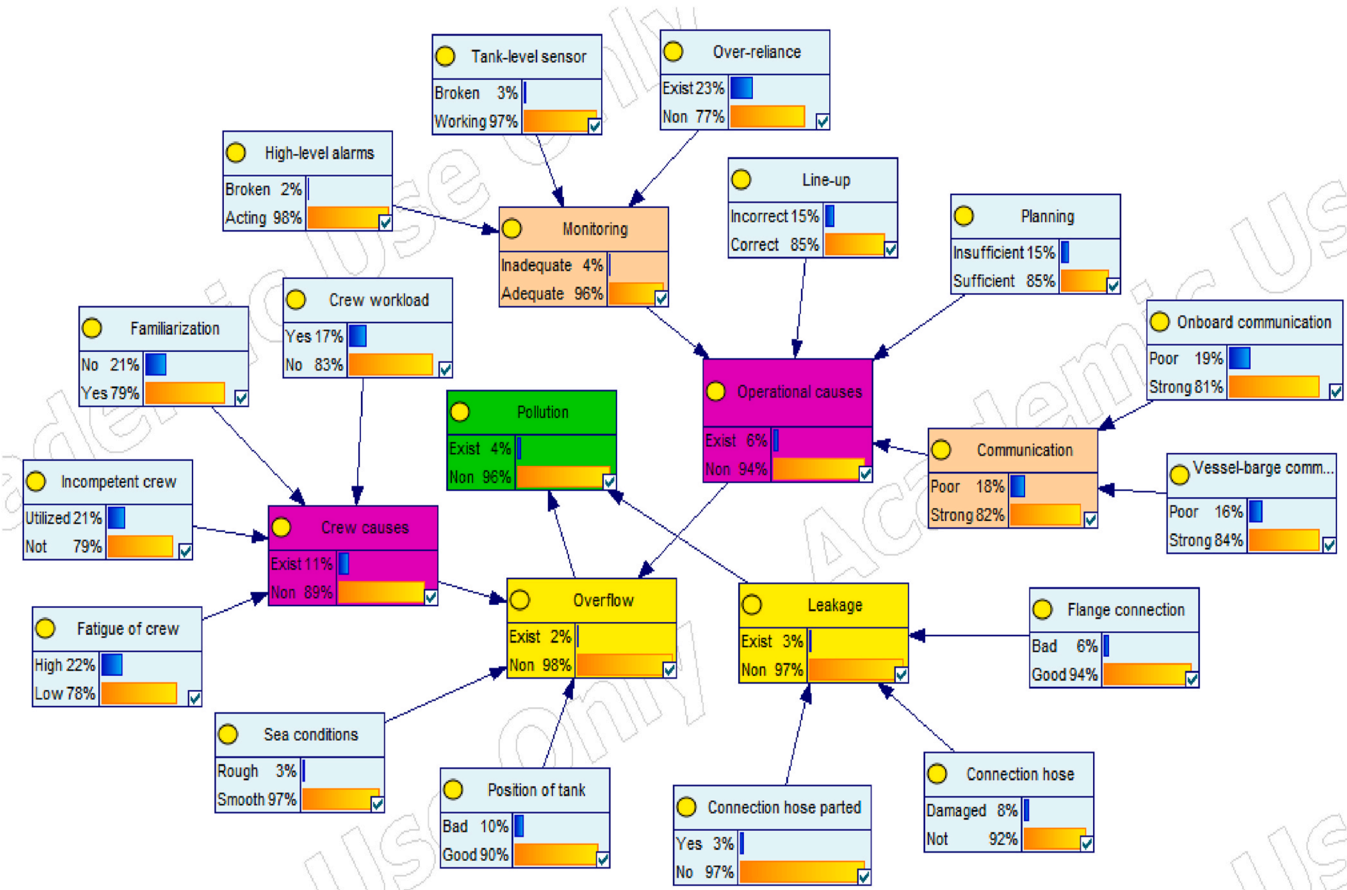

Fig. 3. Posterior probabilities of the causal factors of the oil pollution stemming from bunkering operation.

Table 6
Sensitivity analysis for all nodes.

	Condition 1st	Prior %	Change %	Pollution prior %	Pollution posterior %	Change of probability %
Overflow	Exist	2	100	4	95	91
Operational causes	Exist	6	100	4	19.1	15.1
Crew causes	Exist	11	100	4	12.7	8.7
Monitoring	Inadequate	4	100	4	7.7	3.7
Position of tank	Bad	10	100	4	7.7	3.7
Planning	Insufficient	15	100	4	7.2	3.2
Communication	Poor	18	100	4	7.1	3.1
Leakage	Exist	3	100	4	6.6	2.6
Incompetent crew	Utilized	21	100	4	6.5	2.5
Sea conditions	Rough	3	100	4	6.3	2.3
Line-up	Incorrect	15	100	4	6.3	2.3
Familiarization	No	21	100	4	6.1	2.1
Crew workload	Yes	17	100	4	5.6	1.6
Fatigue of crew	High	22	100	4	5.4	1.4
Onboard communication	Poor	19	100	4	5.3	1.3
Connection hose parted	Yes	3	100	4	4.9	0.9
Tank level sensor	Broken	3	100	4	4.8	0.8
Vessel-barge communication	Poor	16	100	4	4.8	0.8
High level alarms	Broken	2	100	4	4.7	0.7
Connection hose	Damaged	8	100	4	4.7	0.7
Over-reliance	Exist	23	100	4	4.6	0.6
Flange connection	Bad	6	100	4	4.5	0.5

In technical management context of the bunkering operation, in light of the findings, it is suggested that utmost importance should be given to the elimination of overflow. In this way, a recent paper by Krata and Jachowski (2021) confirm the design failure of bunker tanks as a significant overflow cause. In this regard, it is recommended that the fuel storage tanks should be constructed as smooth rectangular prism as possible, or the tanks should be situated in a position that it does not be affected by the non-linear shape of the ship's hull sections. Moreover, the overflow line that exists between fuel storage tanks and overflow tank should be designed to function more effectively. If this is achieved, excess fuel will be canalized to the overflow tank, not to the deck. On the other hand, in crew management context of the bunkering operation, it is important to take the necessary corrective actions to mitigate the errors occurring due to crew causal factors. In this regard, it should be

Table 7
Test of Axiom 1 for the node "Operational Causes".

Condition	Parent Nodes	Child node
Inadequate	Monitoring	Operational Causes
	prior	0.06
	100%	0.28
	0%	0.04
Incorrect	Line-up	Operational Causes
	prior	0.06
	100%	0.18
	0%	0.03
Insufficient	Planning	Operational Causes
	prior	0.06
	100%	0.24
	0%	0.02
Poor	Communication	Operational Causes
	Prior	0.06
	100%	0.23
	0%	0.02

underlined that the vessel crew participating in the bunkering operation must be well-trained and experienced to run the operation. As pointed out by Chen et al. (2020) and Senol and Yasli (2021), it is suggested that, in addition to regular training, adopting continual training and assessment programs for the vessel crews involved in bunkering operations would be an effective strategy to minimize the risk of pollution stemming from bunkering operation. It is vital to systematically examine and evaluate the practical training and practical capabilities of personnel who are in the course of being recruited as trainees, and to proactively understand the outcomes obtained for risk mitigation purposes. Furthermore, as indicated by Chen et al. (2020), many seafarers acquire their certificates from maritime education/training institutions and maritime colleges and at this education centers, emphasis should be placed on the quality rather than quantity. Considering commercial management context, vessels should refrain from receiving bunker fuel under rough sea conditions due to charterer pressure or price advantage of cheap location. Because in case of pollution, the extent of the penalties and indemnities to be incurred can be much more than the advantage of cheap fuel received under rough sea conditions.

Besides theoretical insights, the paper has practical implications. Considering that bunkering operations mainly take place in an anchorage area or at berth alongside, high impact of overflow on the oil pollution occurrence in the bunkering operation presents a high risk for locations, premises which are close to the coastal areas. Spill in these regions can arrive at the shore in a short period and might have a greater effect on the environment. Thus, fast first response, clean-up approaches, and equipment to be utilized become important to prevent the spill from arriving the shore. The speed of first response and equipment to be exploited should be prioritized to design response methods and develop strategies, countermeasures, particularly for such regions.

5. Conclusion

In this study, the causal mechanism of the oil pollution stemming from bunkering operation is evaluated comprehensively. Causal factors in the developed model have been disclosed by experts who have long experience in the industry and to uncover the probabilistic relations among the causal factors, the Fuzzy Bayes method is exploited. While the Fuzzy logic handles the ambiguity, the BN approach performs effectively in establishing and classifying the spill causes. To display the performance of each causal factor on the occurrence of the oil spill, a sensitivity analysis is conducted. To verify the solidity of the findings, three axiom tests are carried out. Therefore, the validity of the BN structure was approved. With an inference analysis on the Bayes network, this paper elicitates the casual factors to account for the bunkering operation-sourced oil spills and reveal the probabilistic weights of them. Outcomes of the research indicate that the overflow has the highest effect to explain the occurrence probability of the oil spill during bunkering operation. Operational causes, crew causes, inadequate monitoring, bad position of tank follow the overflow as major contributory causes in order. On the other hand, broken tank level sensor, connection hose parting, poor vessel-barge communication, broken high-level alarms, damaged connection hose, existence of over-reliance, and bad flange connection have the least effect to account for the occurrence of pollution during bunkering operation. Findings of this research have important implications for developing countermeasures and the formulation of pollution preventive policies. In this regard, it is suggested that it should be put much emphasis on the existence of overflow to reduce the pollution probability and to prevent overflow, operational causal factors should be given priority. To eliminate operational causal factors, the primary focus should be on the elimination of

Table 8
Axiom Test 3 for the node "Overflow".

Parent nodes				Child node	Percentage Effect (Differences)
Position of tank	Sea conditions	Crew causes	Operational causes	Overflow	
10	3	11	6	0,02	
100	50	92	82	0,05	3%
55	100	92	82	0,04	2%
55	50	100	82	0,11	9%
55	50	92	100	0,18	16%
100	100	100	100	0.995	97.5%

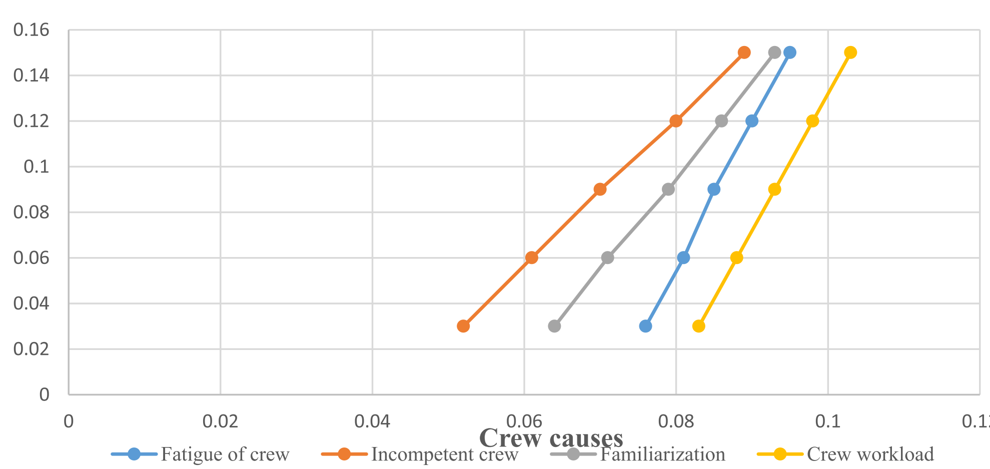

Fig. 4. Axiom test 2 for the node "Crew causes".

inadequate monitoring and insufficient planning. It is considered that the results of the paper offer valuable insights into the causal mechanism of oil pollution pertaining to bunkering operations, thus shipowning companies, loss-prevention departments of the P&I Clubs and regulatory authorities can utilize the outcomes of this paper to prevent the recurrence of spill, take necessary measures and protect marine environment. This study is limited with the modeling of bunkering operations between bunker barge and bunkered vessels and in a further study, a complete holistic approach can be demonstrated for the bunkering operation occurring between road vehicle and bunkered vessel. Similarly, the current study utilized expert views in establishing the BN structure due to lack of data, and in a further study, to develop a better model a data-driven BN approach, in which BN structure is learned from a dataset under a machine learning algorithm, can be carried out after compiling the data of large historical oil spill cases sourced by bunkering operations. Also, a real case analysis for bunker oil spill will be scope of a further study.

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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