Journal of Hazardous Materials 192 (2011) 465–475

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Application of a generic bow-tie based risk analysis framework on risk management of sea ports and offshore terminals

Kambiz Mokhtari, Jun Ren*, Charles Roberts, Jin Wang

Liverpool Logistics, Offshore and Marine (LOOM) Research Institute, School of Engineering, Technology and Maritime Operations, Liverpool John Moores University, Liverpool UK

ARTICLE INFO

Article history:
Received 27 January 2011
Received in revised form 12 April 2011
Accepted 10 May 2011
Available online 18 May 2011

Keywords:
Bow-tie framework
Risk management (RM)
Sea ports and offshore terminals operations and management (PTOM)
Fuzzy Set Theory (FST)
Fuzzy Possibility Score (FPS)

ABSTRACT

Ports and offshore terminals are critical infrastructure resources and play key roles in the transportation of goods and people. With more than 80 percent of international trade by volume being carried out by sea, ports and offshore terminals are vital for seaborne trade and international commerce. Furthermore in today's uncertain and complex environment there is a need to analyse the participated risk factors in order to prioritise protective measures in these critically logistics infrastructures. As a result of this study is carried out to support the risk assessment phase of the proposed Risk Management (RM) framework used for the purpose of sea ports and offshore terminals operations and management (PTOM). This has been fulfilled by integration of a generic bow-tie based risk analysis framework into the risk assessment phase as a backbone of the phase. For this reason Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) are used to analyse the risk factors associated within the PTOM. This process will eventually help the port professionals and port risk managers to investigate the identified risk factors more in detail. In order to deal with vagueness of the data Fuzzy Set Theory (FST) and possibility approach are used to overcome the disadvantages of the conventional probability based approaches.

1. Introduction

In the past decade, dynamic and enforced changes have been occurring in sea port's business, operational and organisational related environments. There has been growing concern in public and private sectors regarding the threats of the risk factors associated within the ports and offshore terminals to people, assets and the environment resulting from the port and 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 [1]. This paper focuses on the sea ports and offshore terminals and 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 [2], and 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 ports and terminals. On the port RM area, GAO [3] has stressed for "further refinements needed to assess risks and prioritise protective measures at ports and other critical infrastructure". In the UK, DETR [4] has required all ports to carry out risk assessment of marine operations in order to implement the safety management system.

In ports and terminals a high quality RM is absolutely necessary for their sustainable development. Risk analysis, a key part of RM, defines risk as a measure of human injury, environmental damage or economic loss in terms of both the incident chance and the magnitude of the injury, damage or loss [5]. 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 analysis model to evaluate and prioritise risk factors in PTOM. The proposed framework for the purpose of PTOM consists of the following three main phases:

- Hazard identification
- Risk assessment
- Risk mitigation

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* Corresponding author. Tel.: +44 151 231 2236.
E-mail address: J.Ren@ljmu.ac.uk (J. Ren).

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doi:10.1016/j.jhazmat.2011.05.035

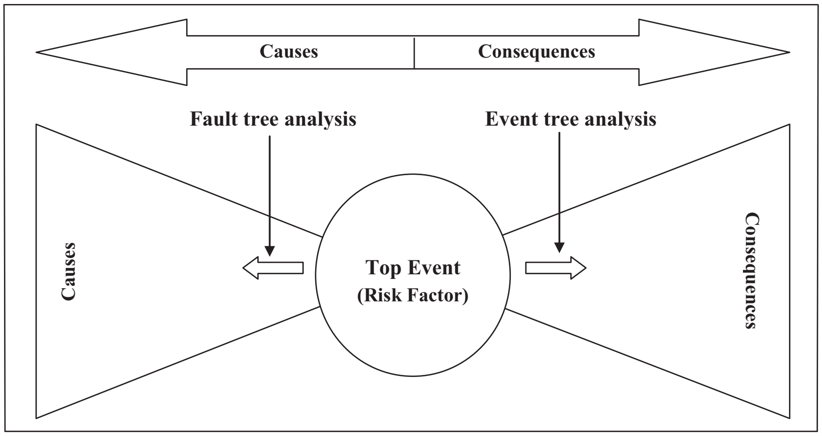

Fig. 1. A bow-tie diagram [15].

Overall the developed risk analysis model can facilitate on achieving the objectives of the RM framework within the PTOM. 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 assessment in PTOM including the risk assessment hierarchy, the bow-tie based risk analysis model and the methodology for risk assessment in PTOM. Section 4 provides a case study to demonstrate the use of the proposed methodology and the models. 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 [6]. 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 [7]. Dickson as discussed that every risk is caused by some factor or factors and results in some effect or effects. 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 [8]. Nowadays a 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) [6,7,9,10]. 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 [11]. 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 regarded 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 toward the causes [12]. A 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 [13]. In particular it has 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 [14]. 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 set of 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 [16,17]. 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 [18–20]. It can be used to demonstrate how effective a marine facility's safety management system is to complete gap analyses [21]. 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 [22–24].

2.2. FTA

FTA was first introduced 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

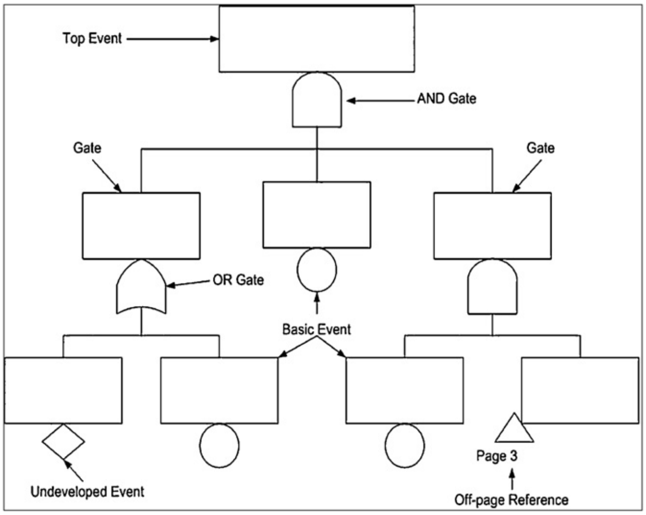

Fig. 2. Standard fault tree symbols [1].

critical event in a system and the reasons for this event [25]. A typical fault tree consists of the top event, the basic events, and the logic gates. 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 and the basic event represents the state of the systems component. 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 [26].

2.3. ETA

In risk analysis, 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 [27–31]. Qualitative analysis in an event tree identifies the possible outcome events of an initiating event, whereas quantitative 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 [27,28] in conventional Event Tree Analysis, the branch probabilities have been treated as exact values. 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. As it is shown P_n denotes the Success/True/Yes probability of the nth event whereas the $(1 - P_n)$ denotes the Failure/False/No probability of the nth event within the same column. S_n is also the calculated outcome event frequency for the nth outcome event within the depicted event tree. In relation to ETA [27] 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. Risk analysis in PTOM

This paper will analyse the operational risk factors associated within the ports and offshore terminals which have been identified in the authors' previous works [32]. As an illustrative example a hierarchy of the contributing operational risk factors within PTOM is shown in Fig. 4 and Table 1. Table 1 gives the pre-assessed and ranked operational risk factors along with their relative (global) weights used to demonstrate the most significant risk factors within the PTOM. The illustrated operational risk factors have been previously identified through the hazard identification, i.e. HAZID process of the introduced RM framework which is one of the hazard identification techniques [33]. This paper will evaluate one of the most significant operational risk factors while using the bow-tie methodology accompanying the FTA and ETA methods. This has been fulfilled by introducing a generic risk analysis model in Fig. 5.

Fig. 5 shows a generic risk analysis model which has been integrated into a RM framework of the PTOM. The previously identified PTOM's operational risk factors have been prioritised and ranked with the use of the Fuzzy Analytical Hierarchy Process (FAHP) method.

3.1. Methodology for risk analysis in PTOM

The cause-consequence diagram method (see Fig. 2) [34] is based on the occurrence of a 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 one or more protection systems not functioning as designed. In this paper with the use of the CCA and Fuzzy Set Theory, failure possibility for a top event and also consequences of the basic events for one of the most significant operational risk factors explored in the previous works as illustrated in Fig. 5 and Table 1 will be estimated. The

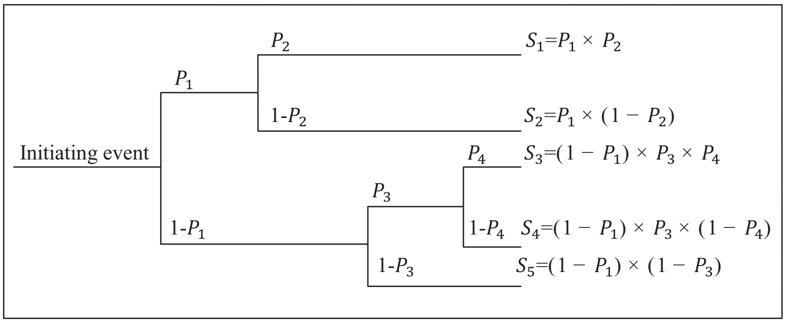

Fig. 3. Sample of a conventional event tree [27,28].

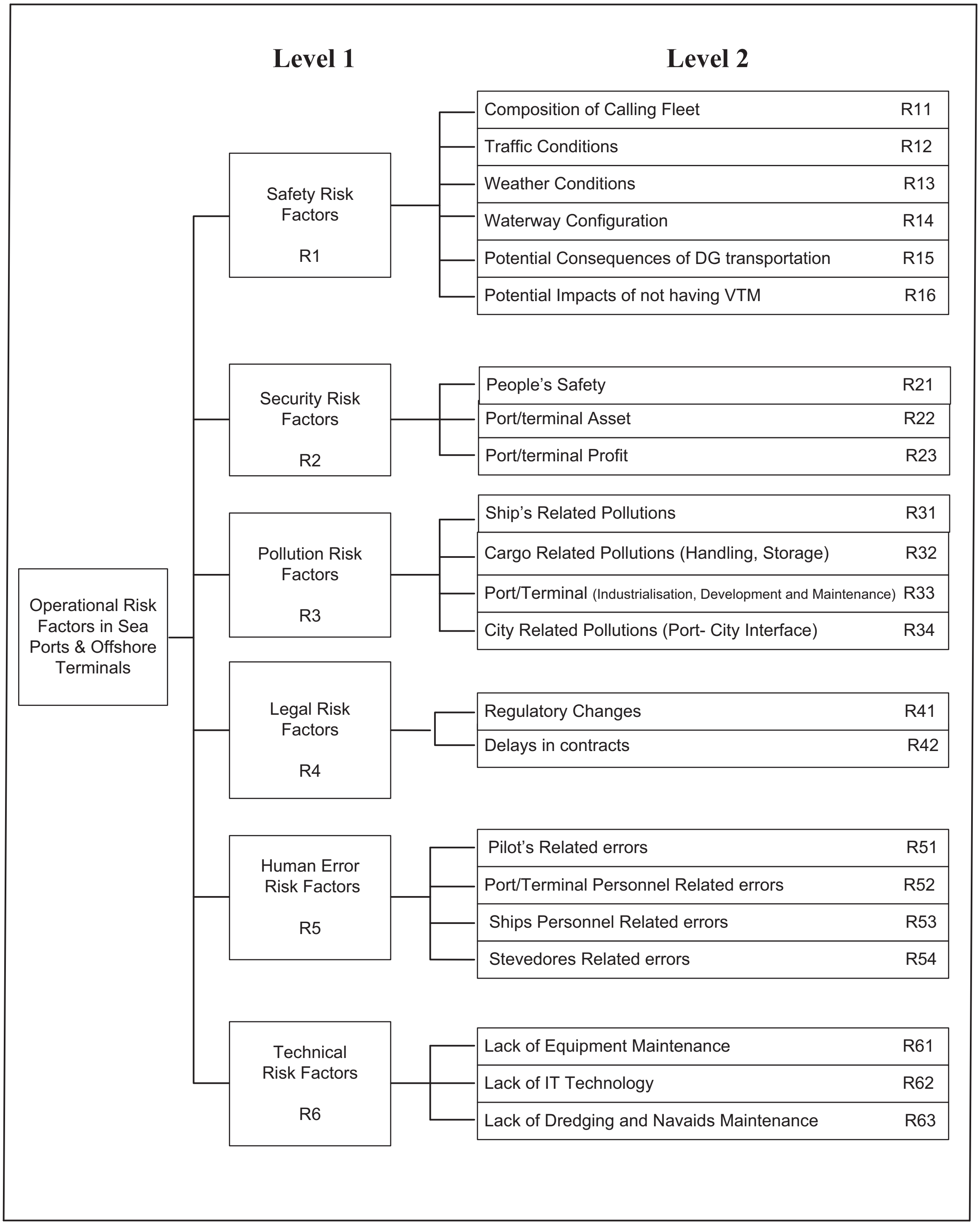

Fig. 4. An illustrative example of operational risk factors hierarchy in sea ports and offshore terminals.

selected risk factor will be evaluated and analysed with the use of a case study. This will help examining the introduced risk analysis tool that could suit for RM purposes during the PTOM. Fuzzy Set Theory, experts' judgements, converting linguistic terms to fuzzy numbers and defuzzification processes will be used to obtain the possibilities of the basic events as well as the occurrence possibly of the 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 the evaluation of the selected risk factor by the use of CCA and in form of FFTA and FETA are explained in the next sections.

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 [35–39]. 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, in which each object is assigned with a grade of membership ranging between 0 and 1. 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

Table 1
An illustrative example of operational risk factors along with the relative weights.

Main goal	Level 1 risk factors	Local weights	Level 2 risk factors	Local weights	Global weights
Operational risk factors	Safety risk factors	(0.186)	Composition of calling fleet	(0.048)	(0.0089)
			Traffic conditions	(0.340)	(0.0632)
			Weather conditions	(0.099)	(0.0184)
			Waterway configuration	(0.398)	(0.0740)
			Potential consequences of dangerous goods transportation	(0.027)	(0.0058)
			Potential impacts of not having vessel traffic management (VTM) system	(0.088)	(0.0168)
	Security risk factors	(0.297)	People's safety	(0.670)	(0.1989)
			Port/terminal asset	(0.274)	(0.0813)
			Port/terminal profit	(0.056)	(0.0166)
	Pollution risk factors	(0.178)	Ship related pollutions	(0.496)	(0.0877)
			Cargo related pollutions	(0.178)	(0.0316)
			Port/terminal related pollutions	(0.220)	(0.0389)
			City/local area related pollutions	(0.106)	(0.0187)
	Legal risk factors	(0.007)	Regulatory changes	(0.693)	(0.0055)
			Fraud in contracts	(0.307)	(0.0024)
	Human error factors	(0.243)	Pilot's related errors	(0.498)	(0.1210)
			Ships personnel related errors	(0.161)	(0.0390)
			Port/terminal personnel related errors	(0.189)	(0.0459)
			Stevedores related errors	(0.152)	(0.0369)
	Technical risk factors	(0.089)	Lack of equipment maintenance	(0.078)	(0.0069)
			Lack of IT technology	(0.566)	(0.0503)
			Lack of dredging and navigational aids maintenance	(0.356)	(0.0316)

sets only allow full membership or non-membership at all, whereas fuzzy sets allow partial membership [40].

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 [41]. 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 [42]. As [43] 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. $\tilde{M}$ is shown in Fig. 6.

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 [44]. Their membership functions as shown in Fig. 6 can be defined as follows:

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

There are various operations on TFNs. However, three of the main operations used in this study are illustrated here. Moreover two positive TFNs are $\tilde{M}_1 = (l_1, m_1, u_1)$ and $\tilde{M}_2 = (l_2, m_2, u_2)$ and l_1, m_1, u_1, l_2, m_2, u_2 are real numbers. The distance measurement $(d\tilde{M}_1, \tilde{M}_2)$ is identical to the Euclidean distance [45,46]. 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 [47]:

$$\begin{aligned} \tilde{M}_1 \oplus \tilde{M}_2 &= (l_1, m_1, u_1) \oplus (l_2, m_2, u_2) \\ &= (l_1 \oplus l_2, m_1 \oplus m_2, u_1 \oplus u_2) \end{aligned} \tag{2}$$

$$\begin{aligned} \tilde{M}_1 \otimes \tilde{M}_2 &= (l_1, m_1, u_1) \otimes (l_2, m_2, u_2) \\ &= (l_1 \times l_2, m_1 \times m_2, u_1 \times u_2) \end{aligned} \tag{3}$$

$$\begin{aligned} \tilde{M}_1 \ominus \tilde{M}_2 &= (l_1, m_1, u_1) \ominus (l_2, m_2, u_2) \\ &= (l_1 \ominus u_2, m_2 \ominus m_1, u_1 \ominus l_2) \end{aligned} \tag{4}$$

Other algebraic operations such as change of sign, subtraction, and division with fuzzy numbers can be found in [48–50].

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 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 [51]. As TFNs are decided to be used in this paper to represent the linguistic variables for this purpose they have been shown in Table 2 [47]. Thus membership degrees of risk parameters as they range from 0

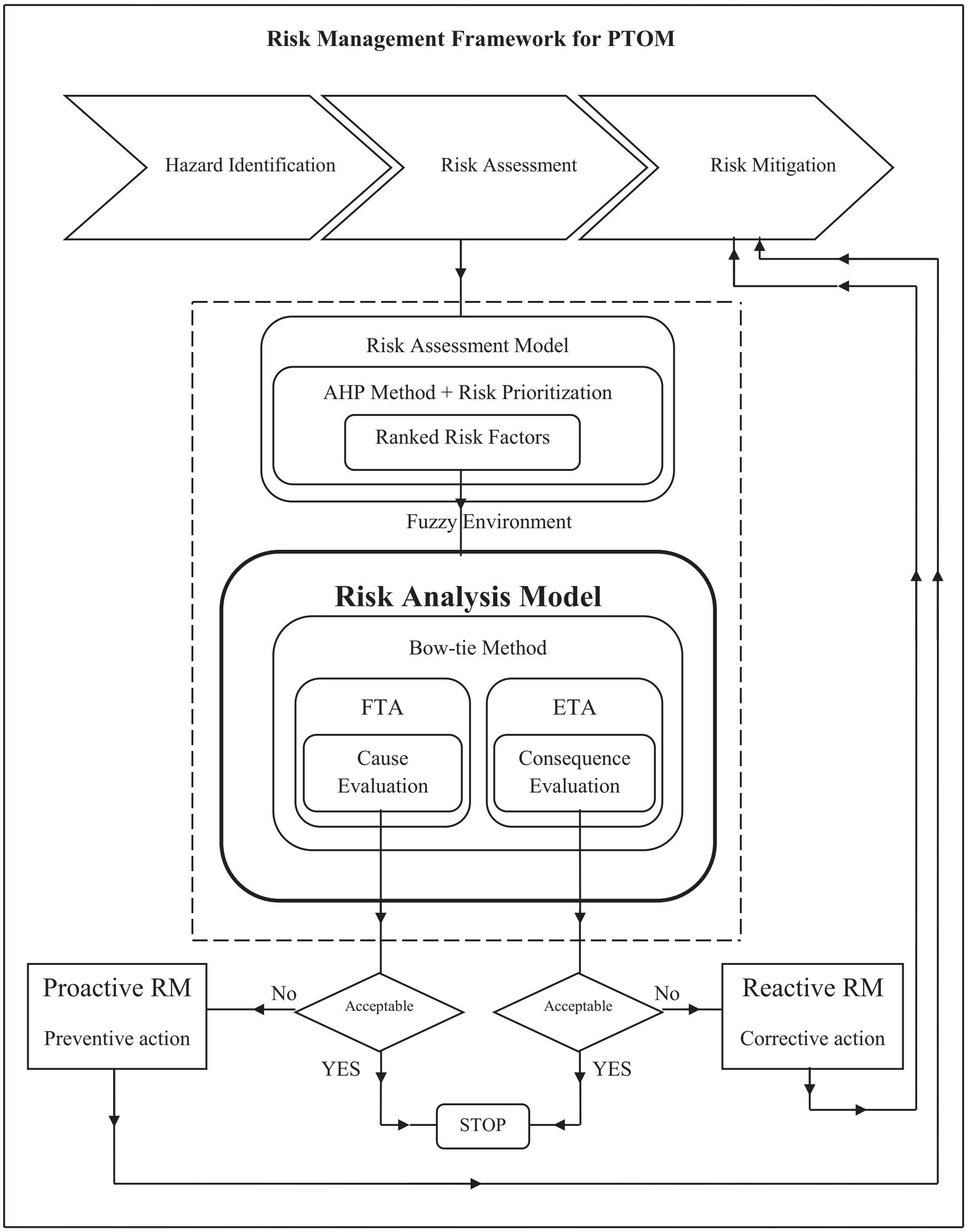

Fig. 5. A generic risk analysis model integrated into a RM framework of the PTOM.

to 1 can be assigned by experts, with reference to Table 2 in a fuzzy environment.

A common risk (R) evaluation and presentation method is simply to multiply the likelihood (L) of each undesirable event by each severity (S), and then sum these products for all situations considered in the evaluation. This definition indicates that if (L) and/or (S), i.e. risk parameters are represented by fuzzy numbers, R will also be a fuzzy number [52], that means: $\tilde{R} = \tilde{L} \otimes \tilde{S}$.

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 proba-

Table 2
Transformation for fuzzy membership function.

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)

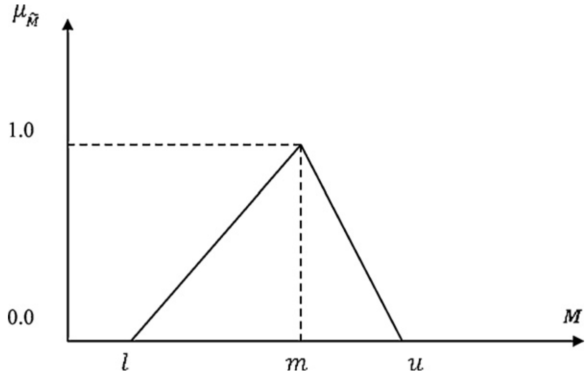

Fig. 6. A Triangular Fuzzy Number (TFN), $\tilde{M}$ [39,45].

bilities of 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 [53]. To overcome these difficulties the use of FST [54,55] is being considered. In this respect the failure possibility defined by a triangular fuzzy number on the interval (0, 1) is used to characterise the possible deviation of the basic events. Therefore the concept of the failure possibility is applied to replace failure rate (probability) in Fault Tree Analysis [54]. 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 occurrence probability of an event is only a relative frequency [56,57] for an AND gate event, its probability can be obtained by Eq. (5).

$$P_{(\mathrm{AND})} = \prod_{i=1}^{n} P_i \tag{5}$$

where P is the occurrence probability of the top event; 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 occurrence probability is determined by Eq. (6).

$$P_{(\mathrm{OR})} = 1 - \prod_{i=1}^{n} (1 - P_i) \tag{6}$$

Furthermore there is also a gate called NEG gate in which its occurrence probability is equivalent to $1 - P_i$ [58].

Whereas due to the scarcity of the hazard events 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 [58]:

$$\tilde{P}_{(\mathrm{AND})} = \prod_{i=1}^{n} \tilde{P}_i \tag{7}$$

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

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.

Step 2: Divide the elements (i.e. basic events) of any fault tree logic diagram into probability analysis of the known events and subjective linguistic evaluations of vague events, i.e. possibility analysis.

If all of the events are unknown a subjective linguistic evaluation as explained in the next section should be carried out in the form of a possibility analysis in order to obtain the failure possibilities for basic events and eventually for the top event under a fuzzy environment. Moreover if all the events are known, they will be evaluated by the use of conventional or traditional FTA method, i.e. probability analysis. Nevertheless, if all of the events or some of them are unknown they will be evaluated by use of the fuzzy fault tree concept, i.e. a possibility analysis/approach.

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 [59] 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 for aggregating fuzzy numbers; an appealing approach is as follows (functions needed for this aggregation are shown in Section 3.1.1):

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

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

Step 5: Convert fuzzy numbers for failure rates into the Fuzzy Possibility Scores (FPSs).

Three fuzzy parameters will be added together and then be divided by three, i.e. centre of gravity will be found [60,61].

Step 6: Obtain the possibility failure rate of the top event by integrating FPSs of the vague basic events using Eqs. (7) and/or (8).

As it was explained before there is a chance that some of the failure rates for the basic events are known and some remain vague or unknown. In this case first failure probabilities for the known events must be transformed into the fuzzy numbers enabling them to be used along with FPSs of the vague basic events.

Step 7: Analyse and interpret the results.

3.1.3. Fuzzy ETA

In practice, it is hard and costly to obtain exact values of event occurrences because in many cases these estimated values are the results of an expert’s 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 [62,63]. The existing research [64–66] discusses methods to handle uncertainties in experts’ judgments and to interpret them for the purpose of conducting risk analysis. Fuzzy theory has proven effective and efficient in handling these types of uncertainties [46,66–70]. Therefore under fuzzy environment $\tilde{P}_n$ denotes the Success/True/Yes possibility of the nth event whereas the $(\tilde{1} \ominus \tilde{P}_n)$ denotes the Failure/False/No possibility of the nth event within the same column. Furthermore S_n 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 judgement of event possibility is assumed linguistic and described using a TFN. In an ETA, fuzzy possibilities are then used to estimate each outcome event possibility that is also estimated as a fuzzy number. The fuzzy-based approach used for ETA comprises the following five steps:

Step 1: For an initiating event identified within the PTOM, 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 and 4 of the FFTA).
Step 3: Determine each of the outcome events' possibility as a TFN by calculating all fault tree paths by the use of Eqs. (2)–(4).
Step 4: Defuzzify the outcome events' possibilities for event tree consequences (i.e. FPSs, See Step 5 of the FFTA).
Step 5: Analyse and interpret the results.

Due to the scarcity of data fuzzy fault tree and fuzzy event tree analyses (i.e. CCA under a fuzzy environment) will be applied on one of the most significant operational risk factors associated within the PTOM for representing the proposed approach. This CCA is depicted in the following case study.

4. Case study

This case study relates to the risk factor R_{51}, i.e. "pilot's related errors" which is one of the most significant risk factors among operational risk factors within the PTOM. It was identified through the HAZID process in the literature review of the previous works as shown in Fig. 4 and Table 1. Considering that the top event is "pilot's related errors", which for example can be initiated by channel, canal, harbour and/or local offshore-based pilots giving 'an inappropriate command'. This may happen when a tanker ship is navigating inside of a narrow channel or a canal. In another instance the same situation can happen during tandem operations for a Shuttle Tanker or a Liquefied Natural Gas (LNG) Tanker while approaching to offshore terminals in oil and gas fields whether the terminals are fixed or they are floating, e.g. Floating, Production, Storage and Offloading (FPSO) units. As a result consequences of the "pilot's related errors" can be grounding, collision (with other ships, jetties in ports and structures or installations of offshore terminals), fire, explosion, spillage, loss of life, etc. [23,71].

Table 3
Potential basic events which cause top events of "pilot's related errors" [23].

Basic events	Basic event (BE) no.
Inappropriate command from pilot	BE1
Pilot unaware of ship's behaviour	BE2
Pilot make an error	BE3
Ship master make an error of judgement	BE4
Over friendly relationship with pilot	BE5
Inadequate passage plan	BE6
Inappropriate or fail aids	BE7
Command execution failure	BE8

During a pilotage if a hazard is released, the accidental event can escalate to one of the several possible consequences. In the analysis of marine or engineering operations, the fault and event trees describe not only mechanical failures, but also operators' (human) front line and recovery errors [72]. As it is mentioned in the above section there are many consequences as a result of the pilot's related errors but the major causes of pilotage errors based on [23] are illustrated in Table 3 and Fig. 7.

Due to the scarcity of data and the fact that all the basic events are vague and in order to evaluate the risk factor, i.e. "pilot's related errors" it has been decided to carry out the evaluation by using the experts' judgements. For this purpose in this case study one of the Iranian ports called Port of Shahid Rajaei has been selected for evaluation. To carry out an reasonable experts' judgements in this paper, three experts have been selected to carry out the judgement process. All the 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 ports and offshore terminals. Each expert has about 15 years experience on sea ports' and offshore terminals' operations and management. The experts are now holding managerial positions in different operational fields in Port of Shahid Rajaei. The main factor in selecting these experts was based on their expertise that they have equally contributed in the fields related to the operational risk factors (R_4) illustrated in Fig. 4. For this reason these experts have equal weights in respect of each other that would affect equally the evaluation processes. After collecting the experts' opinions and integrating them by means of Eqs. (2) and (9) with the use of Eq. (8) the required calculations were carried out in order to find out FPS of the nominated top event, i.e. "pilot's related errors" in Port of Shahid Rajaei. The calculated FPS of the top event, i.e. $\tilde{P}_{TE(R51)}$ was found to be 0.750. Then by eliminating of each basic event the new FPSs for the new top events, i.e. $\tilde{P}_{TEi}$ $(i = 1, 2, 3, \ldots 8)$ are obtained

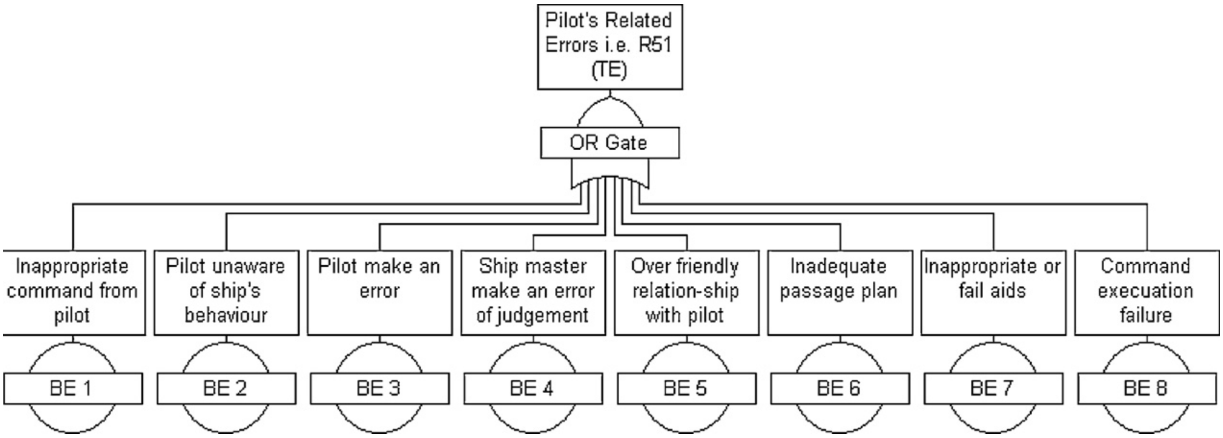

Fig. 7. Fault tree diagram for top event "pilot's related errors" along with basic events.

Table 4
Importance of elimination of each basic events in failure possibility of the top events.

Elimination of basic events	Possibility approach					
	Fuzzy number			Failure possibility	Deviation index	Ranking
	l	*m*	*u*			
BE1	0.297	0.946	0.995	0.746	0.004	4
BE2	0.154	0.922	0.991	0.689	0.061	1
BE3	0.297	0.940	0.994	0.744	0.006	3
BE4	0.236	0.933	0.993	0.721	0.029	2
BE5	0.236	0.933	0.993	0.721	0.029	2
BE6	0.297	0.940	0.994	0.747	0.003	5
BE7	0.297	0.940	0.994	0.747	0.003	5
BE8	0.297	0.955	0.996	0.749	0.001	6

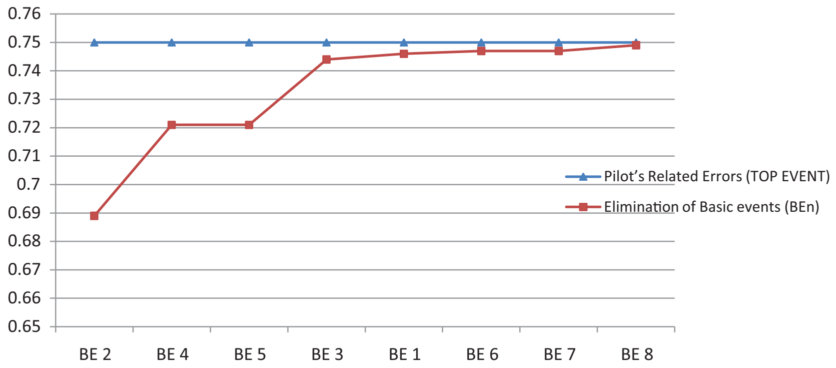

Fig. 8. Sensitivity analysis of the top event pilot's related errors.

respectively as shown in Table 4. Subsequently the amount of each deviation, i.e. [$\tilde{P}_{TE(R51)} \ominus \tilde{P}_{TEi}$] has been recorded under the deviation index column in Table 4. The greater number for deviation index means having higher importance on the failure possibility of the top event. That means elimination of any basic even which can lead to a higher deviation index will reduce the occurrence possibility of the top event (R_{421}) more than in the case of other eliminations. As it is shown in Table 4 basic event number two, i.e. BE2 has the highest importance. In [$\tilde{P}_{TE(R51)} \ominus \tilde{P}_{TEi}$]; $TE(R51)$ denote top event R_{51}, i.e. "pilot's related errors" and *TEi* denotes the top event for which its *i*th basic event is eliminated.

Fig. 8 illustrates the sensitivity analysis carried out for the risk factor "pilot's related errors", based on the results shown in Table 4. It shows how the possibility of occurrence for the top event will be reduced by elimination of any basic event. Fig. 9 illustrates the Event Tree Analysis of the risk factor "pilot's related errors" along with the linguistic fuzzy variables after aggregation of the experts' judgements as described previously:

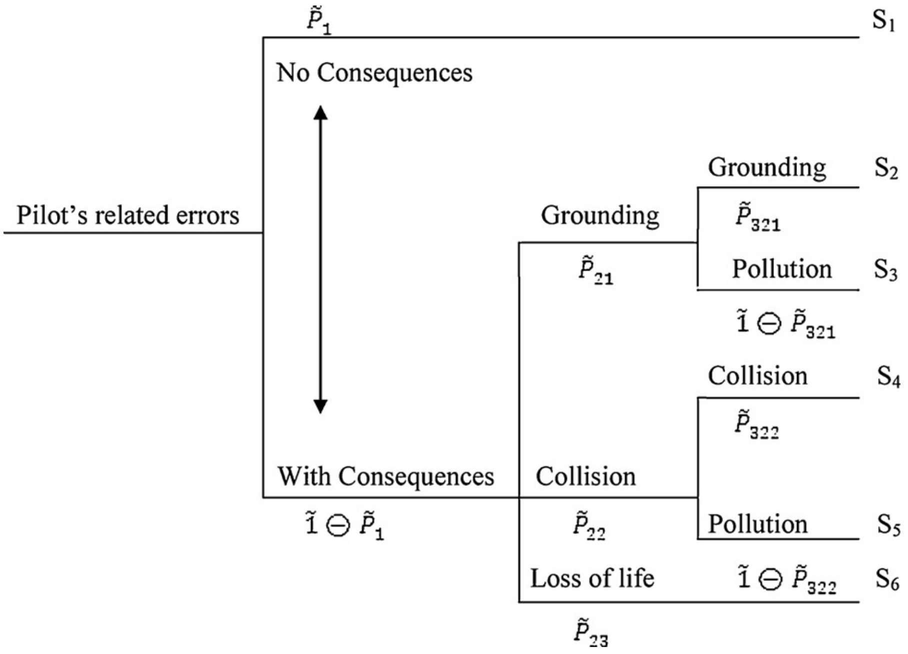

Fig. 9. Event tree analysis for risk factor of pilot's related errors [23].

Table 5
Occurrence possibility scores (FPSs) for different consequences.

Consequences as a result of pilot's related errors	Occurrences possibility scores (FPSs)	Ranking
No consequences	0.330	1
Grounding	0.200	3
Pollution as a result of grounding	0.087	4
Collision	0.205	2
Pollution as a result of collision	0.055	6
Loss of life	0.077	5

In order to estimate the occurrence possibility scores (FPSs) of the consequences initiated from the selected risk factor it has been decided to carry out the evaluation using the experts' judgements. The same experts used for FFTA have been asked for the evaluation purposes. By using Eqs. (2)–(4) the final results obtained are listed in Table 5 along with rankings for consequences. As it can be seen consequence number one, i.e. "pilot's related errors with no consequences" will have the highest occurrence possibility score.

5. Conclusion and further suggestions

This paper evaluated the most significant operational risk factors (hazards) by use of the CCA in order to complete the risk assessment phase of the RM framework within the PTOM. In the first part of this paper after introducing the CCA and bow-tie method, their application on PTOM was investigated. They were used for evaluating the nominated operational risk factors and for this purpose the causes and consequences for one of the most significant risk factor were investigated. In the second part in order to evaluate the main causes of the selected risk factor by using the FFTA and experts' judgements the possibility of occurrence for the top event was calculated and by eliminating each basic event again the occurrence probability of the top event was determined to see the amount of the changes. Consequently the most signisicant basic events influencing the nominated risk factor were identified through the introduced risk analysis model. In the third part in order to evaluate the consequenses of the same risk factor by using the FETA and experts' judgements the occurrence possibility for each consequence was calculated. Consequently the most significant consequence within the nominated risk factor was identified through this analysis process.

Although in this study only one of the most significant risk factors was analysed, in the future works all of the introduced risk factors can be analysed one by one as per availability of the data using the suitable model and methods explained in this study. Furthermore in the future studies in order to mitigate the analysed risk factors through the CCA within the PTOM by introducing an appropriate method, risk control solutions can be selected. The selected solutions can be used as preventive or corrective measures (barriers) which will lead to implimentation of either a proactive or a reactive RM strategy toward a successful PTOM.

Acknowledgements

This research was partially supported by the European Regional Development Fund (ERDF) under the Interreg IVB North West Europe Programme (WEASTflows project).

References

[1] Y. Wang, Development of a computer-aided fault tree synthesis methodology for quantitative risk analysis in the chemical process industry, PhD thesis, 2004.
[2] UNCTAD, Maritime Security: Elements of an Analytical Framework for Compliance Measurement and Risk Assessment, 2006.
[3] GAO, United States Government Accountability Office, Port risk management: Further Refinements Needed to Assess Risks and Prioritize Protective Measures at Ports and Other Critical Infrastructure, Report to Congressional Committees, 2006.
[4] DETR, Department of Transport, Port Marine Safety Code, 2000, ISBN:1-85112-365-2.
[5] CCPS, Center for Chemical Process Safety, Guideline for Chemical Process Quantitative Risk Analysis, Centre for Chemical Process Safety, American Institute of Chemical Engineers (AIChE), New York, 2000.
[6] F.P. Lees, Loss Prevention in the Process Industries, 2nd ed., Butterworth-Heinemann, Boston, 1996.
[7] G.C.A. Dickson, Risk Analysis. The Institution of Risk Management, IRM, Witherby Publishing, 2003.
[8] K. Krishna, Y. Wang, S.R. Saraf, W.J. Rogers, J.T. Baldwin, J.P. Gupta, M.S. Mannan, Hydroxylamine production: Will a QRA help you decide? Reliability Engineering & System Safety 81 (2003) 215–224.
[9] CIA, Chemical Industries Association, A Guide to Hazard and Operability Studies, 1992.
[10] ABS, American Bureau Shipping, A Guide for Risk Evaluations for the Classification of Marine-related Facilities, 2003.
[11] J.P. Visser, Developments in HSE management in oil and gas exploration and production, in: A.R. Hale, M. Baram (Eds.), Safety Management, the Challenge of Change, Pergamon, Oxford, 1998.
[12] J. Groeneweg, Controlling the Controllable, DSWO Press, Leiden, 1998.
[13] L.J. Bellamy, B.J.M. Alea, T.A.W. Geyerc, L.H.J. Goossensd, A.R. Haled, J. Ohe, M. Mude, A. Bloemhofe, I.A. Papazoglouf, J.Y. Whistong, Story builder – a tool for the analysis of accident reports, Reliability Engineering and System Safety 92 (2007) 735–744.
[14] HSE, Feasibility of Storybuilder Software Tool for Major Hazards Intelligence. Prepared by the Health and Safety Laboratory for the Health and Safety Executive, 2010, Available from: www.hse.gov.uk (accessed 08.05.2010).
[15] Storybuilder, White Queen BV, the Netherlands, 2008, Available from: http://www.storybuilder.eu/catalog.htm (accessed 07.05.2010).
[16] DNV, Det Norske Veritas, Frequency Analysis of Accidental Oil Releases for FPSO Operations in the Gulf of Mexico, Final Report, Houston, 2000.
[17] RIVM. National Institute for Public Health and the Environment of Netherlands. RIVM Report 620801001, 2008. Available from: www.rivm.nl (accessed 08.05.2010).
[18] C.J. Edwards, Developing a safety case with an aircraft operator, in: Proc. Second Annual Two-day Conference on Aviation Safety Management, May, 1999.
[19] C. Zuijderduijn, Risk Management by Shell Refinery/Chemicals at Pernis The Netherlands; Implementation of SEVESO-II Based on Build up Experiences Using a Hazards and Effects Management Process, 1999.
[20] H.A.P. Blom, M.H.C. Everdij, J. Daams, ARIBA Final Report Part II: Safety Cases for a new ATM operation, NLR report TR-99587, Amsterdam, 1999.
[21] TSO, The Application of Bow-ties in Marine Safety Management, 2006, Available from: www.tankeroperator.com (accessed 08.05.2010).
[22] ABS, American Bureau Shipping, Thesis Bow-tie, Solution for the management of risk, 2007, Available from: www.absconsulting.com (accessed 08.05.2010).
[23] V.M. Trbojevic, B.J. Carr, Risk based methodology for safety improvements in ports, Journal of Hazardous Materials 71 (2000) 467–480.
[24] J.E. Cockshott, Probability bow-ties. A transparent risk management tool, Process Safety and Environmental Protection B 83 (4) (2005) 307–316.
[25] A. Hoyland, M. Rausand, Systems Reliability Theory Models and Statistical Methods, John Willey and Sons, New York, 1994.
[26] I.M. Dokas, D.A. Karras, D.C. Panagiotakopoulos, Fault tree analysis and fuzzy expert systems: early warning and emergency response of landfill operations, Environmental Modelling and Software 24 (2009) 8–25.
[27] ABS, American Bureau Shipping, Risk Assessment Applications for Marine and Offshore Oil and Gas Industries, 2000.
[28] R. Ferdous, F. Khan, R. Sadiq, P. Amyotte, B. Veitch, Handling data uncertainties in event tree analysis, Process Safety and Environmental Protection 87 (2009) 283–292.
[29] AIChE, Guidelines for Chemical Process Quantitative Risk Analysis, 2nd ed., AIChE, New York, 2000.
[30] F.P. Lees, Loss Prevention in the Process Industries, 3rd ed., Butterworths, London, 2005, pp. 9/05–9/122.
[31] CMPT, A Guide to Quantitative Risk Assessment for Offshore Installations, The Centre of Marine and Petroleum Technology, UK, 1999.
[32] J. Ren, I. Jenkinson, J. Wang, D.L. Xu, J.B. Yang, A methodology to model causal relationships on offshore safety assessment focusing on human and organisational factors, Journal of Safety Research 39 (1) (2008) 87–100.
[33] K. Mokhtari, Advanced Risk Management in Offshore Terminals and Marine Ports, PhD Thesis, Liverpool John Moores University, 2011.
[34] J.D. Andrew, L.M. Ridley, Application of the cause-consequence diagram method to static systems, Reliability Engineering and System Safety 75 (2002) 47–58.
[35] J.M. Keller, H. Tahani, Implementation on conjunctive and disjunctive fuzzy logic rules with neutral networks, International Journal of Approximate Reasoning 6 (1992) 221–240.
[36] T.L. Saaty, Decision Making with Dependence and Feedback: Analytic Network Process, RWS Publications, Pittsburgh, 2001.
[37] M.B. Murtaza, Fuzzy-AHP Application to Country Risk Assessment. American Business Review, Middle Tennessee State University, TN, 2003.
[38] H. Takagi, I. Hayashi, NN-driven fuzzy reasoning, International Journal of Approximate Reasoning 5 (1991) 191–212.

[39] L.A. Zadeh, Fuzzy sets, Information and Control 8 (1965) 338–353.

[40] S. Balli, S. Korukoglu, Operating system selection using fuzzy AHP and TOPSIS methods, Mathematical and Computational Applications 14 (2) (2009) 119–130.

[41] H.T. Nguyen, E.A. Walker, A First Course in Fuzzy Logic, Chapman and Hall/CRC, Florida, 2000.

[42] G.J. Klir, B. Yuan, Fuzzy Sets and Fuzzy Logic: Theory and Application, Prentice Hall, New Jersey, 1995.

[43] D. Ertugrul, N. Karakasoglu, Performance evaluation of Turkish cement firms with fuzzy analytic hierarchy process and TOPSIS methods, Expert Systems with Applications 36 (1) (2007) 702–715.

[44] A. Kaufmann, M.M. Gupta, Introduction to Fuzzy Arithmetic: Theory and Applications, Van Nostrand Reinhold, New York, 1985.

[45] D.Y. Chang, Applications of the extent analysis method on fuzzy AHP, European Journal of Operational Research 95 (1996) 649–655.

[46] C.T. Chen, Extensions of the TOPSIS for group decision-making under fuzzy environment, Fuzzy Sets and Systems 114 (2000) 1–9.

[47] T. Yang, C.C. Hung, Multiple-attribute decision-making methods for plant layout design problem, Robotics and Computer-Integrated Manufacturing 23 (2007) 126–137.

[48] H.J. Zimmerman, Fuzzy Sets Theory and its Applications, Kluwer Academic Publishers, Boston, 1996.

[49] C. Kahraman, Capital budgeting techniques using discounted fuzzy cash flows, in: D. Ruan, J. Kacprzyk, M. Fedrizzi (Eds.), Soft Computing for Risk valuation and Management: Applications in Technology, Environment and Finance, Physica-Verlag, Heidelberg, 2001, pp. 375–396.

[50] J. Ren, J. Wang, I. Jenkinson, D.L. Xu, J.B. Yang, A Bayesian network approach for offshore risk analysis through linguistic variables, China Ocean Engineering 21 (3) (2007) 371–388.

[51] Y. Li, X. Liao, Decision support for risk analysis on dynamic alliance, Decision Support Systems 42 (2007) 2043–2059.

[52] M.B. Anoop, R.K. Balaji, S. Gopalakrishnan, Conversion of probabilistic information into fuzzy sets for engineering decision analysis, Computers and Structures 84 (2006) 141–155.

[53] P.S. Jackson, R.W. Hockenbury, M.L. Yeater, Uncertainty analysis of system reliability and availability assessment, Nuclear Engineering and Design 68 (1981) 5–29.

[54] G.S. Liang, M.J. Wang, Fuzzy fault-tree analysis using failure possibility, Microelectronics and Reliability 33 (1993) 583–597.

[55] D. Singer, A fuzzy set approach to fault tree and reliability analysis, Fuzzy Sets and Systems 34 (1990) 145–155.

[56] J.D. Andrews, R.T. Moss, Reliability and Risk Assessment, 2nd ed., Professional Engineering Publishing, UK, 2002.

[57] J. Henley, H. Kumamoto, Reliability Engineering and Risk Assessment, Prentice Hall, Englewood Cliff, NJ, 1981.

[58] C.W. Cheng, A.L.H. Lan, Web access failure analysis fuzzy reliability approach, International Journal of the Computer, the Internet and Management 12 (1) (2004) 65–73.

[59] R.T. Clemen, R.L. Winkler, Combing probability distribution from experts in risk analysis, Risk Analysis 19 (2) (1999) 187–203.

[60] D. Yuhua, Y. Dataob, Estimation of failure probability of oil and gas transmission pipelines by fuzzy fault tree analysis, Journal of Loss Prevention in the Process Industries 18 (2005) 83–88.

[61] R. Zhao, R. Govind, Defuzzification of fuzzy intervals, Fuzzy Set and Systems 43 (1991) 45–55.

[62] T. Rosqvist, On use of experts judgment in the quantification of risk assessment. Dissertation for the degree of Doctor of Technology, Helsinki University of Technology, Espoo, Finland, 2003.

[63] R.B. Druschel, M. Ozbek, G. Pinder, Application of Dempster–Shafer theory to hydraulic conductivity, in: CMWR-XVI, Conference Programme Copenhagen, Denmark, 2006, pp. 31–33.

[64] M. Abrahamsson, Uncertainty in quantitative risk analysis-characterization and methods of treatment. Report No. 1024 Department of Fire Safety Engineering, Lund University, Sweden, 2002, ISSN:1402-3504.

[65] B. Thacker, L. Huyse, Probabilistic assessment on the basis of interval data, in: 44th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics, and Materials Conference, American Institute of Aeronautics and Astronautics, Inc., 2003.

[66] C.R. Wilcox, M.B. Ayyub, Uncertainty modelling of data and uncertainty propagation for risk studies, in: IEEE Proceedings of the Fourth International Symposium on Uncertainty Modelling and Analysis, 2003, pp. 184–191.

[67] K. Sentz, S. Ferson, Combination of Evidence in Dempster–Shafer Theory. SAND 2002-0835, 2002.

[68] H. Bae, V.R. Grandhi, A.R. Canfield, An approximation approach for uncertainty quantification using evidence theory, Reliability Engineering and System Safety 86 (2004) 215–225.

[69] H. Agarwal, E.J. Renaud, L.E. Preston, D. Padmanabhan, Uncertainty quantification using evidence theory in multidisciplinary design optimization, Reliability Engineering and System Safety 85 (2004) 281–294.

[70] B. Ayyub, J.G. Klir, Uncertainty Modelling and Analysis in Engineering and the Sciences, Chapman and Hall/CRC, 2006.

[71] NE P&I Club, An Introduction to P&I Insurance and Loss Prevention. Loss Prevention Guide, 2008.

[72] V.M. Trbojevic, L.J. Bellamy, P.G. Brabazon, O.T. Gudmestad, W.K. Rettedal, Methodology for the analysis of risks during the construction and installation phases of an offshore platform, special issue: safety on offshore process installation: North Sea, Journal of Loss Prevention in the Process Industries 7 (4) (1994).