Quantitative risk modelling of maintenance work on major offshore process equipment

Xingwei Zhen[a,b,*] , Jan Erik Vinnem[b,*], Changyi Peng[a], Yi Huang[a]

a School of Naval Architecture and Ocean Engineering, Dalian University of Technology (DUT), NO-116024 Dalian, China

b Department of Marine Technology, Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway

ABSTRACT:

Investigations of major offshore accidents show that both technical and non-technical factors have crucial effects on the accident sequences. Nonetheless, quantitative risk analyses (QRAs) have traditionally focused on the technical safety systems while applications and findings in the non-technical fields are to a large extent missing. This paper proposes a new quantitative risk modelling methodology reflecting and analyzing how specific factors with respect to human, operational and organizational risk influencing factors (RIFs) influence the barrier performance for offshore maintenance work. New RIF-Index is proposed to identify and structure diverse RIFs for all failure events. RIFs are assessed by experts according to the established fuzzy scoring criterion. Further, the modified fuzzy analytic hierarchy process (AHP) addressing the fuzzy consistency is used to assess the importance degree of RIFs. On this basis, the industry average frequencies/probabilities are revised through an integrated assessment of the priority weights and the status of RIFs. Thus, input of the revised frequencies/probabilities results in an updated risk picture, which takes the specific conditions of technical, human, operational and organizational RIFs into account. Specific hydrocarbon release incident on the offshore installation is used as a case study with the purpose to apply and test the proposed methodology. It has been demonstrated that the proposed methodology is an effective tool for analyzing the failure of safety barriers, and handling the uncertainties and subjectivities arising in the operational risk analysis. The methodology is useful in demonstrating the effects on the barrier performance of installation specific conditions of non-technical RIFs.

Keywords: Quantitative Risk Analysis; Risk influencing factors; Human and organizational factors; Fuzzy AHP; Operational barriers

1. Introduction

1.1 Background

In the present days, there are less and less new offshore installations since the year of 2000 in the entire North Sea. Thus, the operation, maintenance and modification of existing offshore installations are the main focus for the Norwegian offshore industry. This suggests that in contrast to design safety, the operational safety with respect to risk minimization is more and more brought into focus. This also implies that more detailed analyses, which can reflect installation specific operational factors, are of great importance and have a strong need to the offshore industry. At the same time, against the background of learning from major offshore accidents (Cullen, 1990; Sklet,

* Corresponding author.
Email address: xingwei.zhen@ntnu.no (X.W. Zhen); jan.erik.vinnem@ntnu.no (J.E. Vinnem).
Tel.: +4794207768 (X.W. Zhen); +47 91152125 (J.E. Vinnem)

2004; Vinnem et al., 2006; Montara Commission of Inquiry, 2010; The National Academies, 2010), it is shown that technical, operational, human and organizational factors all have crucial effects on the accident sequences. In spite of these facts, QRAs have traditionally been focused on technical systems and capabilities, while applications and findings in the non-technical fields are to a large extent missing (Aven et al., 2006a; Røed et al., 2009; Skogdalen and Vinnem, 2009; Vinnem et al., 2012).

Considering this, some models and methods have been developed aiming to take human and organizational factors into account for QRAs in the offshore industry, such as ORIM (Organizational Risk Influence Model) (Øien, 2001), BORA (Barrier and Operational Risk Analysis) method (Aven et al., 2006a; Sklet et al., 2006), OTS (Operational Conditional Safety) method (Vinnem et al., 2007; Vinnem et al., 2009) and Risk_OMT (Risk modelling-Integration of Organizational, Human and Technical factors) model (Vinnem et al., 2012; Gran et al., 2012). Common emphases of these models/methods are on a more comprehensive modelling of RIFs and their influence on risk. In many circumstances, a typical problem presented by these models/methods is the fact that it is difficult to address the uncertainties and subjectivities associated with quantitative assessment of status of RIFs as relevant data is frequently limited and expert judgments are necessary. With this background, there is a strong need to provide a systematic methodology to handle these uncertainties and subjectivities arising in the quantitative analysis of RIFs.

1.2 Research objective

The main objective of this paper is to propose a new risk modelling methodology, which is to reflect and analyze how specific factors with respect to human, operational and organizational RIFs influence the barrier performance for offshore maintenance work. Particular emphasis is placed on the quantitative status assessment and weights measurement of RIFs. A new RIF-Index is proposed and used to identify as well as structure the diverse RIFs for the initiating events and the basic events. Each RIF at the bottom level of the RIF-Index is assessed by experts in accordance with the established fuzzy scoring criterion. The modified fuzzy AHP method is used to assess the importance degree of each RIF. On this basis, the industry average frequencies/probabilities are revised through an integrated assessment of the priority weights and the status of RIFs.

Experience gained in the BORA methodology, which has been recognized by the offshore industry, provides an important basis for the study. Thus, a concise introduction of the BORA method is presented in the Section 1.3.

1.3 The BORA method

The emphasis in the BORA method has been on a more detailed modelling of both technical and operational conditions. The objective of the BORA program was that a BORA analysis can engage in the modelling and analysis of barriers on offshore production installations, including human, technical and organizational barrier elements. Compared with the traditional QRAs, the BORA method represents a step forward with respect to the use of risk-informed decision-making in the offshore industry (Aven et al., 2006b).

Fig.1 illustrates the main steps of the BORA method. It can be seen that the qualitative and quantitative analyses of the risk related to hydrocarbon leaks consist of the following processes:

(1) Development of a basic risk model including hydrocarbon release scenarios and safety barriers.

(2) Modelling the performance of safety barriers.

(3) Assignment of industry average probabilities/frequencies and quantification based on these probabilities/frequencies.

(4) Development of risk influence diagrams.

(5) Assignment of weights and scores of RIFs.

(6) Calculation of the platform specific leak frequency.

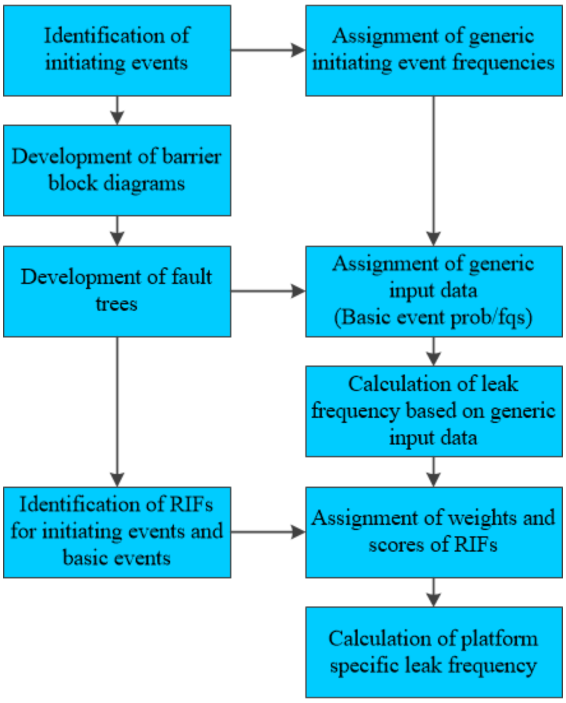

Fig.1 Summary of main aspects of the BORA method (Seljelid et al., 2007)

1.4 Structure of paper

The paper is organized as follows. Section 2 presents the proposed risk modelling methodology. A specific hydrocarbon release incident on the offshore installation is used as a detailed case study for applying and testing the proposed methodology in Section 3. Some critical issues of the proposed risk modelling methodology are discussed in Section 4. In final, Section 5 presents the main conclusions and recommendations for the future work.

2. Risk modelling methodology putting forward

The framework of the proposed risk modelling methodology for incorporation of human, operational and organizational RIFs is proposed and indicated in Fig.2.

The algorithm consists of five main processes, as follows. (1) Quantification of the experts' priority weights and determination of scoring criterion as well as fuzzy membership functions. (2) Qualitative analysis of scenarios, barrier performance and RIFs. (3) Quantification of the industry average frequencies/probabilities. (4) Quantification of the priority weights and the status of RIFs. (5) Quantification of the specific frequencies/probabilities. The specific procedures are described as follows.

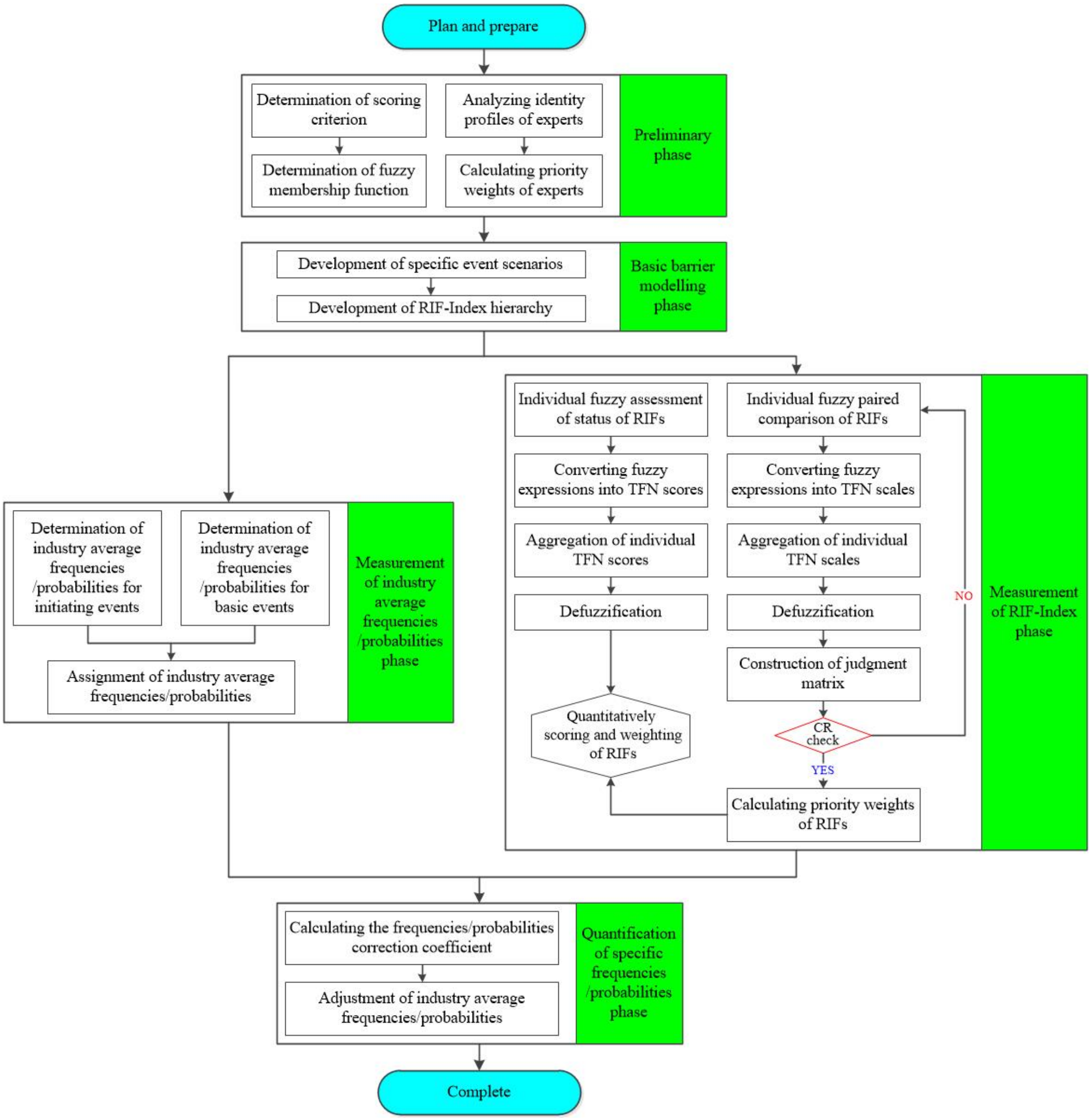

Fig.2 Main aspects of the proposed methodology

2.1 Preliminary phase

2.1.1 Allocating priority weights to experts

With respect to the assessment of various factors in QRA based on massive data and information, an expert team needs to be established first. The team should involve a range of experts associated with different knowledge, essential experience, service time, etc. It is necessary to allocate the priority weights to experts in order to distinguish experts' competence as well as their impacts on the judgments. In this study, four indices (Lavasani et al., 2015; Zhang et al., 2017) including professional position, service time, education level and age are taken into account so as to determine the priority weights of experts. Indices of the scoring criterion of experts are presented in Table 1.

Table 1

Indices of the scoring criterion of experts

Index	Classification	Score	Index	Classification	Score
professional position	Senior academic	5	Service time (year)	⩾30	5
	Junior academic	4		20-29	4
	Engineer	3		10-19	3
	Technician	2		6-9	2
	Worker	1		⩽5	1
Education level	PhD	5	Age (year)	＞60	5
	Master	4		50-59	4
	Bachelor	3		40-49	3
	Higher National Diploma (HND)	2		30-39	2
	School level	1		＜30	1

There are mainly three steps to calculate the priority weight of each expert, as follows. Firstly, the priority weights of the four indices are obtained by AHP method. This process is accomplished beforehand by administrative staffs who are in charge of the project. Then, the weighting score of each expert can be obtained in accordance with the scoring criterion (see Table.1). Lastly, the weighted average score of each expert is normalized and the expert's priority weight is obtained. It should be noted that the judgment matrix of AHP method must pass the consistency check (see further down, in section 2.4.2). Otherwise, a modified judgment matrix should be established.

*2.1.2 Determination of scoring criterio*n for assessing the status of RIFs

Scoring criterion lays the foundation for assessing the status of RIFs on the specific installation. Thus, scoring criterion has to be discussed and reached a consensus by the expert team in advance on the basis of existing information and data. In this study, the six-point scale is adapted from the Technical Condition Safety (TTS) project (Aven et al., 2006a; Thomassen and Sørum, 2002) as the scoring criterion (see Table 2), where score A, score C and score F represent the best standard, average standard and worst practice in the industry respectively. Corresponding values of the status scores (A, C, F) are determined in accordance with Eq. (1), where the lower and upper limits for the industry average probability are determined by expert judgment. The status scores (A, C, F) act as anchor values. A linear relationship is assumed between neighboring anchor values. Then, values of the status scores (B, D, E) can be assigned.

$$Q_i(s) = \begin{cases} P_l / P_a & (if \;\; s = A) \\ 1 & (if \;\; s = C) \\ P_h / P_a & (if \;\; s = F) \end{cases} \tag{1}$$

where Q_i is a measure of the status of RIF no i, P_a is the industry average probability, P_l and P_h are the lower and upper limits for the industry average probability respectively, s denotes the score of RIF no i.

Table 2

Scoring criterion for assessing the status of RIFs

Score	Grade characteristics
A	Status corresponds to the best standard in the industry
B	Status corresponds to a level better than the industry average
C	Status corresponds to the industry average
D	Status corresponds to a level slightly worse than the industry average
E	Status corresponds to a level considerably worse than the industry average
F	Status corresponds to the worst practice in the industry

2.1.3 Determination of fuzzy membership function (MF)

In order to quantify the status of RIFs, there lies a great challenge in determining appropriate values for the status scores A-F even when the scoring criterion is definite. In the BORA project (Aven et al., 2006a; Sklet et al., 2006), each crisp value is required to be associated with each of the status scores A-F by experts on the basis of their knowledge and expertise. Nonetheless, experts sometimes find that it is difficult to provide a precise numerical value as there often involves certain amount of uncertainty and subjectivity. Thus, fuzzy logic is introduced and fuzzy expressions are used in the proposed methodology. It is also recognized that using fuzzy numbers is more appropriate for human thinking (Zadeh, 1965; Sahin and Leung, 2017).

The scoring criterion is further developed by triangular MFs while trapezoidal fuzzy number (TFN) is applied for capturing and converting experts' fuzzy information, as an illustration example shown in Fig.3. A TFN can be defined as (l, m, n, u), where $l \le m \le n \le u$. Triangular and trapezoidal membership functions of M^* are given by the Eq. (2) and Eq. (3) respectively. It can be seen from Fig.3 that the ratio of P_l / P_a is set as 0.1 while the ratio of P_h / P_a is set as 10.

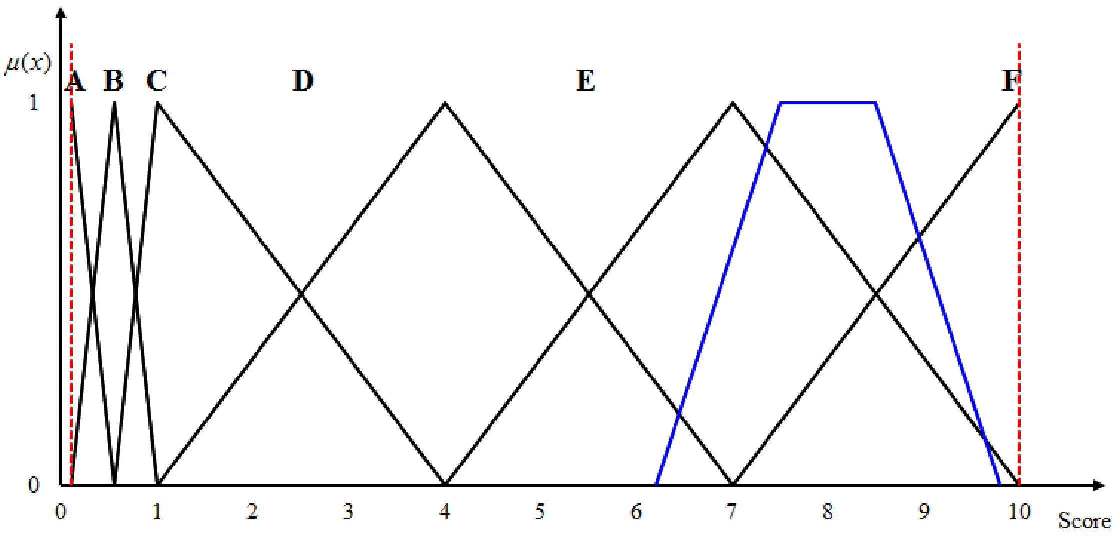

Fig.3. MFs of the scoring criterion

$$\mu_{M^*}(x) = \begin{cases} 0, & x < l \\ \dfrac{x-l}{m-l}, & l \le x \le m \\ \dfrac{u-x}{u-m}, & m \le x \le u \\ 0, & x > u \end{cases}, \text{ where } l < m < u \tag{2}$$

$$\mu_{M^*}(x) = \begin{cases} \dfrac{x-l}{m-l}, & l \le x \le m \\ 1, & m \le x \le n \\ \dfrac{u-x}{u-n}, & n \le x \le u \\ 0, & \text{otherwise} \end{cases}, \text{ where } l < m < n < u \tag{3}$$

2.2 Basic barrier modelling phase

The basic barrier modelling phase is to develop a basic risk model that focuses on qualitative analysis of the scenarios, barrier performance and RIFs. The main modelling principle for the event scenarios is shown in Fig. 4. It can be seen that the overall model takes the contributions to risk in accordance with fuzzy logic technique, barrier block diagrams/event trees, fault trees and RIF-Index hierarchy on the basis of BORA approach (Aven et al., 2006a; Sklet et al., 2006). RIF-Index hierarchy is developed to identify and structure diverse RIFs for all the initiating events in the barrier block diagrams/event trees and basic events in the fault trees. In contrast to the risk influence diagram used in the BORA modelling, which was just a one-level structure, RIF-Index hierarchy can decompose RIFs into adequate details. Thus, RIFs can be better analyzed and efficiently assessed. A bottom-up approach, where the events to be assessed are chosen as a starting point, is employed for hierarchy construction of RIF-Index, as shown in Fig.5. It can be seen that RIF-Index (level 1) can be divided into RIF groups of N at level 2, such as personal characteristics, characteristics of the technical system, organizational factors/operational philosophy, etc.

Each RIF group can be further decomposed into RIFs or sub-groups for identifying and analyzing all possible root RIFs. The basis for identification of RIFs is the generic framework shown in Fig.6. The generic framework is based on a review, comparison, and synthesis of various schemes of classification of human, technical and organizational factors (Swain and Guttmann, 1983; Embrey et al., 1984; Davoudian et al., 1994; Jacobs and Haber, 1994; Gibson et al., 1998a; Groeneweg, 1998; Hollnagel, 1998; Bellamy et al., 1999; Bento, 2001).

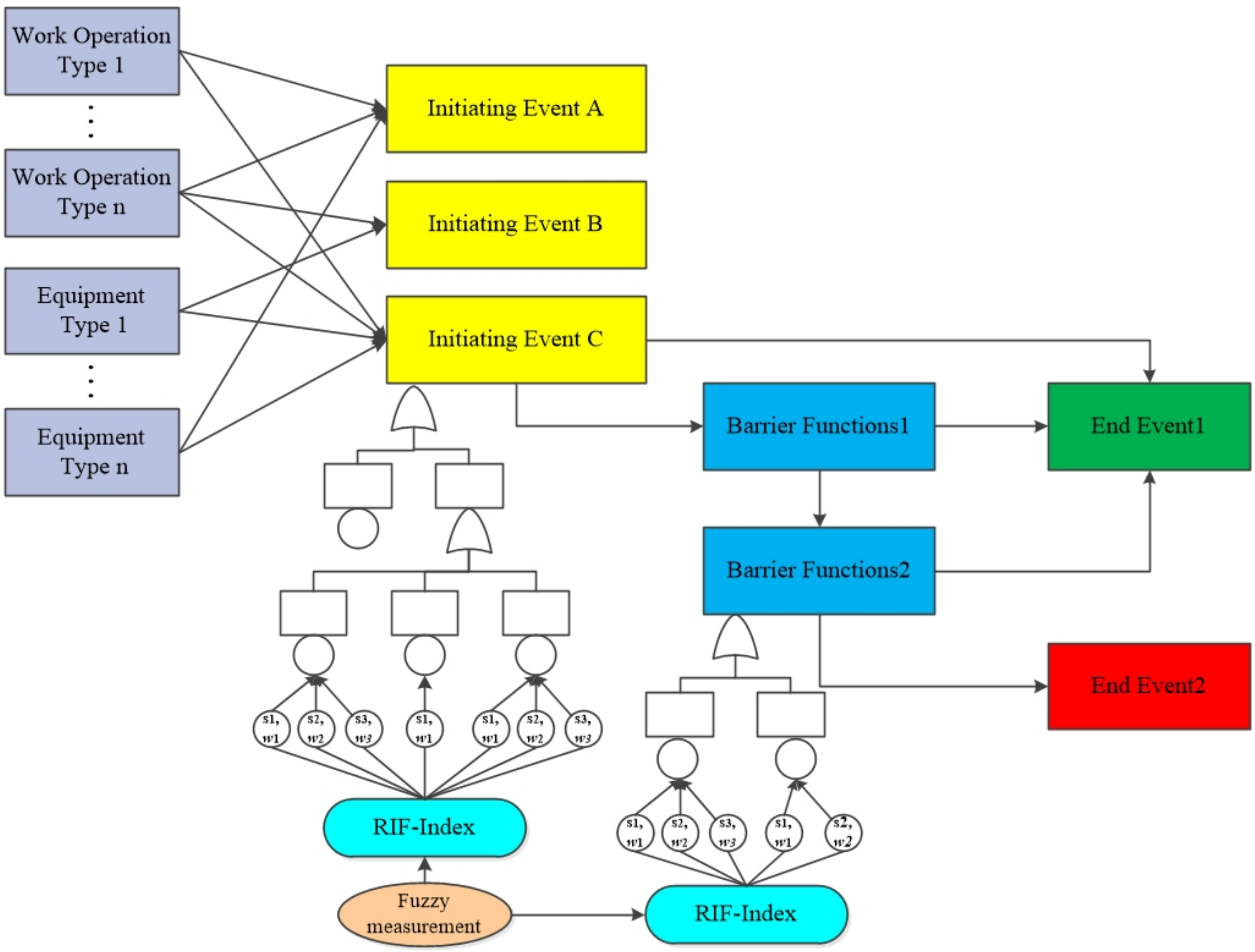

Fig.4. Modelling principle for the event scenarios

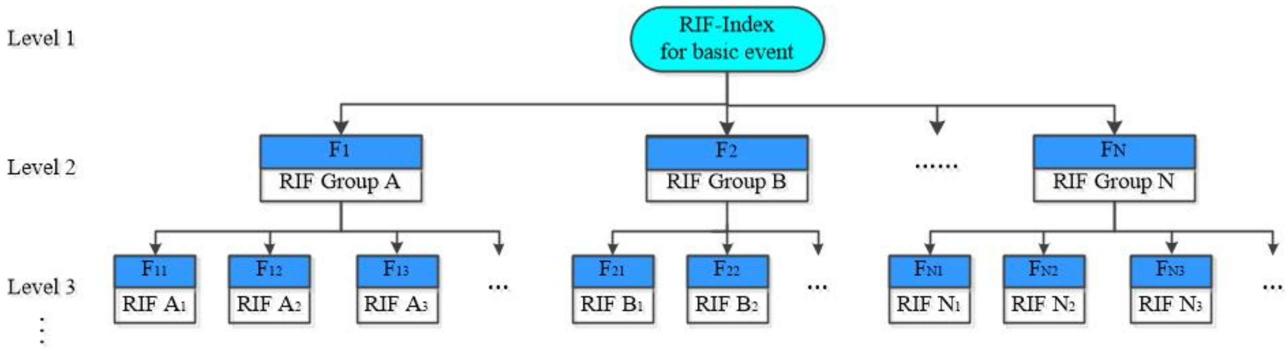

Fig.5. Hierarchy construction principle for RIF-Index

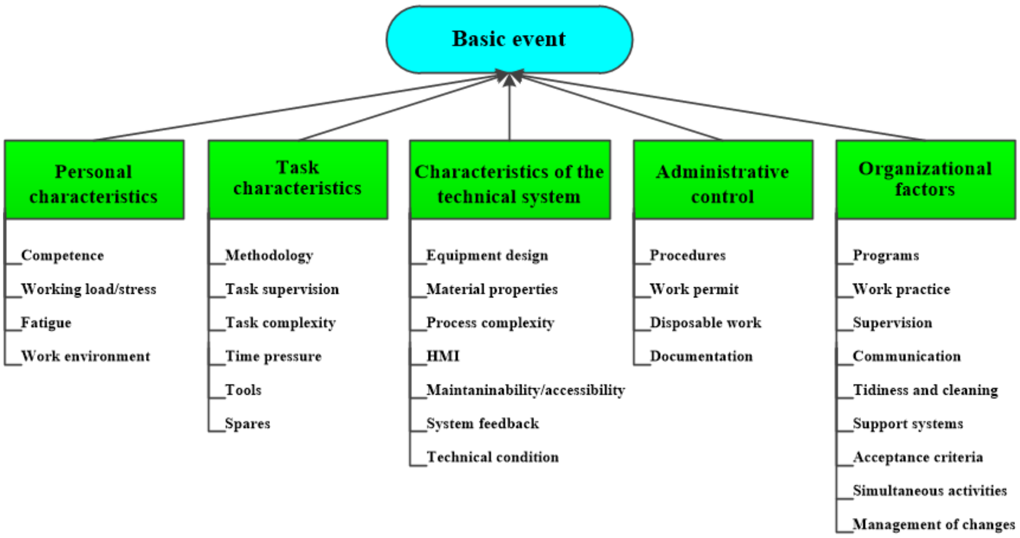

Fig.6. Generic framework for identification of RIFs (Seljelid et al., 2007)

2.3 Measurement of industry average frequencies/probabilities phase

Industry average frequencies/probabilities are of importance to risk quantification. There are two sets of data that go into the risk modelling: the initiating event frequencies for the barrier block diagrams/event trees and basic event probabilities for fault trees. The types of data sources can be used for measurement of industry average frequencies/probabilities, as follows: generic data sources, accident statistics, failure databases, equipment failure databases, physical properties of various substances, company internal accident and incident databases. A systematic overview of data sources and network accessible resources is presented in the literature of Offshore Risk Assessment (Vinnem, 2014), such as OREDA (OREDA, 2015) for offshore and onshore equipment reliability data, CORE-DATA (Gibson et al., 1998b; Gibson et al., 1998c) for human reliability, etc.

2.4 Measurement of RIF-Index phase

2.4.1 Quantitative measurement of the status of RIFs

Experts are required to assess each RIF at the bottom level of the RIF-Index hierarchy in accordance with the fuzzy logic and the established scoring criterion. Experts are encouraged to provide fuzzy expressions when they are not sure about the exact scores, or provide absent values once they find that it is hard to assess the RIFs. For instance, the fuzzy measurement of the status of RIFs can be provided by experts are that:

(1) A possible range of numerical values, such as (2, 5), the measurement is likely between 2 and 5.

(2) A fuzzy number, such as (2, 5, 6, 7), the measurement is between 2 and 7, most likely between 5 and 6.

(3) 0, the measurement means that the expert fails to assess the RIF.

It can be seen that the fuzzy measurement of the status of RIFs provided by different experts will naturally be multifarious. TFN is applied to convert these multifarious measurements into a universal format for aggregating individual measurement into a group. Thus, various TFNs are corresponding to the quantitative status of RIFs. The aggregation of TFN scores is performed as follows:

$$Q_i^* = \frac{Q_{i1}^* \otimes p_1 \oplus Q_{i2}^* \otimes p_2 \oplus \cdots \oplus Q_{im}^* \otimes p_m}{1-\sum p_r} \tag{4}$$

where Q_i^* is the fuzzy aggregated score of the status of RIF no i; Q_{i1}^*, $Q_{i2}^*,\cdots$, Q_{im}^* are the fuzzy scores of the status of RIF no i measured by m experts respectively; p_1, $p_2,\cdots$, p_m are the priority weights of experts respectively; p_r is the priority weight of the expert who fails to assess the RIF; $\otimes$ is the fuzzy multiplication operator while $\oplus$ represents the fuzzy plus operator.

Fuzzy measurement of the status of RIFs needs to be converted into crisp output for the final adjustment of industry average probabilities/frequencies. The centre-average method is used for defuzzification. Assume the fuzzy aggregated value of the status of RIF no i is $Q_i^* = \left\{ \nu_i, \mu_{Q_i^*}(\nu_i) \middle| \nu_i \in V, \mu_{Q_i^*} \in [0,1] \right\}$, the corresponding crisp value of the RIF is given by:

$$Q_i = \left(\frac{\sum_{i=1}^{N} \nu_i \mu_{Q_i^*}(\nu_i)}{\sum_{i=1}^{N} \mu_{Q_i^*}(\nu_i)} \right) \tag{5}$$

where ν_i indicates the centre of the ith fuzzy set of Q_i^*; $\mu_{Q_i^*}(\nu_i)$ is the MF of the centre of the ith fuzzy set of Q_i^*, N represents the number of elements.

2.4.2 Weights measurement of RIFs in the hierarchy

In order to assess the importance degree of each RIF, the modified fuzzy AHP method addressing the fuzzy consistency is employed in this study. Experts are required to make pair-wise comparison for each RIF in the subordinate RIF group of RIF-Index hierarchy. A comparison criterion of 1-9 scale (Zhang et al., 2017) is applied and presented in Table 3. Here, the experts are also encouraged to provide fuzzy expressions when they are not sure about the exact scores, or to provide absent values once they fail to compare the two factors. Then, TFN is applied to convert experts' multifarious measurements into a universal format for aggregating individual measurement into a group. The aggregation of TFN scales is performed as follows:

$$a_{ij}^* = \frac{a_{ij1}^* \otimes p_1 \oplus a_{ij2}^* \otimes p_2 \oplus \cdots \oplus a_{ijm}^* \otimes p_m}{1-\sum p_r} \tag{6}$$

where a_{ij}^* is the fuzzy aggregated scales of the ith RIF comparing to the jth RIF; a_{ij1}^*, $a_{ij2}^*,\cdots$, a_{ijm}^* are the fuzzy scales of the ith RIF comparing to the jth RIF by m experts respectively.

Table 3

Pair-wise comparison criterion

Importance value scale	Description
1	Two RIFs have equal importance
3	The first RIF is slightly more important than the second RIF
5	The first RIF is strongly important compared to the second RIF
7	The first RIF is absolutely very important compared to the second RIF
9	The first RIF is extremely more important than the second RIF
2,4,6,8	Medium value between adjacent scale

Further, the step involves converting the aggregated TFN scales into crisp values, suitable for the establishment of the judgment matrix and verifying whether the judgment matrix is reasonable or not. Assume an aggregated TFN scale $a_{ij}^{*}=(a_{ij}^{l},a_{ij}^{m},a_{ij}^{n},a_{ij}^{u})$, the corresponding crisp value that represents the final fuzzy output can be calculated by Eq. (7) (Zeng et al., 2007).

$$a_{ij}=\frac{a_{ij}^{l}+2(a_{ij}^{m}+a_{ij}^{n})+a_{ij}^{u}}{6} \tag{7}$$

On this basis, the judgment matrix (J) can be constructed, as presented in Eq. (8). Then, the consistency of the judgment matrix (J) is analyzed. The consistency ratio (CR) of 0.1 or less is considered as acceptable. The CR is to measure how consistent the judgments have been relative to large samples of purely random judgments. If the CR is more than 0.1, the judgments are considered untrustworthy (Celik and Akyuz, 2018). This indicates that the experts are required to revise the judgments on the pair-wise comparison for each RIF in the subordinate RIF group of RIF-Index hierarchy, and thus the judgment matrix will be modified. This step needs to be performed repeatedly until the judgment matrix is consistent. CR can be calculated in accordance with Eq. (9) (Saaty, 1990).

$$J=\begin{pmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{pmatrix})=\begin{pmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{pmatrix} \tag{8}$$

$$CR=\frac{(\lambda_{\max}-n)}{(n-1)RI} \tag{9}$$

where $\lambda_{\max}$ is the maximum eigenvalue of the judgment matrix; RI is the random index and can be selected from Table. 4.

Table 4

RI for different order of the judgment matrix

Order	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49	1.52	1.54	1.56	1.53	1.59

The priority weight of each RIF in the RIF-Index hierarchy w_i can be calculated through the arithmetic averaging method (Saaty, 1990) as follows.

$$w_i=\left(\frac{1}{n}\sum_{j=1}^{n}\frac{a_{ij}}{\sum_{k=1}^{n}a_{kj}}\right)\times\prod_{k=1}^{t}w_{group}^{(k)} \qquad i,j=1,2,\cdots,n \tag{10}$$

where $w_{group}^{(k)}$ is the priority weight of the RIF group in the kth upper group in which the corresponding RIF belongs to.

2.5 Quantification of specific frequencies/probabilities phase

Further, the industry average frequencies/probabilities are adjusted in accordance with an integrated assessment of the priority weights and the status of RIFs. The principle for adjustment is to introduce the frequency/probability correction coefficient, as presented in Eq. (11) and Eq. (12).

$$P_{spec.}(\mathrm{A})=P_{ave}(\mathrm{A})\bullet\gamma(\mathrm{A}) \tag{11}$$

$$\gamma(\text{A}) = \sum_{i=1}^{n}(w_i \bullet Q_i) = \sum_{i=1}^{n}\left\{\left[\left(\frac{1}{n}\sum_{j=1}^{n}\frac{a_{ij}}{\sum_{k=1}^{n}a_{kj}}\right)\times\prod_{k=1}^{t}w_{group}^{(k)}\right]\bullet\left(\frac{\sum_{i=1}^{N}v_i\mu_{Q_i^*}(v_i)}{\sum_{i=1}^{N}\mu_{Q_i^*}(v_i)}\right)\right\} \tag{12}$$

where $P_{spec.}(\text{A})$ denotes the specific frequency/probability of occurrence of event A; $P_{ave}(\text{A})$ denotes the industry average frequency/probability of occurrence of event A; $\gamma(\text{A})$ denotes the correction coefficient of the industry average frequency/probability of occurrence of event A.

Finally, the specific input frequencies/probabilities for all the events are applied in the risk model and thus the revised risk picture can take all the specific conditions of technical, human, operational and organizational RIFs into account.

3. Case study description and results

Specific hydrocarbon release incident for selected systems and activities on the offshore installation is used as a case study with the purpose to apply and test the proposed risk modelling methodology.

Table.5 presents the general description of the selected hydrocarbon release scenario, which is on the basis of BORA project (Sklet el al., 2006; Sklet, 2006).

Table 5

General description of the selected HC release scenario (Sklet el al., 2006)

Scenario name:
Release due to valve(s) in wrong position after maintenance

General description:
Release due to valve(s) set in wrong position after flowline inspection may occur if the area technician forget to close some SP valves prior to start-up of production

Initiating event:
Valve(s) in wrong position after flowline inspection

Operational mode when failure is introduced:
During maintenance, i.e., while disconnecting hoses after the leak test

Operational mode at time of release:
Release may occur during start-up after maintenance

Barrier functions:
The release may be prevented if the following barrier functions are fulfilled.
- Detection of valve(s) in wrong position

Barrier systems:
The release may be prevented if the following barrier functions are fulfilled.
- The system for self-control/use of checklist in order to detect possible valve(s) in fail position
- The system for third party control of work (actually, no third party control of work is required in this scenario)

Assumptions:
- On the flowline system, SP1-and SP2- valves may be in wrong positions after the flowline inspection. In addition, the two valves on the closed drain system connected to the hoses may be in wrong position after the inspection.
- The area technician operates these valves.
- No third party control of the work is performed by the area technician.
- Corrective action is carried out if a valve is revealed in wrong position.
- These valves are used during the leak test, and the valves may be left in open position after the leak test.
- A leak due to an open valve on the flowline system will most probably be detected during start-up of normal production, either manually by the are technician, or automatically by gas detector in the area. The area technician will stay in the wellhead area during start-up of production and may manually close the open SP-valve, or close the choke valve.

3.1 Preliminary phase

The expert team with five experts, who own high qualification in relation to hydrocarbon release scenario, is established. Identity profiles of the selected experts are presented in Table. 6.

The judgment matrix J_{e1} is established for the experts' identity profiles by administrative staffs, as presented in Eq. (13). The maximum eigenvalue of the judgment matrix J_{e1} is 4.05. The consistency ratio is 0.0187, which is less than 0.1. Thus, the judgment matrix meets the consistency requirement. Then, the priority weights of experts' identity profiles are calculated by Eq. (10). The priority weight of each expert is obtained by normalizing the weighted average score of each expert. Table.7 presents the priority weights of the identity profiles, the comprehensive score for each expert, and the final priority weights of the experts.

The fuzzy scoring criterion for assessing the status of RIFs is determined by experts' agreement in accordance with Eq. (1) and fuzzy MFs, as shown in Table.8. In order to quantify the status scores A-F for each initiating event or basic event, the lower and upper limits for the industry average probability are determined by experts seriatim and are further presented in Table.9 in section 3.3.

Table 6

Identity profiles of experts

Experts	Professional position	Educational level	Service time (year)	Age (year)
E1	Senior academic	PhD	28	56
E2	Junior academic	PhD	15	45
E3	Engineer	Master	19	43
E4	Engineer	Bachelor	11	33
E5	Worker	HND	30	48

$$J_{e1}=\begin{bmatrix} 1 & 3 & 1/4 & 5 \\ 1/3 & 1 & 1/5 & 6 \\ 4 & 5 & 1 & 7 \\ 1/5 & 1/6 & 1/7 & 1 \end{bmatrix} \tag{13}$$

Table 7

Priority weights allocated to experts

Experts	Score of professional position (0.5724)	Score of educational level (0.1192)	Score of service time (0.2451)	Score of age (0.0633)	Comprehensive score	Expert weight
E1	5	5	4	4	4.6916	0.2795
E2	4	5	3	3	3.8108	0.2270
E3	3	4	3	3	3.1192	0.1858
E4	3	3	3	2	2.9367	0.1750
E5	1	2	5	3	2.2262	0.1327

Table 8

Fuzzy scoring criterion for assessing RIFs

Score	Grade characteristics	Fuzzy number
A	Status corresponds to the best standard in the industry	$(Q_i(A), Q_i(A), Q_i(B))$
B	Status corresponds to a level better than the industry average	$(Q_i(A), Q_i(B), Q_i(C))$
C	Status corresponds to the industry average	$(Q_i(B), Q_i(C), Q_i(D))$
D	Status corresponds to a level slightly worse than the industry average	$(Q_i(C), Q_i(D), Q_i(E))$
E	Status corresponds to a level considerably worse than the industry average	$(Q_i(D), Q_i(E), Q_i(F))$
F	Status corresponds to the worst practice in the industry	$(Q_i(E), Q_i(F), Q_i(F))$

3.2 Basic barrier modelling phase

The basic risk model that includes the barrier block diagram for the selected hydrocarbon release scenario (see Table. 5) as well as the fault trees for the safety barriers "Self control of work"(BE1) and "3rd party control of work"(BE2) is developed, as illustrated in Fig.7.

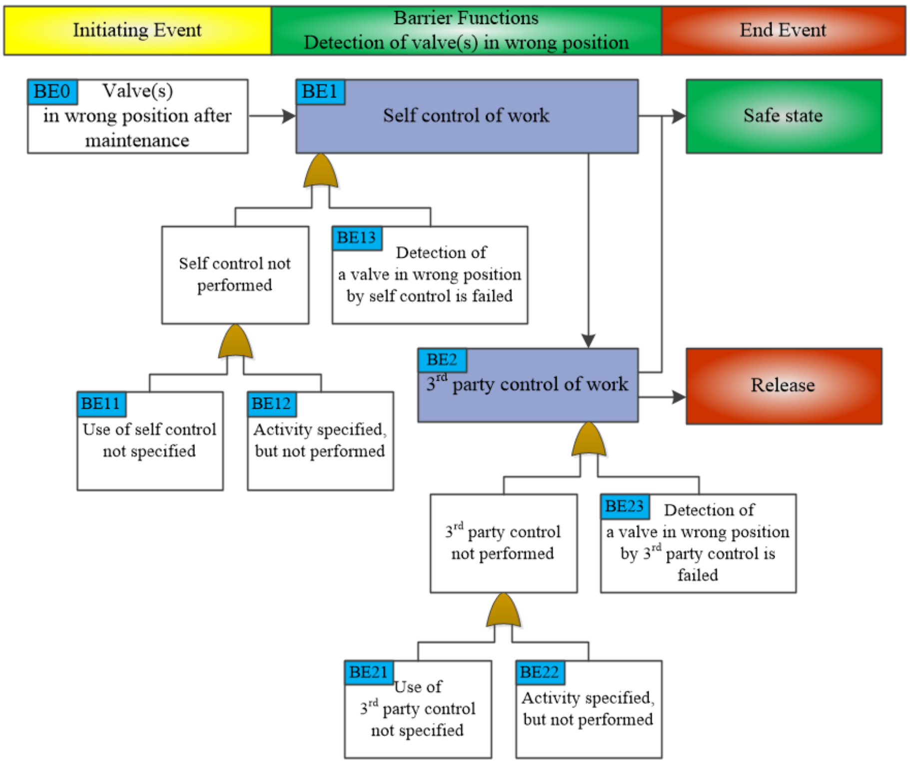

Fig.7. The basic risk model for the selected hydrocarbon release scenario (Sklet el al., 2006)

Further, RIF-Index hierarchies for the basic events BE0, BE11, BE12, BE13, BE21, BE22 and BE23 are developed, respectively. The RIF-Index hierarchies for the basic events BE0, BE11, BE12, BE13 are shown in Figs.8-11. The RIF-Index hierarchies for the basic events BE21, BE22 and BE23 are the same as the RIF-Index hierarchies for the basic events BE11, BE12 and BE13, respectively. It can be seen from Fig.8 that there are four RIF groups, i.e. characteristics of the technical system (F1), Task characteristics (F2), personal characteristics (F3) and administrative control (F4). Each RIF group can be further decomposed into detailed RIFs. For instance, there are three RIFs in the RIF group of “characteristics of the technical system (F1)”, i.e. process complexity (F11), maintainability/accessibility (F12), and human machine interface (F13).

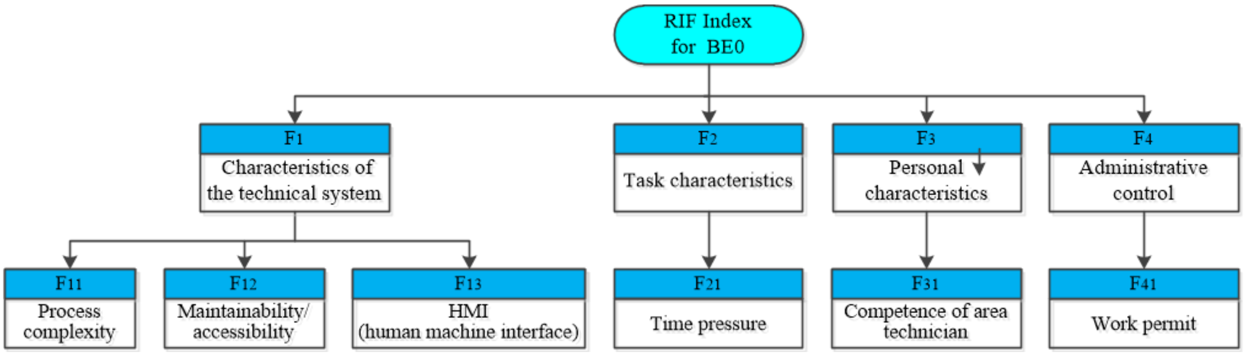

Fig.8. RIF-Index hierarchy for the basic event BE0

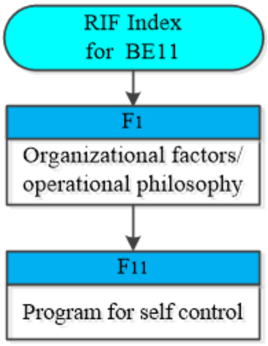

Fig.9. RIF-Index hierarchy for the basic event BE11

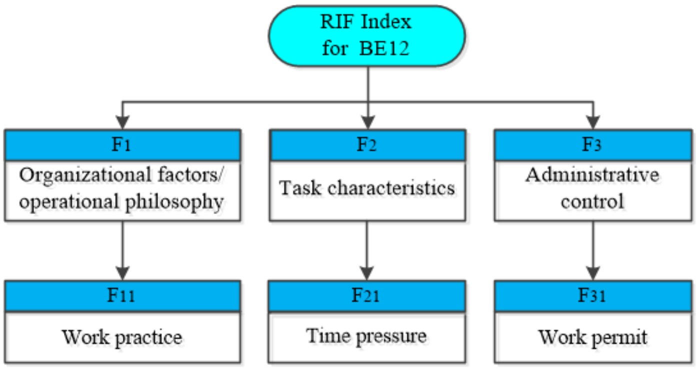

Fig.10. RIF-Index hierarchy for the basic event BE12

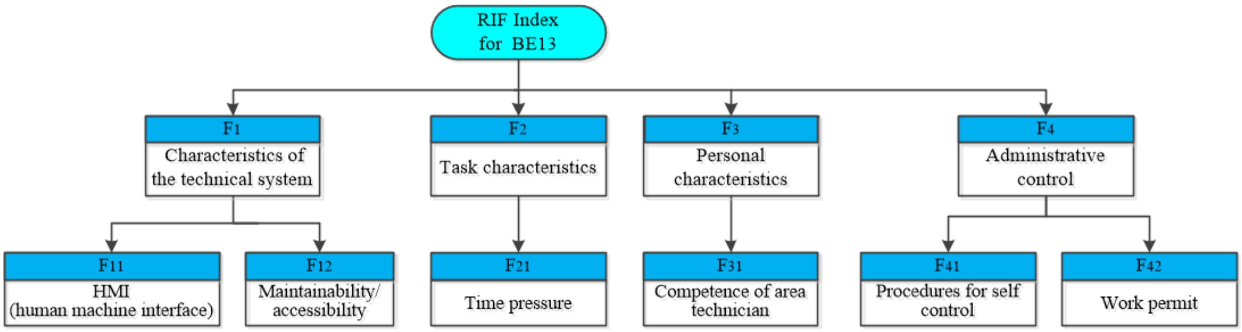

Fig.11. RIF-Index hierarchy for the basic event BE13

3.3 Measurement of industry average frequencies/probabilities phase

The industry average probabilities/frequencies as well as corresponding lower and upper limits for the basic events are presented in Table.9. There are two aspects that should be noted. On the one hand, the industry average probability of failure to specify self-control (BE11) is 0 as self-control is specified in this case study. On the other hand, the industry average probability of failure to specify 3rd party control (BE21) is 1 as 3rd party control of work is not specified.

Table 9

Industry average frequencies/probabilities and the corresponding lower and upper limits for the basic events

Basic event	BE0	BE11	BE12	BE13	BE21	BE22	BE23
No. of flowline inspections per year	28	---	---	---	---	---	---
P_{ave}	0.003	0.000	0.010	0.330	1.000	0.010	0.100
P_l	0.001	---	0.003	0.066	---	0.002	0.020
P_h	0.009	---	0.030	0.660	---	0.050	0.500

3.4 Measurement of RIF-Index phase

The status of each RIF at the bottom level of the RIF-Index hierarchy is assessed by experts in accordance with the fuzzy scoring criterion (see Table.8). The aggregation of TFN scores is performed in accordance with Eq. (4). As an illustration example, Table.10 presents the fuzzy scores of RIFs in the basic event (BE0). In the same way, other aggregated scores of RIFs can also be obtained.

Table 10

TFN scores of RIFs in the basic event (BE0)

RIF group	Characteristics of the technical system (F1)			Task characteristics (F2)	Personal characteristics (F3)	Administrative control (F4)
RIF / Expert	Process complexity (F11)	Maintainability/ Accessibility (F12)	Human machine interface (F13)	Time pressure (F21)	Competence of area technician (F31)	Work permit (F41)
E1	(2/3,4/3,4/3,2)	(1/3,2/3,2/3,4/3)	(1,5/3,5/3,7/3)	(1/3,4/3,4/3,5/3)	(1/3,1,1,5/3)	(2/3,2/3,2/3,2/3)
E2	(1/3,1/3,1/3,1/3)	(1/3,4/3,4/3,7/3)	(1,1,1,1)	(5/3,5/3,5/3,5/3)	(1/3,2/3,2/3,1)	(1/3,1/3,2/3,2/3)
E3	(1,1,4/3,4/3)	(1/3,1/3,2/3,2/3)	(5/3,7/3,7/3,8/3)	(1,2,2,8/3)	(1,4/3,4/3,5/3)	(1/3,4/3,4/3,7/3)
E4	(2/3,1,1,2)	(4/3,5/3,2,7/3)	(1,2,2,7/3)	(2/3,4/3,4/3,5/3)	(1/3,1/3,4/3,4/3)	(1,5/3,5/3,2)
E5	(1,1,4/3,4/3)	(2/3,2/3,1,1)	(2/3,1,5/3,2)	(4/3,5/3,7/3,8/3)	(4/3,4/3,4/3,4/3)	(2/3,4/3,5/3,7/3)
Aggregation	(0.696,0.940, 1.047,1.407)	(0.552,0.930, 1.095,1.566)	(1.079,1.607, 1.696,2.046)	(0.950,1.576, 1.664,1.983)	(0.589,0.913, 1.088,1.411)	(0.587,0.978, 1.097,1.430)

In accordance with the pair-wise comparison criterion (see Table.3), the comparisons among RIFs in the subordinate group of RIF-Index hierarchy are conducted. Table.11 presents the pair-wise comparisons among RIFs in the RIF group of "characteristics of the technical system (F1)". The aggregation of TFN scales is performed in accordance with Eq. (6). In the same way, other aggregated scales of RIFs can also be obtained.

Further, the aggregated scales are defuzzified into crisp values by Eq. (7). On this basis, the corresponding judgment matrix can be established by Eq. (8). Eq. (14) presents the judgment matrix J_{e2} for RIFs in the RIF group of "characteristics of the technical system (F1)". The consistency ratio is 0.0, which is less than 0.1. Thus, the judgment matrix meets the consistency requirement.

In final, the priority weight of each RIF in the RIF-Index hierarchy can be calculated by Eq. (10). The fuzzy aggregated score of each RIF is defuzzified into the crisp value by Eq. (5). Priority weights and quantitative status for all RIFs are summarized in Table.12.

Table 11

Fuzzy scales of "characteristics of the technical system (F1)"

Characteristics of the technical system (F1)		Process complexity (F11)	Maintainability/ Accessibility (F12)	HMI (F13)
Process complexity (F11)	E1	1.000	(1/2, 1/2, 1/2, 1/2)	(1/2, 1/2, 1, 1)
	E2		(2, 2, 2, 2)	(2, 2, 2, 2)
	E3		(1, 1, 1, 1)	(1/2,1/2,1/2,1/2)
	E4		(1/2, 1/2, 1, 1)	(1, 1, 1, 1)
	E5		(1/2, 1/2, 1, 1)	(1/2, 1/2, 1/2, 1/2)
	Aggregation		(0.933, 0.933,1.087, 1.087)	(0.927, 0.927, 1.067, 1.067)
Maintainability/ Accessibility (F12)	E1		1.000	(1, 1, 1, 1)
	E2			(1/2, 1/2, 1, 1)
	E3			(1, 1, 3, 3)
	E4			(1/2, 1/2, 1/2, 1/2)
	E5			(1/2, 1/2, 1, 1)
	Aggregation			(0.732, 0.732, 1.283, 1.283)
HMI (F13)	E1			1.000
	E2			
	E3			
	E4			
	E5			
	Aggregation			

$$J_{e2} = \begin{bmatrix} 1 & 1.0098 & 0.9971 \\ 1/1.0098 & 1 & 1.0073 \\ 1/0.9971 & 1/1.0073 & 1 \end{bmatrix} \tag{14}$$

Table 12

Priority weights and quantitative status for all RIFs

Basic event	Basic event/RIF group	Basic event/RIF	Q_i	w_i
BE0	F_1 Characteristics of the technical system	F_{11} Process complexity	1.2041	0.0714
		F_{12} Maintainability/accessibility	1.1717	0.0712
		F_{13} Human Machine Interface (HMI)	1.6534	0.0711
	F_2 Task characteristics	F_{21} Time pressure	1.6031	0.3603
	F_3 Personal characteristics	F_{31} Competence of area technician	1.1592	0.3552
	F_4 Administrative control	F_{41} Work permit	1.1780	0.0708
BE11	F_1 Organizational factors	F_{11} Program for self-control	---	---
BE12	F_1 Organizational factors	F_{11} Work practice	1.6135	0.3857
	F_2 Task characteristics	F_{21} Time pressure	1.6203	0.3831
	F_3 Administrative control	F_{31} Work permit	1.2241	0.2312
BE13	F_1 Characteristics of the technical system	F_{11} Human Machine Interface (HMI)	1.3018	0.0643
		F_{12} Maintainability/accessibility	1.0794	0.0645
	F_2 Task characteristics	F_{21} Time pressure	1.3057	0.3363
	F_3 Personal characteristics	F_{31} Competence of area technician	1.1019	0.3362
	F_4 Administrative control	F_{41} Procedures for self-control	1.0924	0.0657
		F_{42} Work permit	1.0835	0.1130
BE21	F_1 Organizational factors	F_{11} Program for 3rd party control	---	---
BE22	F_1 Organizational factors	F_{11} Work practice	2.3930	0.3844
	F_2 Task characteristics	F_{21} Time pressure	2.2678	0.3843
	F_3 Administrative control	F_{31} Work permit	1.3575	0.2313
BE23	F_1 Characteristics of the technical system	F_{11} Human Machine Interface (HMI)	2.0262	0.0666
		F_{12} Maintainability/accessibility	1.4321	0.0673
	F_2 Task characteristics	F_{21} Time pressure	2.3296	0.3363
	F_3 Personal characteristics	F_{31} Competence of area technician	1.0035	0.3337
	F_4 Administrative control	F_{41} Procedures for self-control	1.0129	0.0658
		F_{42} Work permit	1.0503	0.1303

3.5 Quantification of specific frequencies/probabilities phase

The industry average frequencies/probabilities for basic events are adjusted in accordance with Eq. (11) and Eq. (12). The frequency/probability correction coefficient integrates the priority weights and measurement of the status of RIFs. The results from the quantitative analysis of the release frequency due to valve(s) in wrong position after maintenance are shown in Table.13. It can be seen that the release frequency is 0.028 per year by use of the industry average data while the corresponding specific frequency allowing for conditions of the identified RIFs is 0.045 per year. This indicates an increase in the release frequency by 62% by use of the revised input data. Thus, these revised frequencies/probabilities result in an updated risk picture, which incorporates both technical and operational conditions.

Table 13

Results from the quantitative analysis of the release frequency

Event	P_{ave}	γ	$P_{spec.}$
f(BE0) Frequency of valves in wrong position after inspection per year	0.084	1.360	0.114
P(BE1) Probability of failure to reveal failure by self-control	0.340	1.168	0.397
P(BE2) Probability of failure to reveal failure by 3rd party control	1.000	1.000	1.000
f Release frequency from the selected scenario per year	0.028	1.620	0.045

4. Discussion of the methodology

4.1 Comparison between the proposed methodology and other models

The methodology is intended to represent a generalization and improvement of the BORA-Release methodology. The comparison of results between the current study and the BORA study from the quantitative analysis of the release frequency due to valve(s) in wrong position after maintenance is presented in Table. 14. The release frequency obtained from both the current study and the BORA study is higher than the industry average data as the revised frequencies/probabilities take installation specific conditions of the identified RIFs into account. In contrast to the release frequency calculated by the BORA study, there is a slight increase in the proposed methodology as more thorough improvement studies on both the qualitative and quantitative aspects of the BORA model are performed.

In the qualitative aspects, a new RIF-Index hierarchy is developed to identify and structure all relevant RIFs for each initiating event in the event trees and each basic event in the fault trees. The RIF-Index hierarchy can decompose RIFs into adequate details in which RIFs can better be analyzed and efficiently assessed. In addition, the RIF-Index hierarchy can also assess the relative importance of RIF groups, such as personal characteristic, task characteristic, characteristic of the technical system, etc. Thus, the RIF-Index hierarchy can be more targeted to relevant risk reducing measures. In contrast to the one-level structure of RIFs in the BORA modelling, the RIF-Index hierarchy indicates the key elements on how installation specific conditions of technical, human, operational, and organizational RIFs influence the barrier performance. These key elements include the identification of RIFs, hierarchy construction of the identified diverse RIFs, assessment of status of RIFs at the bottom level and assessment of the importance degree of RIFs by AHP.

In the quantitative aspects, the improvement focuses on the scoring and weighting process for RIFs. At first, fuzzy logic is introduced for dealing with vague or not well-defined information. Experts can assess the status of RIFs by using the exact scores, natural language, a range of numerical values or a fuzzy number. The fuzzy logic efficiently transforms the fuzzy information into useful data, and thus, the uncertainty of experts' expression and judgment can be overcome. The fuzzy scoring criterion for assessing the status of RIFs can be developed in accordance with the fuzzy numbers and MFs. Then, the fuzzy AHP approach, which is the multiple criteria decision-making method (MCDM), is applied to prioritize RIFs based on a crisp 9-point scale. Fuzzy AHP approach properly reflects the vagueness associated with human thoughts and helps to choose a best decision-making strategy using a weighting process through pair-wise comparisons (Beşikçi et al., 2016). In particular, the consistency of the fuzzy pair-wise comparison is analyzed and addressed to measure how consistent the judgments have been relative to large samples of purely random judgments.

Table 14

Comparison results of the release frequency between the current study and BORA study

Event	Probabilities/frequencies		
	Industry average	The current study	BORA study
f(BE0) Frequency of valves in wrong position after inspection per year	0.084	0.114	0.108
P(BE1) Probability of failure to reveal failure by self-control	0.340	0.397	0.385
P(BE2) Probability of failure to reveal failure by 3rd party control	1.000	1.000	1.000
f Release frequency from the selected scenario per year	0.028	0.045	0.041

In Table 14, it can also be noted that in contrast to the release frequency calculated by the BORA study, the result of the proposed methodology is not too different. Nonetheless, this is not due to the limitation of the proposed methodology. This is mainly because that all the fuzzy measurements with respect to the assignment of weights and scores of RIFs in the current study are on the basis of the information provided by the BORA project. As a rule of thumb, the more detailed models are, the more credible are the results. It is certain that in contrast to the BORA method, the proposed methodology with increased knowledge and information in the both qualitative and quantitative aspects can be expected to reduce the uncertainties and subjectivities arising in the quantitative analysis of RIFs to a large extent.

It is worth noting that the Risk_OMT model (Vinnem et al., 2012) is also a generalization and improvement of the BORA model. More emphases of the Risk_OMT model are placed on how activities are performed and what influences critical activities. Also, the hierarchy of RIFs is considered as an improvement. The RIF structure is restricted to one-to-many relationships and RIFs in the level 2 can only affect basic events through RIFs in the level 1. The complexity of the model can therefore be reduced to a large extent. The differentiation between mistakes, violations and slips/lapses with distinctions between RIFs that influence on these error types is also an important refinement of the model. A detailed comparison between the Risk_OMT model and the proposed methodology can be further studied.

4.2 Fuzzy measurement and pair-wise comparison of RIFs

Measurement of the status of RIFs and the pair-wise comparison of each RIF in the subordinate group of RIF-Index hierarchy are accomplished by use of expert judgment. In a typical expert judgment method, experts are asked to provide precise numerical values. However, experts sometimes find that it is difficult to give precise numerical values as the judgments are beyond their capabilities or there is a lack of sufficient information and data. This process therefore involves certain amount of uncertainty and subjectivity. In this study, the fuzzy logic is introduced for capturing and converting experts' fuzzy information as fuzzy logic specializes in dealing with vague or not well-defined information. Experts can provide a precise value, a possible range of numerical values, a fuzzy number, etc. Experts can also provide absent values if they fail to make the judgment. In accordance with the process of fuzzification, fuzzy aggregation and defuzzification, problems of fuzzy factors in the operational risk can be solved.

4.3 Scoring criterion and scoring of RIF

Scoring criterion lays the foundation for assessing the status of RIFs. In this study, the six-point scale is adapted from the TTS project as the scoring criterion. Each RIF can be assigned a separate score on the scale from A to F, where scores (A, C and F) represent the best standard, average standard and worst practice in the industry respectively. Some RIFs can also be assigned a score that is distributed between two scores of A-F. This distribution reflects the real variation in observed scores. However, TTS project focuses on technical systems and is only relevant to limited RIFs. Thus, alternative scoring criteria, which are suitable for the assessment of each RIF in the specific RIF group, should be further developed.

With respect to the transformation of qualitative scoring to a quantitative status, the principle is similar to the I-RISK project and BORA project. The upper and lower limits for the industry average probability are determined by expert judgment. Then, the status scores (A, C, F) determined by Eq. (1) act as anchor values while a linear relationship is assumed between the neighboring anchor values. Other types of relationship between the neighboring anchor values can also be assumed. It can be seen that the determination of anchor values is of great importance as the final results are dependent on these values. Thus, the upper and lower limits should be determined carefully. The process of the determination is probably better accomplished by use of expert judgment together with the industry statistical data. Fig.12 shows the MFs of the scoring criterion with different anchor values. It can be seen that a wide range between the quantitative score A and F implies the major changes in the risk level while a small range implies the minor ones. Fig.12 also indicates that the risk improvement potential is less than the risk worsening potential as the offshore industry has been at a lower risk level for many years.

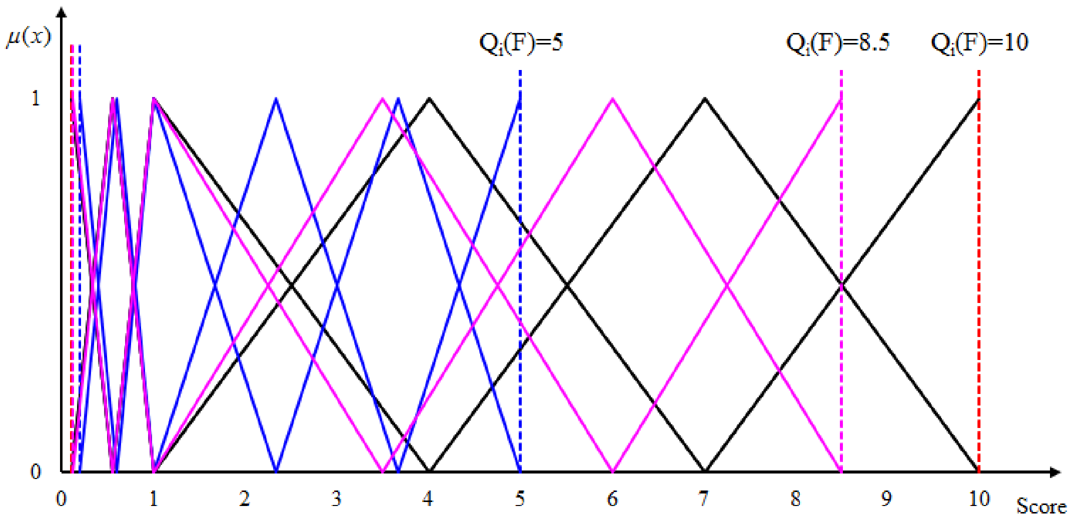

Fig.12. MFs of the scoring criterion with different anchor values

4.4 Human reliability data

With respect to the measurement of industry average frequencies/probabilities, it implies use of generic databases in addition to extraction of installation specific information regarding operational conditions and experience from surveillance of operational activities. The critical aspect is that there is a lack of relevant human reliability data, which can be used as basic probabilities for all failures that are modelled. Thus, some expert judgment is necessary in order to generate relevant data. Nonetheless, great efforts still need to be made for collection of relevant human reliability data to support QRAs. Further research on this field is recommended. A more thorough investigation and discussion on human reliability data is provided by Vinnem et al. (Vinnem et al., 2012).

4.5 Usefulness of the methodology

The purpose of the proposed risk modelling methodology has been to provide a solution for quantification of specific factors regarding to technical, human, operational and organizational RIFs into modelling of risk associated with hydrocarbon leaks on offshore installations. The methodology can then be used to identify critical RIFs and study the effects of both technical and non-technical factors on the risk, and thus provide the support for the decision making. The methodology can also be used to evaluate the relative importance of the safety barriers and the effect of changes with respect to risk control, as well as analyze the effects of possible risk reducing measures.

The intention is that the proposed methodology shall be usable when conducting QRA studies of maintenance work on offshore installations. Thus, it is required that the installation specific data can be used in the methodology by conducting the RIF audits, structured interviews of key personnel, surveys or expert workshops. It is further required that the work involved in the methodology is not prohibitive.

The case study has demonstrated that the methodology is practical and can be successfully applied to various offshore installations. Especially, the methodology integrates the industry average data with the installation specific conditions for barrier analysis.

5. Conclusions and future work

The study is primarily developed for loss of containment incidents due to maintenance work on major process equipment on offshore petroleum installations. This is the application domain for this study. The Norwegian offshore petroleum industry has had a high fraction of such incidents for ten years, without significant improvement (Vinnem et al., 2012). In addition, some incidents and accidents indicate the potentially catastrophic consequences induced by human and organizational errors.

In view of this, the study presents a new risk modelling methodology, which is a generalization and improvement of the relatively coarse BORA-Release methodology, aiming to better reflect and analyze how specific conditions of technical, operational, human and organizational RIFs influence the barrier performance for offshore maintenance work. Central elements in the proposed methodology are use of techniques with respect to fuzzy logic, barrier block diagrams/event trees, fault trees and RIF-Index hierarchy. Particular emphasis is placed on the quantitative assessment of the priority weights and the status of RIFs, by which the industry average frequencies/probabilities can be revised.

There are five important aspects deserving to be addressed in the proposed methodology. (1) Expert judgment is employed for assessing the status as well as the importance degree of each RIF. Different experts may make different judgments with respect to their different competence and background. Thus, a scoring criterion with four indices including professional position, service time, education level and age is introduced in the determination of experts' priority weights. The fact that different indices have different influence is taken into account and different indices are weighted. All of these steps try to make the expert judgment more comprehensive and reasonable. (2) The fuzzy logic is introduced for capturing and converting experts' fuzzy information and subjective judgment. It is recognized that the fuzzy expression is more appropriate for human thinking as there involves certain amount of uncertainty and subjectivity with respect to judgments. An improved fuzzy scoring criterion, which lays the foundation for assessing the status of RIFs, is established correspondingly. (3) A new RIF-Index hierarchy is developed to identify and structure diverse RIFs for all the initiating events and basic events. In contrast to the one-level structure of RIFs in the BORA modelling, RIF-Index hierarchy can decompose RIFs into adequate details in which RIFs can better be analyzed and efficiently assessed. It should be noted that RIF-Index hierarchy can also identify the relative importance among RIF groups, such as personal characteristics, characteristics of the technical system, organizational factors, etc. Thus, it can be more targeted to relevant risk reducing measures. (4) A traditional fuzzy AHP method has the complicated fuzzy operation and is lack of proven techniques to address fuzzy consistency and fuzzy priority vector. A modified fuzzy AHP method, in which the consistency of the judgment matrix is analyzed and addressed, is proposed and used to assess the importance degree of RIFs. The priority weight of each RIF in the RIF-Index hierarchy can be obtained through the arithmetic averaging method. (5) A new formula regarding to fuzzy frequency/probability correction coefficient is developed for revising the industry average frequencies/probabilities. It takes the specific conditions of technical, human, operational and organizational RIFs into account and can be used to identify critical RIFs as well as evaluate the effect of risk reducing measures.

The case study with respect to the specific hydrocarbon release incident for selected systems and activities on the offshore installation is presented. It has been demonstrated that the proposed risk modelling methodology is an effective tool for analyzing the failure of safety barriers, and reflecting how specific factors with respect to technical, human, operational and organizational RIFs influence the barrier performance. The methodology can also be successfully applied to various offshore installations.

There is still a need for further research with respect to some key issues in the proposed risk modelling methodology, as follows. (1) More suitable and specific scoring criterion for assessment of the RIFs status should be developed in order to obtain credible score for each RIF. In addition, more research work should be carried out on the determination of the fixed ratios (P_h / P_a , P_l / P_a), which describe the variations caused by different status of RIFs. (2) A new methodology for prioritizing critical RIFs for each basic event should be developed in order to keep the operational risk analysis in a manageable size. Normally, maximum six RIFs (the most important ones) for each basic event are recommended (Aven et al., 2006b). (3) An improved RIF-Index hierarchy should be developed for analyzing the interaction effects among RIFs. (4) Several aspects of dependencies between barriers in a wide sense that need to be addressed and further studied, such as dependencies among RIFs, common barrier elements (M&O type) for several barrier functions, common barrier influence factors for several barrier element failures, etc. (5) The applicability of the proposed risk modelling methodology on consequence reducing barriers should be studied with the purpose to test whether the proposed methodology is suitable for an overall QRA or not.

Declaration of conflicting interests

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Nomenclature

Abbreviations

AHP	Analytic hierarchy process
BORA	Barrier and Operational Risk Analysis
CR	Consistency ratio
MCDM	Multiple criteria decision-making method
MF	Membership function
ORIM	Organizational Risk Influence Model
OTS	Operational Conditional Safety
QRAs	Quantitative risk analyses
RI	Random index
RIF	Risk influencing factors
Risk_OMT	Risk modelling-Integration of Organizational, Human and Technical factors
TFN	Trapezoidal fuzzy number
TTS	Technical Condition Safety

Variables

a_{ij}^{*}	The fuzzy aggregated scales of the *i*th RIF comparing to the *j*th RIF
a_{ijm}^{*}	The fuzzy scales of the *i*th RIF comparing to the *j*th RIF by the *m*th expert
$P_{ave}(\mathrm{A})$	The industry average frequency/probability of occurrence of event A
P_a	The industry average probability
P_h	The upper limit for the industry average probability

P_l	The lower limit for the industry average probability
p_m	The priority weight of the *m*th expert
p_r	The priority weight of the expert who fails to assess the RIF
$P_{spec.}(\mathrm{A})$	The specific frequency/probability of occurrence of event A
Q_i	A measure of the status of RIF no *i*
Q_i^*	The fuzzy aggregated value of the status of RIF no *i*
Q_{im}^*	The fuzzy values of the status of RIF no *i* measured by the *m*th expert
s	The score of RIF no *i*
$\mu_{M^*}(x)$	Membership function of M^*
$\mu_{Q_i^*}(v_i)$	The MF of the centre of the *i*th fuzzy set of Q_i^*
v_i	The centre of the *i*th fuzzy set of Q_i^*
w_i	The priority weight of the *i*th RIF
$w_{group}^{(k)}$	The priority weight of the RIF group in the *k*th upper group
$\lambda_{\max}$	The maximum eigenvalue of the judgment matrix
$\gamma(\mathrm{A})$	The correction coefficient of the industry average frequency/probability of occurrence of event A
$\otimes$	The fuzzy multiplication operator
$\oplus$	The fuzzy plus operator

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