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Risk analysis of offshore terminals in the Caspian Sea

Kambiz Mokhtari* and Jamshid Amanee

ECO College of Insurance, Allameh Tabataba'i University, Tehran, Iran

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Abstract. Nowadays in offshore industry there are emerging hazards with vague property such as act of terrorism, act of war, unforeseen natural disasters such as tsunami, etc. Therefore industry professionals such as offshore energy insurers, safety engineers and risk managers in order to determine the failure rates and frequencies for the potential hazards where there is no data available, they need to use an appropriate method to overcome this difficulty. Furthermore in conventional risk based analysis models such as when using a fault tree analysis, hazards with vague properties are normally waived and ignored. In other word in previous situations only a traditional probability based fault tree analysis could be implemented. To overcome this shortcoming fuzzy set theory is applied to fault tree analysis to combine the known and unknown data in which the pre-combined result will be determined under a fuzzy environment. This has been fulfilled by integration of a generic bow-tie based risk analysis model into the risk assessment phase of the Risk Management (RM) cycles as a backbone of the phase. For this reason Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) are used to analyse one of the significant risk factors associated in offshore terminals. This process will eventually help the insurers and risk managers in marine and offshore industries to investigate the potential hazards more in detail if there is vagueness. For this purpose a case study of offshore terminal while coinciding with the nature of the Caspian Sea was decided to be examined.

Keywords: risk analysis; risk management; fault tree analysis; event tree analysis; bow-tie model; fuzzy set theory; offshore terminals; Caspian Sea

1. Introduction

There has been growing concern in public and private sectors regarding the threats of the hazards associated within offshore terminals to people, assets, environment and reputations resulting from the offshore terminals' operations and management. Investigations show that almost all the major accidents and losses in terms of delays and costs could be avoided with effective RM programmes Wang (2004), Tarila and Edward (2017).This paper is focusing on offshore terminals, discusses recently emergent RM-related issues with taking into consideration of the externally and internally driven elements e.g. pure risks (i.e. uncertainty of damage to property by fire, flood or the prospect of premature death caused by accidents) and speculative risks (i.e., risks which are linked directly to the business function, decision making processes and management). This view has been steadily increasing, for example, a number of studies have reported such trend in the United Nations Conferences on Trade and Development from 1996 to 2006 UNCTAD

*Corresponding author, Ph.D., Ex-Master Mariner, E-mail: kambiz.mokhtari@atu.ac.ir

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(2006),developed a security risk assessment and management framework that is capable of reflecting the logistics scope of transport networks.

The focus was mostly on the development, management, commercial, operational and organisational issues of the marine ports and terminals. On the marine related RM area, GAO (2019) has stressed for "further refinements needed to assess risks and prioritise protective measures at related critical infrastructure". In UK, DETR (2000) and required all marine ports and terminals to carry out risk assessment of marine operations in order to implement the safety management system. Additionally UK, HSE (2019) has urged offshore contactors and operators to conduct safety cases and safety reports on different stages of their operations e.g. design, commissioning, operation, transportation, decommissioning as well as reviewing them periodically.

In offshore industry e.g., for offshore terminals a high quality RM is absolutely necessary for their sustainable development. In this regard risk is defined as "a measure of human injury, environmental damage or economic loss in terms of both the incident likelihood and the magnitude of the injury, damage or loss" CCPS (2000) and Mokhtari (2012). Risk analysis involves the development of an overall estimation of risk by gathering and integrating information about scenarios, frequencies and consequences. It is one of the major components of the whole RM process of any particular enterprise.

The main aim of this paper is to use a proposed RM framework and a developed generic risk analyse model to evaluate and prioritise hazards in offshore terminals. The proposed framework for the purpose of offshore terminals consists of the following three main phases:

- Hazard Identification
- Risk Assessment
- Risk Mitigation

Overall the developed risk analyse model can facilitate on achieving the objectives of the RM framework within the offshore terminals. The research results can help professionals to decide whether to take preventive actions or corrective actions during the risk mitigation phase of the RM framework. This will lead to proceed toward a proactive or a reactive RM process.

This paper is organised as follows. Section 2 reviews the existing literature. Section 3 presents and discusses risk analysis in offshore terminals that including bow-tie based risk analysis model and proposing the methodology for implementing the risk analysis. Section 4 provides a case study based on Caspian Sea to demonstrate the use of the proposed methodology on offshore terminals. Conclusions and further work are discussed in Section 5.

2. Literature review

Along with the rapid progress of industrialisation, the risk of incidents is increasing and it has become increasingly recognised that there is a worldwide trend for losses due to accidents to rise even more rapidly than gross national product Lees (1996). As a result in order to analyse the potential risk factors appropriately there is a need to utilise risk analysis model. Moreover no course in a RM cycle would be complete without the inclusion of a major component on risk analysis. Risk analysis acts as a kind of hub, around which many other practical aspects of RM rotate Dickson (2003). Dickson discuss that every risk is caused by some factor or factors and results in some effect or effects. It can be viewed rather like a chain. The cause is linked to the nature of the risk and the risk itself is linked to the effect.

In the process of risk analysis, both qualitative and quantitative techniques can be used Krishna*et al*.(2003). Nowadays variety of techniques are used for risk analysis including Physical Inspections, Organisational Charts, Flow Charts, Safety Review, Checklist Analysis, Relative Ranking, "What-if" Analysis, Preliminary Hazard Analysis (PHA), Hazard and Operability Study (HAZOP), Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Cause-Consequence Analysis (CCA), Human Reliability Analysis (HRA) (Lees 1996, Dickson 2003, CIS 2002, Krishna *et al*. 2003, ABS 2019, Chiara and Giuseppe 2014, Jichuan *et al*. 2018, Mareike and Athanasios 2018). These techniques have all been developed in the industrial setting, normally in response to some practical business problems. It is, however, unlikely that one technique will solve all problems for different industry types.

2.1 Bow-tie analysis

A bow-tie framework has been proposed to integrate a broad group of cause–consequence models Visser (1998). The traditional fault tree and event tree models are 'bow-tied' and the fault tree's "top event" is connecting with the event tree's "initiating event". The bow-tie will be regard as a "lens" for focusing on causes of an event and "projecting" that onto the space of the event's consequences. The consequences will eventually be attributed into decision problems for the purpose of RM. The bow-tie's consequence side can make an interface with the decision models, ultimately decisions taken will be reflected back towards the causes Groeneweg (1998). Bow-tie framework not only has proven a valuable conception in mishap prediction, but also has demonstrated its importance in analysing the past accidents and signifying improvements to avoid further re-occurrence of undesired events Bellamy *et al*. (2007). In particular it proved for being able to provide a suitable level of simplification of the causal factors in order to be able to summarise large quantities of data into a relatively small number of common scenarios, which can cover the majority of the accidents. In an accident scenario, the link between an accident and all its possible causes can be represented in the form of a fault tree HSE (2010). In the same time, the relationship between an accident and its possible multiple consequences can be represented by means of an event tree. Fault and event trees can be integrated in the form of a bow-tie diagram where the centre event represents 'the release of a hazardous agent' as presented in Fig. 1. This framework is particularly useful for analysing accidents, as their causes and consequences remain linked together. Moreover, it provides the user with a simplified classification framework where the usually varied information available in incident reports can be consistently stored and summarised according to a fixed common criteria.

A number of research groups have used the bow-tie framework to manage the occupational risks by developing a risk assessment model and software tools DNV (2000) and RIVM (2019). Indeed the bow-tie analysis is a tool that has both proactive and reactive elements and systematically works through the hazard and its management. It uses a methodology known as the Hazards and Effects Management Process (Edwards 1999, Zuijderduijn 1999, Blom *et al*. 1999). It can be used to demonstrate how effective a marine facility's safety management system is performing and also to complete gap analyses Elliott *et al.* (2019). The bow-tie framework can be used to demonstrate how the pertinent safety management system element requirements are met with respect to the control and management of hazards and risk factors (ABS 2019, Trbojevic and Car 2000, Cockshott 2005, Mokhtari and Ren 2014).

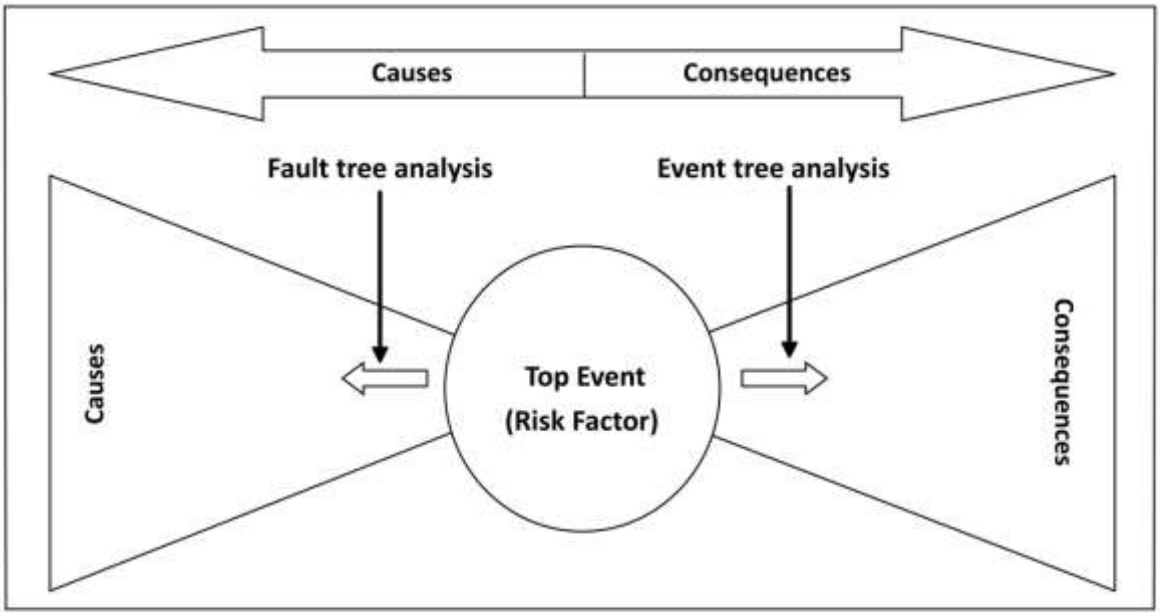

Fig. 1 A Bow-tie diagram
Source: Modified from GEXCON (2019)

2.2 FTA

FTA was first introduce in 1961 and has long been adapted for many applications in the process industry i.e. onshore and offshore sector's quantitative risk analysis to predict the probability of hazardous incidents and to identify the most important risk contributors. Moreover a fault tree is a logic and graphical representation that explores the interrelationships between a potential critical event in a system and the reasons for this event Hoyland and Rausand (1994). A typical fault tree consists of the top event, the basic events, and the logic gates Jichuan *et al*. (2018). Fig. 2 illustrates the key fault tree analysis symbols. There are two important types of events i.e. top event and basic event. The top event represents an undesirable state of the system; the basic events represent the state of the systems' components. FTA uses logic gates to describe the relationships between the basic events and the top event. The AND logic gate denotes that the output is in a failure state, if all the inputs are in failure state. The OR logic gate denotes that the output is in failure state, if at least one of the inputs is in failure state. An intermediate event represents an intermediate state of the system that is related directly or indirectly to the top event with a logic gate Dokas and Karras (2009).

2.3 ETA

The event tree analysis has been successively used in pre-incident applications, to examine the incident precursors and post-incident applications, and to identify the possible hazards (outcome events) for an accidental event (ABS 2019, Ferdous *et al*. 2009, AIChE 2000, Lees 2005, CMPT 1999). Qualitative analysis in an event tree identifies the possible outcome events of an initiating event, whereas qualitative analysis estimates the outcome event probability or frequency (likelihood) for the tree. Traditionally, quantitative analysis of an event tree uses crisp probabilities of events to estimate the outcome event probability or frequency. As argued by ABS (2019) and Ferdous, *et al*. (2009) in conventional event tree analysis, the branch probabilities have been treated as exact value. This provides a quick analysis and it uses crisp probabilities in each branch or path of the event tree. Fig. 3 illustrates a sample of a conventional event tree and the outcome event frequencies, which are crisp numbers.

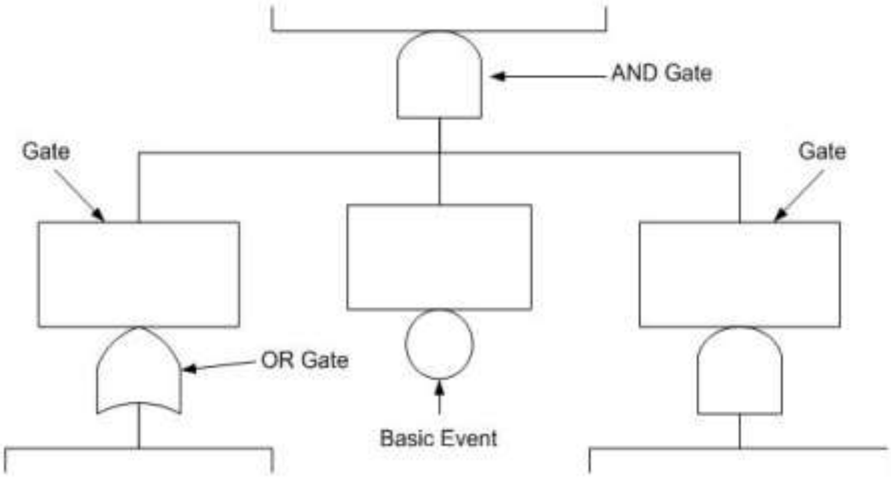

Fig. 2 Standard fault tree symbols
Source: Based on Wang (2004)

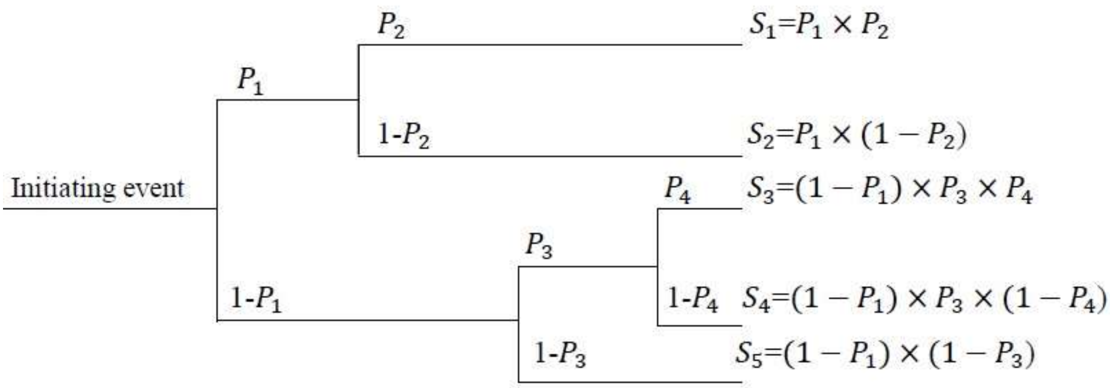

Fig. 3 Sample of a conventional event tree
Source: Based on ABS (2019) and Ferdous (2009)

As it is shown $P_n$denotes the Success/True/Yes probability of the *n*th event whereas the (1- P_n) denotes the Failure/False/No probability of the *n*th event within the same column. $S_n$is alsothe calculated outcome eventfrequency for the *n*th outcome event within the depicted event tree. In relation to ETA, ABS (2019) explains that this type of analysis can provide (1) qualitative descriptions of potential problems (combinations of events producing various types of problems from initiating events) and (2) quantitative estimates of event frequencies or likelihoods, which assist in demonstrating the relative importance of various failure sequences.

3. Hazard analysis in offshore terminals

This paper will analyse the hazards which can be regarded as basic events and main causes for a top event of "physical damage to offshore terminals" that have been identified and explained in the authors' previous works Mokhtari (2011) and Ren *et al.* (2000). The illustrated hazards have been previously identified through the risk identification i.e., HAZID process of the introduced RM framework which is one of the risk identification techniques. This paper will analyse the hazards (Basic Events) and consequences as a result of the mentioned risk factor (Top Event) while using the bow-tie methodology accompanying the FTA and ETA methods.

This has been fulfilled by introducing a generic risk analyse model in Fig. 4 which shows the addressed model has been integrated into a RM Framework of the offshore terminals. The previously identified offshore terminals' risk factors have been prioritised and ranked with the use of the Fuzzy Analytical Hierarchy Process (FAHP) method. Eventually one of the most significant risk factors identified was "physical damage to offshore terminals". As mentioned before if it is considered that this risk factor is top event then with the use of Fig. 4 its main causes (i.e., basic events or hazards) and potential outcome consequences can be analysed while using CCA method.

3.1 Methodology for hazard analysis

The cause-consequence diagram method (See Fig. 1) Andrew and Ridley (2002) is based on the occurrence of critical event, which for example may be an event, involving the failure of components or subsystems that is likely to produce hazardous consequences. Once a critical event has been identified, all relevant causes of it and its potential consequences are developed using two conventional reliability analysis methods i.e., FTA and ETA which were explored previously. FTA is used to describe the causes of an undesired event. ETA shows the consequences that a critical event may lead to if one or more protection systems do not function as designed. In this paper with the use of the CCA and fuzzy set theory, fuzzy failure probability for a top event along withits basic events (potential hazards)will be estimated. The selected risk factor will be evaluated and analysed with the use of a case study. This will help examining the introduced risk analyse tool that can suit for RM purposes in offshore terminals. Fuzzy set theory, experts' judgements, converting linguistic terms to fuzzy numbers and defuzzification processes will be used to obtain the Fuzzy Possibly Scores (FPSs) for the basic events in order to determine their Fuzzy Failure Probabilities (FFPs) as well as to determine a final FFP for top event in this paper. As in this study Triangular Fuzzy Numbers (TFNs) will be employed, these processes are fully explained in the following section. Additional information and steps needed for evaluation of the selected risk factor by the use of CCA and in form of FFTA and FETA have been explained in the next sections.

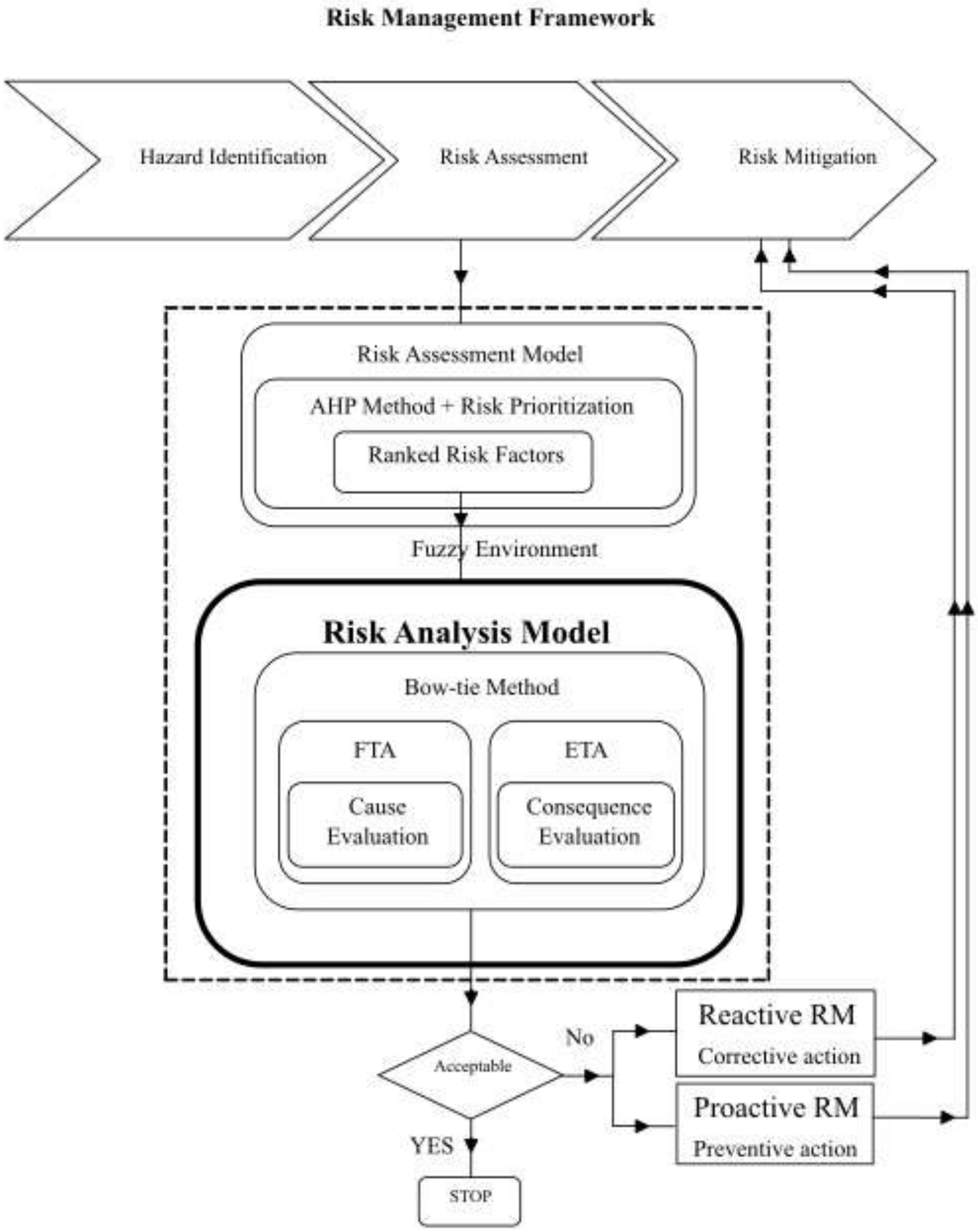

Fig. 4 A generic Risk Analysis Model integrated into a RM Framework

3.1.1 Fuzzy set theory

Fuzzy set theory was introduced to deal with vagueness of human judgement, which was oriented to the rationality of uncertainty caused by imprecision or vagueness (Keller and Tahani 1992, Saaty 2001, Murtaza 2003, Takagi and Hayashi 1991, Zadeh 1965, Marco 2018). A major contribution of fuzzy set theory is its capability of representing vague data. Fuzzy set is a class of objects with a continuum of grades of membership. Such a set is characterised by a membership (characteristic) function, which assigns to each object a grade of membership ranging between zero and one. The theory also allows mathematical operators and programming to apply to the fuzzy domain. Furthermore a fuzzy set is an extension of a crisp set. Crisp sets only allow full membership or non-membership at all, whereas fuzzy sets allow partial membership Balli and Korukoglu (2009).

On the other hand fuzzy numbers are the special classes of fuzzy quantities. A fuzzy number is a fuzzy quantity M that represents a generalisation of a real number r. Intuitively; M (x) should be a measure of how well M(x) "approximates" r Nguyen and Walker (2000). A fuzzy number M is a convex normalised fuzzy set. A fuzzy number is characterised by a given interval of real numbers, each with a grade of membership between 0 and 1. It is possible to use different fuzzy numbers according to the situation and in practice triangular and trapezoidal fuzzy numbers are used Klir and Yuan (1995). As Ertugrul and Karakasoglu (2007) expressed in applications it is often convenient to work with Triangular Fuzzy Numbers (TFNs) because of their computational simplicity, and they are useful in promoting representation and information processing in a fuzzy environment. A TFN i.e., $\widetilde{M}$ is shown in Fig. 5.

A tilde '∼' will be placed above a symbol if the symbol represents a fuzzy set. TFNs are defined by three real numbers, indicated simply as (l,m,u). The parameters l, m and u, respectively, indicate the smallest possible value, the most promising value, and the largest possible value that describe a fuzzy event Kaufmann and Gupta (1985). Their membership functions as shown in the Fig. 5 can be defined as follows

$$\mu_{\widetilde{M}(x)}= \begin{cases} 0, & if\ x \leq l \\ \frac{x-l}{m-l}, & if\ l < x < m \\ 1, & if\ x = m \\ \frac{u-x}{u-m}, & if\ m < x < u \\ 0, & if\ x \geq u \end{cases} \tag{1}$$

There are various operations on TFNs. However, three of the main operations used in this study are illustrated here. Moreover two positive TFNs are $\widetilde{M}_1 = (l_1,\ m_1,\ u_1)$ and $\widetilde{M}_2 = (l_2,\ m_2,\ u_2)$ and $l_1,\ m_1,\ u_1, l_2,\ m_2,\ and\ u_2$ are real numbers. The distance measurement d $(\widetilde{M}_1,\widetilde{M}_2)$ is identical to the Euclidean distance Chang (1996) and Chen (2000). Then under fuzzy environments their basic operations such as their addition i.e., $\oplus$, multiplication i.e., $\otimes$ and subtraction i.e., $\ominus$ can be defined as follows Yang and Hung (2007)

$$\widetilde{M}_1 \oplus \widetilde{M}_2 = (l_1,m_1,u_1) \oplus (l_2,m_2,u_2) = (l_1 \oplus l_2, m_1 \oplus m_2, u_1 \oplus u_2) \tag{2}$$

$$\widetilde{M}_1 \otimes \widetilde{M}_2 = (l_1,m_1,u_1) \otimes (l_2,m_2,u_2) = (l_1 \otimes l_2,\ m_1 \otimes m_2,\ u_1 \otimes u_2) \tag{3}$$

$$\widetilde{M}_1 \ominus \widetilde{M}_2 = (l_1,m_1,u_1) \ominus (l_2,m_2,u_2) = (l_1 \ominus u_2,\ m_2 \ominus m_1,\ u_1 \ominus l_2) \tag{3}$$

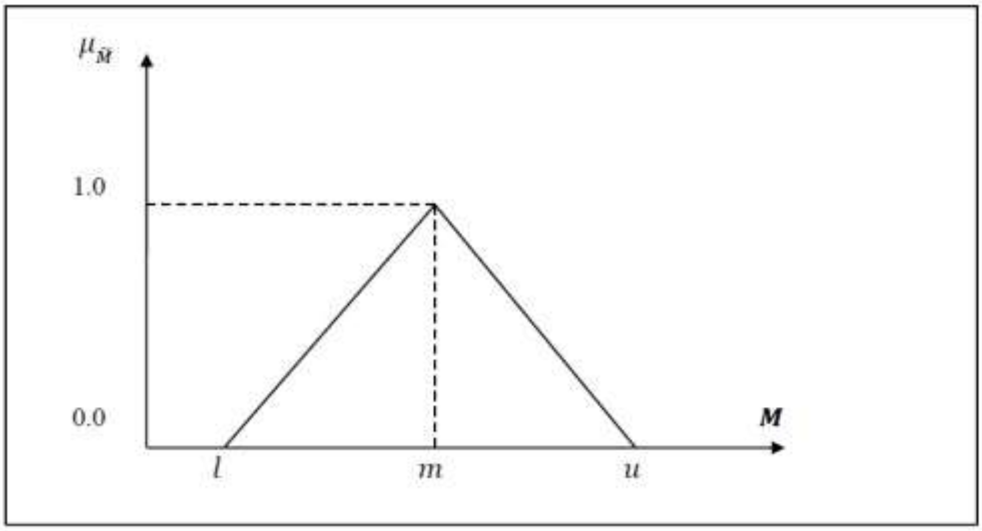

Fig. 5 A Triangular Fuzzy Number (TFN),$\tilde{M}$
Source: Based on Zadeh (1965) and Chang (1996)

Table 1 Transformation for Fuzzy membership functions

Grade	Occurrence Likelihood ($\tilde{L}$)	Consequence Severity ($\tilde{S}$)	Membership Function
1	Very Low (VL)	Slight (SL)	(0.00,0.00,0.25)
2	Low (L)	Minor (MI)	(0.00,0.25,0.50)
3	Medium (M)	Moderate (MO)	(0.25,0.50,0.75)
4	High (H)	Critical (CR)	(0.50,0.75,1.00)
5	Very High (VH)	Catastrophic (CA)	(0.75,1.00,1.00)

Other algebraic operations such as change of sign, subtraction, division etc. with fuzzy numbers can be found in (Zimmerman 1996, Kahraman 2001, Ren *et al*. 2007).

Due to the highly subjective nature and lack of information, it is usually difficult to measure risk parameters i.e., occurrence likelihood and consequence severity of the risk factors precisely. A reasonable and suitable way to express these parameters is to use qualitative linguistic variables particularly during experts' judgments. To estimate the occurrence likelihood, for example, one may often use such variables as very low, low, medium, high and very high. Additionally to assess the consequence severity also one may use such variables as slight, minor, moderate, critical and catastrophic.

These subjective linguistic variables can be further defined in terms of membership functions. A membership function is a curve that defines how each point in the input space is mapped to a membership value between 0 and 1. Of these membership functions, the simplest are the triangular and trapezoidal fuzzy numbers Li and Liao (2007). As TFNs are decided to be used in this paper to represent the linguistic variables for this purpose they have been shown in Table 1 (Yang and Hung, 2007, Anoop *et al.* 2006). Thus membership degrees of risk parameters as they range from 0 to 1 can be assigned by experts, with reference to Table 1 in a fuzzy environment.

3.1.2 Fuzzy FTA

The conventional FTA has been used broadly, however, it is often very difficult to assess the precise failure rates or failure probabilities for individual components or failure events. This happens particularly in systems like nuclear power plants where available data are insufficient for statistical inferences or the data show a large variation Jackson and Hockenbury (1981). To overcome these difficulties the use of FST (Liang and Wang 1993, Singer 1990) is being considered. In this respect the failure possibility defined by a TFN on the interval [0,1] is used to characterise the possible deviation of the basic events. Therefore the concept of the failure possibility can be applied to overcome the deficiencies which probability approach had during implementing of the traditional fault tree analysis to handle vagueness Liang and Wang (1993). In this study the same will be used hereafter and the failure possibilities are considered as triangular fuzzy sets to incorporate the uncertainties in the parameters.

In normal cases where there are sufficient data and considering the fact that the probability of the events are only relative frequencies of their occurrences (Andrew and Moss 2002, Henley and Kumamoto 1981) for an AND gate event, its probability can be obtained by Eq. (5)

$$\boldsymbol{P}_{(\boldsymbol{AND})} = \prod_{i=1}^{n} \boldsymbol{P_i} \tag{5}$$

Where P is the probability of top event; $\boldsymbol{P_i}$ denotes the failure probability of the basic event i and n is the number of basic events associated with the AND gate. For an OR gate event, its probability is determined by Eq. (6).

$$\boldsymbol{P}_{(\boldsymbol{OR})} = \mathbf{1} - \prod_{i=1}^{n} (\mathbf{1} - \boldsymbol{P_i}) \tag{6}$$

Furthermore there is also a gate called NEG gate in which its probability is equivalent to 1-$\boldsymbol{P_i}$ Cheng and Lan (2004). Whereas due to the scarcity of the hazardous events' occurrences and insufficient data as explained before it is realistic to use fuzzy FTA instead of its traditional version. The fuzzy form of "AND" and "OR" operations functions can be obtained in Eqs. (7) and (8) as follows Cheng and Lan (2004)

$$\widetilde{\boldsymbol{P}}_{(\boldsymbol{AND})} = \prod_{i=1}^{n} \widetilde{\boldsymbol{P}}_{\boldsymbol{i}} \tag{7}$$

$$\widetilde{\boldsymbol{P}}_{(\boldsymbol{OR})} = \tilde{\mathbf{1}} \ominus \prod_{i=1}^{n} (\tilde{\mathbf{1}} \ominus \widetilde{\boldsymbol{P}}_{\boldsymbol{i}}); \quad \tilde{\mathbf{1}} = (\mathbf{1}, \mathbf{1}, \mathbf{1}) \tag{8}$$

3.1.2.1 Procedure for carrying out a FFTA

Steps for carrying out a FFTA in this paper are summarised as follows:

Step 1- Select a top event (i.e. a risk factor) and build a logic fault tree diagram for it.

Step 2- Divide the basic events (hazards) of any fault tree logic diagram into probability analysis of the known events and possibility analysis (subjective linguistic evaluations) of unknown or vague events.

If all of the events are unknown a subjective linguistic evaluation as explained in Steps 3 and 4 should be carried out in the form of a possibility analysis in order to obtain the failure possibilities for basic events and eventually for top event under fuzzy environment. Moreover if all the events were known, they will be evaluated by the use of conventional or traditional FTA method i.e. probability analysis. Nevertheless, if some of them are known and some are unknown they will be evaluated by combination approach using the both possibility and probability approaches explained in Steps 5 and 6 respectively.

Step 3- Conduct the linguistic assessments for vague events.

Step 4- Transform linguistic expressions into fuzzy numbers and aggregate the experts' opinions into one fuzzy number.

For this purpose as Clemen and Winkler (1999) explained due to different opinion of possibility of the basic events, it is necessary to combine or aggregate the opinion into a single one. There are many methods to aggregate fuzzy numbers; an appealing approach is the as follows (functions needed for this aggregation is shown in Section 3.1.1)

$$M_i = \sum_{i=1}^{m} W_j A_{ij} \quad , \quad j=1, 2,\ldots, n \tag{9}$$

Where A_{ij} is the linguistic expression of a basic event *i* given by expert *j*. *m* is the number of basic events. *n* is the number of the experts. W_j is a weighting factor of the expert *j* and M_i represents combined fuzzy number of the basic event *i*.

Step 5- Convert fuzzy numbers of the failure possibilities (i.e., FPSs) for the vague events into their Fuzzy Failure Probabilities (i.e., FFPs) using Eq. (10); Onisawa and Nishiwaki (1988).

$$\text{FFP}=\begin{cases} \frac{1}{10^k}, FPS \neq 0 \\ 0, FPS = 0 \end{cases} \quad , \text{K} = \left[\left(\frac{1-FPS}{FPS}\right)\right]^{\frac{1}{3}} \times 2.31 \tag{10}$$

Step 6 – Convert the available failure probabilities (crisp values) of the real data into Fuzzy Failure Probabilities (FFPs) using Table 2 (Lind 1983, Miller and Swain 1987).

Step 7- Obtain the final FFP for the top event by integrating FFPs obtained through Steps5 and 6 using Eqs. (7) and/or (8). In order to defuzzify FFP of the top event three fuzzy parameters will be added together and then will be divided by three to find the centre of their gravity i.e., defuzzification (transforming the fuzzy number to crisp value) (Tuhua and Dataob 2005, Zhao and Govind 1991).

Table 2: Guide line for Lower and Upper Bound of the Estimated Failure Rate

Failure rate (F_i)	**Lower Bound**	**Upper Bound**
0.01< F_i	$F_i \div 5$	$2 \times F_i$
0.001< F_i < 0.01	$F_i \div 3$	$3 \times F_i$
F_i < 0.001	$F_i \div 10$	$10 \times F_i$

Source: Based on Lind (1983); Miller and Swain (1 987)

Step 8- Analyse and interpret the results.

3.1.3 Fuzzy ETA

In practice, it is hard and costly to get exact values for event occurrences because in a most of cases these estimated values are the results of an experts' inadequate knowledge, incomplete information, poor quality data or unsatisfactory analysis of a failure mechanism. These unavoidable problems impart uncertainties in the ETA and make the entire risk analysis process less credible for decision making. In addition, experts' judgments are qualitative and linguistic in nature and may suffer from inconsistency if lack of consensus among various experts arises. The classical probabilistic framework is not very effective to deal with vague or incomplete/inconsistent concepts Rosqvist (2003) and Druschel *et al*. (2006). The existing research (Abrahamsson 2002, Thacker and Huyse 2003, Wilcox and Ayyub 2003) discusses methods to handle uncertainties in experts' judgments and to interpret them for the purpose of conducting risk analysis. Fuzzy sets theory has proven effective and efficient in handling these types of uncertainties (Chen 2000, Wilcox and Ayyub 2003, Sentz and Ferson 2002, Bae *et al*. 2004, Agarwal *et al*. 2004, Ayyub and Klir 2006). Therefore under fuzzy environment $\tilde{P}_n$denotes the Success/True/Yes possibility of the *n*th event whereas the($\tilde{1} \ominus \tilde{P}_n$) denotes the Failure/False/No possibility of the *n*th event within the same column. FurthermoreS_n also is the defuzzified outcome event's occurrence possibility scores for the *n*th outcome event within the nominated event tree.

3.1.3.1 Procedure for carrying out a FETA

The below mentioned steps demonstrate how to analyse an event tree using fuzzy set theory. In the suggested approach, the subjective judgment of event possibility is assumed linguistic and described using a TFN. The fuzzy possibility of initiating event is then used to estimate the outcome events' possibilities that are also estimated as fuzzy numbers. The fuzzy-based approach used for ETA comprises the following five steps:

Step 1- For an initiating event (i.e., a risk factor) identified within the offshore terminals, the set of possible consequence and no consequence states must be defined to construct the event tree logic diagram.

Step 2- Define initiating event's possibility using TFNs. (See Steps 3, 4, 5, 6 and 7 of the FFTA).

Step3- Determine each of the outcome events' possibilities as a TFN by calculating the all fault tree paths (i.e., See Fig. 6) by the use of Eqs. (2)-(4).

Step 4: Defuzzify the outcome events' possibilities (FPSs) to obtain a crisp value for each event tree consequence.

Step 5- Analyse and interpret the results.

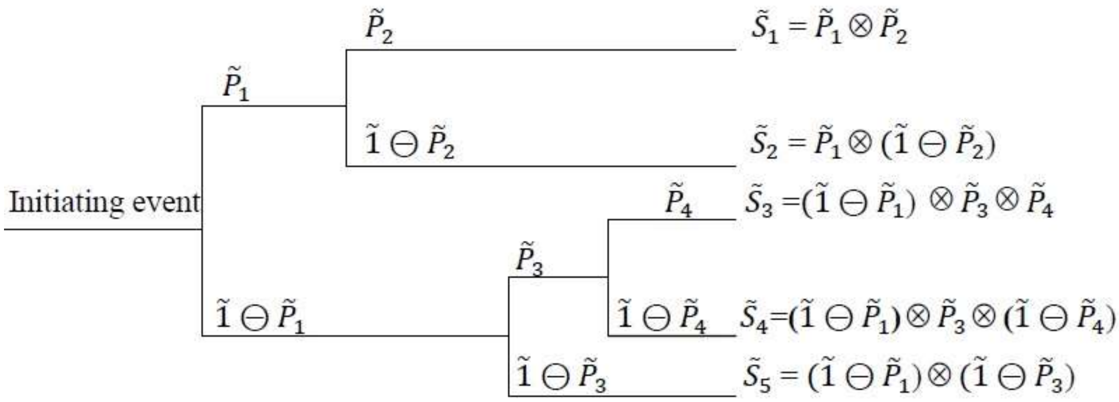

Fig. 6 Sample of a fuzzy event tree
Source: Based on Ferdous *et al.* (2009) and Mokhtari (2012)

As is shown in Fig. 6 under fuzzy environments $\tilde{P}_n$ denotes the Success possibility (i.e., No Consequence) of the *n*th event whereas $(\tilde{1} \ominus \tilde{P}_n)$ denotes the Failure possibility (i.e., With Consequence having negative effect) of the *n*th event within the same column. Furthermore S_n is also the defuzzified outcome event's occurrence possibility scores (i.e. occurrence likelihood) for the *n*th outcome event within the nominated event tree.

Due to the scarcity of data fuzzy fault tree and fuzzy event tree analysis (i.e., CCA under a fuzzy environment) will be applied on one of the most significant risk factors associated within offshore terminals for representing the proposed approaches. The mentioned CCA is depicted in the following case study.

4. Case study

This case study relates to the hazards associated with the potential incidents and accidents in offshore terminals (i.e., installations/rigs) in the form of offshore fixed units engaged in the oil and gas explorations and exploitations located within Caspian Sea (i.e., See Fig. 7).

Fixed units in this study are defined as including all bottom-fixed structures, however excluding Tension Leg Platforms (TLPs), Floating, Production, Storage and Offloading units (FPSOs), Floating, Storage Units (FSUs) and production jack-ups rigs even while they are "fixed" throughout their production stage and therefore are classified as "fixed installations" by the UK's Health and Safety Executive (HSE) under the Safety Case Regulations. However these units are defined and reported under floating units which are defined as including semi-submersibles, jack-ups, ships and tension-leg platforms engaged in drilling, accommodation, production and storage oil and gas UK (2018) and Martins (2016).

Table 3 Basic Events (Hazards) which can cause Top Event of "damage to offshore terminals"

Basic Events (Hazards)	**Basic Event (Hazard) No**
Fire and Explosions	BE_1
Collisions and Contact damages	BE_2
Structural failures	BE_3
Helicopter crush	BE_4
Terrorism and Sabotage	BE_5
War and Political perils	BE_6
Ice damages	BE_7
Storm damages	BE_8
Earthquake and Tsunami	BE_9

Source: Based on UKHSE (2019), Mather (2009) and Sharp (2009)

There are many hazards with different natures and categories and in order to make any analysis of the addressed hazards first it is required to break them down into board categories or areas such as internal/external hazards or other simple frameworks such as operational/technical/legal/environmental types of hazards or risk factors in order for categorising sources of hazards but in this paper only the ones which can directly affect an offshore terminal and cause physical damage or in extreme cases would lead to total destruction of the offshore terminals as shown in Table 3 will be examined hereafter. As is mentioned there are many other types of hazards which can affect the site indirectly and they are not be regarded as direct causes of a damage or destruction. Some of them are such as blowouts, cranes, falling objects, leakages, spills/releases, and wells' problems etc which have been decided not to be incorporated here for the purpose of this paper. Apart from the basic events (hazards) such as BE_1 to BE_4 which can be classified under operational risk factors, others e.g., BE_5 to BE_9 can only be initiated via external sources of uncertainties such as natural disasters, act of war, terrorism etc.

Caspian Sea is the largest lake on the planet. The sea is bordered by the countries of Azerbaijan, Russia, Kazakhstan, Turkmenistan and Iran. There are many of oil and natural gas production platforms along the edges of the sea especially within the coasts of Azerbaijan and Turkmenistan. In addition, large quantities of sturgeon live in its waters, and the caviar produced from their eggs is a valuable commodity. Fresh water flows into the sea via the Volga River and Ural River in the North, however, the sea remains somewhat salty only in centre and South of the Caspian Sea. The highest depth of water is in South which is 1025 m.

Until the date Caspian Sea has not been stroke by any kind of heavy storms, earthquakes/tsunamis or severe ice. However occasional passing fronts in autumns and winters with the North Atlantic origin disturb the sea in timely bases but cannot be accounted as severe types to damage the offshore terminals. As they pass in West-East direction and the area they affect is small in compare to other seas e.g. North Sea, Mediterranean Sea, their effect is not felt harshly. Additionally in North of Caspian Sea during winters formation of ice is always evident. Ice formation is not taken place in central parts and Southern parts of the sea Barannik (2004).

Fig. 7 Map of Caspian Sea
Source: Based on World Atlas (2019)

Presently there is no available data or report on terrorism activities in the region. The nearest of such activities can be traced in Republic of Chechnya (i.e., City of Groznyy) in Russia which is near to Northwest of Caspian Sea CNN (2019). There is no report on any war or potential political perils except the international disputes which have been going on for nearly a decade among the states bordering the Caspian Sea for settling the dispute about the legal status of the sea Haghayeghi (2003).

All five littoral states of Azerbaijan, Iran, Kazakhstan, Russia, and Turkmenistan have plans to further exploit the sea’s estimated oil reserves. Presently major oil companies e.g., TOTAL, BP, EXXONMOBILE, CHEVRON etc with good reputation are active in Caspian Sea near costs of Azerbaijan especially in conjunction with the major pipeline project of BAKU-JIHAN. Such activities mean drilling new wells, highlighting risks for an incident that could cause catastrophic effects such as damage to offshore terminals within the landlocked Caspian Sea i.e., the largest inland body of water on earth OWJE (2019).

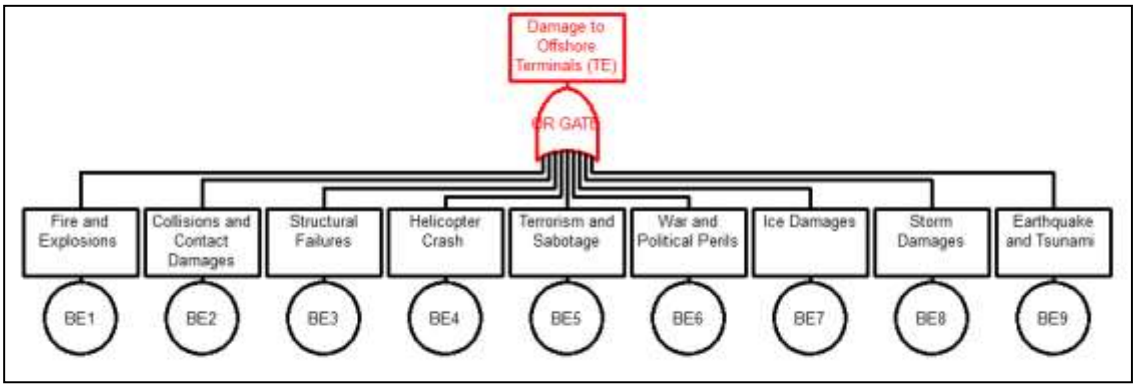

Fig. 8 Fault tree diagram for Top Event of "damage to offshore terminals "along with Basic Events

"The accident in the Gulf of Mexico shows that such a disaster could happen anywhere. The United States, with its super-modern technologies, is barely capable of stopping this disaster," Gulaliyev says. "You can imagine the scale of the damages to the environment from such incidents in countries like Azerbaijan" RFERL (2018). As a result major consequences for the risk factor i.e., "damage to offshore terminals" can be loss of life, property, reputation and damage to environment (ABS 2019, Aneziris *et al.* 2014, Wu 2015, Nagi *et al.* 2018). Fig. 8 is fault tree diagram for Top Event i.e., "damage to offshore terminals".

Failure probabilities or occurrence frequencies (crisp values) for operational types of hazards such as BE_1 [i.e., Fire (0.203) and Explosion (0.011) = 0.214], BE_2 [i.e., Collision (0.0085) and Contact (0.030) = 0.0385], BE_3 [i.e., Structural = (0.0034)] and BE_4 [i.e., Helicopter = (0.0016)] in the form of number of incidences and incidence frequencies (per unit year) are (0.2140), (0.0385), (0.0034) and (0.0016) respectively. Since for the cases of marine losses and/or damages, hazards for instance fire and explosion or others such as collision and contact are considered in same categories therefore each of these two types have been regarded as one individual basic event and for this reason their occurrence frequencies as is mentioned above were added together. The origin of data is based on accident statistics for offshore fixed units from 1990 to 2007. These data are based on the combination of original data gathered from different databases as is mentioned (i.e. See Table 2: All fixed units from Page 8) in oil and gas UK (2018). The available failure probabilities will be transformed into FFPs using Table 2 while implementing the probability approach. The calculated FFPs of the known failure rates (i.e., BE_1 to BE_4) are shown in Table 5.

On the other hand as there is no data for external types of hazards such as BE_5, BE_6, BE_7,BE_8 and BE_9 via using possibility approach the FPSs obtained through the experts' judgements (See Table 4) will be transformed into FFPs through using Eq. (10). In this regard the calculated FFPs of the unknown failure rates (i.e., BE_5 to BE_9) are shown in Table 5. Therefore primarily after collecting the experts' opinions through the predesigned evaluation sheet the following calculations are carried out in order to determine the FPSs for the mentioned basic events listed in Table 4. Furthermore Table 1 is used for carrying out the following estimations:

$$BE_5 = W_1 \otimes L \oplus W_2 \otimes VL \oplus W_3 \otimes L = (0.00, 0.17, 0.42)$$

$$BE_6 = W_1 \otimes L \oplus W_2 \otimes L \oplus W_3 \otimes M = (0.08, 0.33, 0.58)$$

$BE_7 = W_1 \otimes VL \oplus W_2 \otimes L \oplus W_3 \otimes VL = (0.00, 0.08, 0.33)$
$BE_8 = W_1 \otimes VL \oplus W_2 \otimes VL \oplus W_3 \otimes VL = (0.00, 0.00, 0.25)$
$BE_9 = W_1 \otimes L \oplus W_2 \otimes L \oplus W_3 \otimes L = (0.00, 0.25, 0.50)$

Fuzzy Possibility Scores (FPSs) for the basic events BE_5 to BE_9 shown in Fig.4 are transformed into Fuzzy Failure Probabilities (FFPs) in Fig. 5 via using Eq. (10).

Due to the scarcity of data and the fact that some of the basic events (hazards) were vague and in order to determine the failure rate for the risk factor i.e., "damage to offshore terminals" it has been decided to carry out the evaluation by using the experts' judgements. To carry out an optimum experts' judgements in this paper, three experts have been selected to carry out the judgements process. All experts have their Bachelor i.e. BSc and Master i.e., MSc degrees in maritime related fields. In addition each has served as a harbour pilot previously for 5 years in different Iranian offshore terminals. Each expert has near 15 years' experience on offshore terminals' operations and management. Experts are now holding managerial positions in different operational fields for Iranian offshore terminals. The main factor for selecting these experts was based on their expertise that they have equally contributed in the related fields as a result they have a thorough knowledge about the risk factor of "damage to offshore terminals". For this reason these experts will have equal weights (i.e., W_n) in respect of each other that would affect equally the evaluation processes for the mentioned top event in Caspian Sea. After collecting the experts' opinions and integrating them by means of Eqs. (2) and (9) with the use of Eq. (8) the required calculations will be carried out in order to find out the final FFP of the nominated top event for the purpose of Caspian Sea. The calculated FFP of the top event i.e., $\widetilde{\boldsymbol{P}}_{\boldsymbol{TE}}$after defuzzification was found to be 0.265. Then by eliminating of each basic event the new FFPs for the new top events i.e. $\widetilde{\boldsymbol{P}}_{\boldsymbol{TEi}}$; (i=1,2,3,..,9) will be obtained respectively as shown in Table 6. Subsequently the amount of each deviation i.e., $[\widetilde{\boldsymbol{P}}_{\boldsymbol{TE}} \ominus \widetilde{\boldsymbol{P}}_{\boldsymbol{TEi}}]$ has been recorded under the deviation index column in Table 6. The greater number for deviation index means having higher importance on the FFP of the top event. That means elimination of any basic even (hazard) which can lead to a higher deviation index will reduce the failure probability of the top event more than in the case of other eliminations. As it is shown in Table 6 basic event number one i.e., BE1 has the highest importance among others. In $[\widetilde{\mathbf{P}}_{\mathbf{TE}} \ominus \widetilde{\mathbf{P}}_{\mathbf{TEi}}]$; TE denote top event of "damage to offshore terminals" and TE_i denotes the top event which its ith basic event (hazard) is eliminated.

Table 4 Table of Fuzzy Possibility Scores (FPSs) for unknown failure rates

Basic Event (BE) Number	FPSs
5	(0.00, 0.17, 0.42)
6	(0.08, 0.33, 0.58)
7	(0.00, 0.08, 0.33)
8	(0.00, 0.00, 0.25)
9	(0.00, 0.25, 0.50)

Table 5 Table of Fuzzy Failure Probabilities (FFPs) for known and unknown failure rates

Basic Events (Hazards) Number	**FFPs**
BE $_1$	(0.0428, 0.2140, 0.4280)
BE $_2$	(0.0077, 0.0385, 0.0770)
BE $_3$	(0.0011, 0.0034, 0.0102)
BE $_4$	(0.0005, 0.0016, 0.0048)
BE $_5$	(0.0000, 0.0001, 0.0027)
BE $_6$	(0.000006, 0.0012, 0.0048)
BE $_7$	(0.0000, 0.000006, 0.0012)
BE $_8$	(0.0000, 0.0000, 0.0005)
BE $_9$	(0.0000, 0.0005, 0.0049)

Table 6 Importance of elimination of each basic event in failure probability of the top event

Elimination of Basic Events	**FFPs for new Top Events after elimination of the related Basic Events (Hazards)**			**Defuzzified FFPs for new Top Events**	**Deviation index**	**Ranking**
	l	***m***	***u***			
BE $_1$	0.010	0.045	0.114	0.0563	0.2087	1
BE $_2$	0.045	0.219	0.451	0.2383	0.0267	2
BE $_3$	0.051	0.246	0.488	0.2616	0.0034	3
BE $_4$	0.052	0.248	0.491	0.2637	0.0013	6
BE $_5$	0.052	0.250	0.492	0.2647	0.0003	9
BE $_6$	0.052	0.248	0.489	0.2630	0.0020	4
BE $_7$	0.052	0.249	0.489	0.2633	0.0017	5
BE $_8$	0.052	0.249	0.492	0.2643	0.0007	8
BE $_9$	0.052	0.249	0.491	0.2640	0.0010	7

FFP for the top event i.e. "damage to offshore terminals" are calculated by the use of the fuzzy fault three analysis using Eq. (8) as follows:

$$\tilde{P}_{(OR)} = \tilde{1} \ominus \prod_{i=1}^{n} (\tilde{1} \ominus \tilde{P}_i); \qquad \tilde{1} = (1,1,1)$$

$\tilde{P}_{TE} = \tilde{1} \ominus [(\tilde{1} \ominus \tilde{P}_{BE1}) \otimes (\tilde{1} \ominus \tilde{P}_{BE2}) \otimes (\tilde{1} \ominus \tilde{P}_{BE3}) \otimes (\tilde{1} \ominus \tilde{P}_{BE4}) \otimes (\tilde{1} \ominus \tilde{P}_{BE5}) \otimes (\tilde{1} \ominus \tilde{P}_{BE6}) \otimes (\tilde{1} \ominus \tilde{P}_{BE7}) \otimes (\tilde{1} \ominus \tilde{P}_{BE8}) \otimes (\tilde{1} \ominus \tilde{P}_{BE9})]$ = (0.052, 0.249, 0.493) = 0.265 i.e., defuzzified FFP for the risk factor of "damage to offshore terminals".

Fig. 9 illustrates the sensitivity analysis carried out for the top event i.e., "damage to offshore terminals", based on the results shown in the Table 6. It shows that by elimination of any basic event (hazard) how the FFP for the related new top event will be reduced.

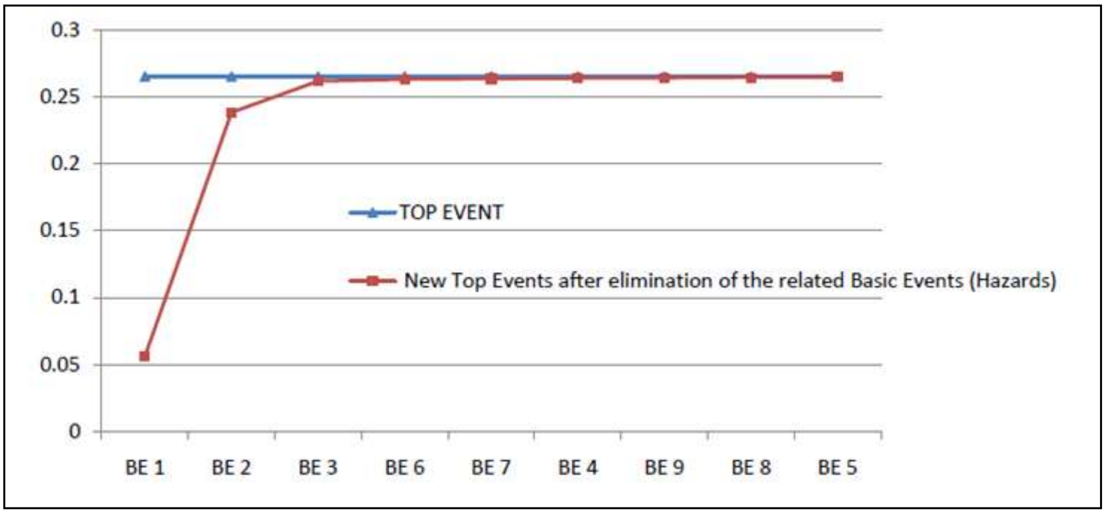

Fig. 9 Sensitivity analysis for top event of i.e. "damage to offshore terminals"

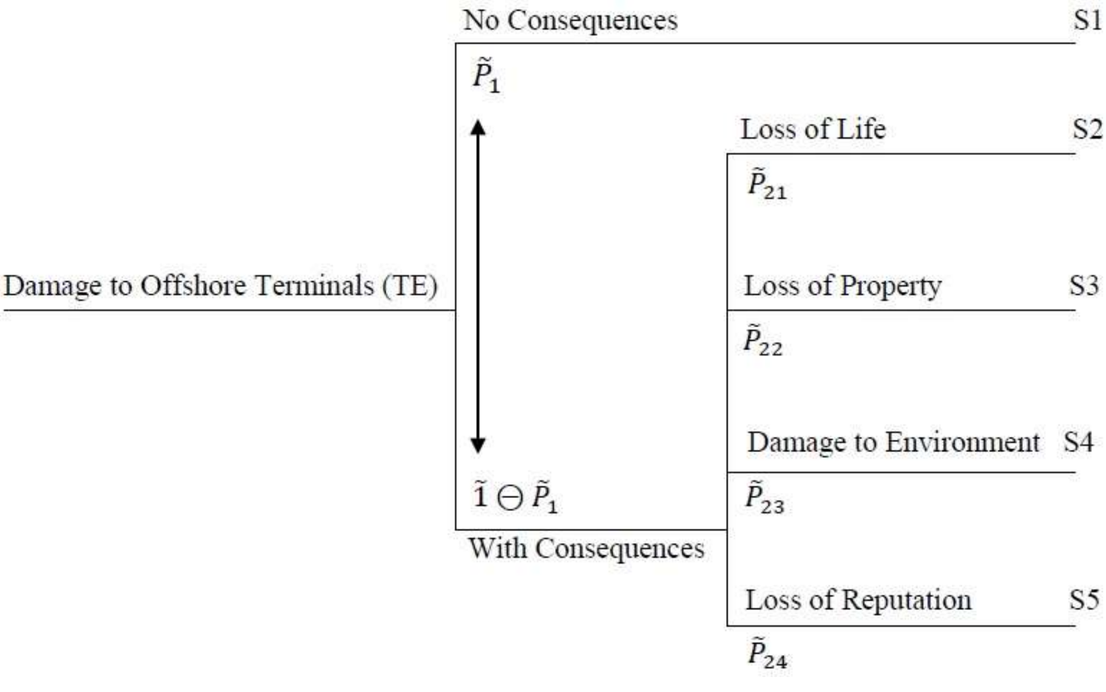

Fig. 10 Event tree analysis for risk factor "damage to offshore terminals"
Source: Consequences are based on ABS (2019)

Table 7 Occurrence possibility scores for different consequences

No	Consequences	Likelihoods	Rankings
1	No Consequences	0.803	1
2	Loss of Life	0.133	3
3	Loss of Property	0.187	2
4	Damage to Environment	0.117	4
5	Loss of Reputation	0.084	5

Fig. 10 illustrates the event tree analysis for the risk factor "damage to offshore terminals" along with linguistic fuzzy variables. In order to evaluate the addressed consequences it has been decided to carry out the evaluation using the experts' judgements. The same experts used in previous section have been asked for the evaluation purposes here (See Page 18). Estimations for the event tree shown in Fig. 10 are as follows

$\tilde{P}_1 = W_1 \otimes H + W_2 \otimes H + W_3 \otimes VH = (0.58, 0.83, 1.00)$; $S_1 = 0.803$ defuzzified value

$(\tilde{1} \ominus \tilde{P}_1) \otimes \tilde{P}_{21} = (0.00, 0.17, 0.42) \otimes (W1 \otimes M \oplus W2 \otimes M \oplus W3 \otimes M) =$

$(0.00, 0.17, 0.42) \otimes (0.25, 0.50, 0.75) = (0.00, 0.085, 0.315)$;

$S_2 = 0.133$ defuzzified value

$(\tilde{1} \ominus \tilde{P}_1) \otimes \tilde{P}_{22} = (0.00, 0.17, 0.42) \otimes (W1 \otimes H \oplus W2 \otimes H \oplus W3 \otimes VH) =$

$(0.00, 0.17, 0.42) \otimes (0.58, 0.83, 1.00) = (0.00, 0.141, 0.42)$;

$S_3 = 0.187$ defuzzified value

$(\tilde{1} \ominus \tilde{P}_1) \otimes \tilde{P}_{23} = (0.00, 0.17, 0.42) \otimes (W1 \otimes M \oplus W2 \otimes L \oplus W3 \otimes M) =$

$(0.00, 0.17, 0.42) \otimes (0.17, 0.42, 0.67) = (0.00, 0.071, 0.281)$;

$S_4 = 0.117$ defuzzified value

$(\tilde{1} \ominus \tilde{P}_1) \otimes \tilde{P}_{24} = (0.00, 0.17, 0.42) \otimes (W1 \otimes L \oplus W2 \otimes L \oplus W3 \otimes L) =$

$(0.00, 0.17, 0.42) \otimes (0.00, 0.25, 0.50) = (0.00, 0.042, 0.21)$;

$S_5 = 0.084$ defuzzified value

As there is no data for the mentioned consequences therefore only possibility approach under fuzzy environment have been incorporated in this section of the study. By using Eqs. (2)-(4); Table 1 and procedure mentioned in Subsection 3.1.3.1 (i.e., See Fig. 6) the final results obtained in this paper are listed in Table 7 along with rankings for consequences. As it can be seen consequence number one i.e., "damage to offshore terminals" with no consequences (i.e., Near Miss) will have the highest occurrence possibility score.

5. Conclusions

This paper evaluated one of the most significant risk factors in offshore terminals by use of the CCA in order to complete the risk assessment phase of the RM framework within the offshore terminals. However through this process all the potential hazards causing damage to offshore terminals in Caspian Sea were analysed and also the resultant consequences were investigated. In addition the proposed risk analysis model in fact is an objective way to handle subjective information in establishing a hazard analysis to guide development of hazard control measures in next phase of the addressed RM framework.

The main managerial implication is to help risk managers in offshore terminals to design and establish an integrated RM strategy, philosophy and policy statement for communication throughout their sites and facilities. The proposed model will facilitate risk managers to establish and maintain a detailed RM methodology appropriate to their needs. It includes formalised risk (hazard) identification techniques, quantitative and qualitative risk assessment and cost effective methods with the aim of elimination, reduction and controlling of the prospective risk factors and hazards.

Although in this paper only limited number of hazards were analysed, but for the future works all of the potential hazards can be analysed as per availability of the data using suitable model and methods explained in this paper. Furthermore in the future studies in order to mitigate the analysed hazards through the CCA within the offshore terminals by introducing an appropriate method the ideal solutions can be selected for mitigating the potential hazards. The selected ideal solutions eventually can be used as preventive or corrective actions (barriers) which will lead to implimentation of either a proactive or a reactive RM strategy toward a successful operation and managenet in offshore terminals.

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