AN OFFSHORE SAFETY ASSESSMENT FRAMEWORK USING FUZZY REASONING AND EVIDENTIAL SYNTHSIS APPROACHES

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Abstract. The operation of tandem loading/offloading is associated with a high level of uncertainty because it usually operates in a dynamic environment in which both technical and human and organisational malfunctions may cause possible accidents. There is a lack of approaches for dealing with uncertainty and vagueness in expert judgements in assessment of safety of the operations. This paper proposes a framework for modelling the safety of offshore and marine engineering systems using fuzzy reasoning and evidential synthesis approaches. The proposed method is capable of dealing with uncertainties including ignorance and vagueness, which traditional methods or frameworks for multiple criteria decision analysis such as expected utility theory cannot handle. A case study of the collision risk between a Floating Production, Storage and Offloading unit (FPSO) and a shuttle tanker due to technical failure during a tandem offloading operation is used to illustrate the application of the proposed model.

Key Words. Safety assessment, fuzzy reasoning, evidential reasoning, uncertainty, decision making method, FPSO

1. Introduction

A Floating Production, Storage and Offloading (FPSO) unit is one of the most popular floating systems used by the offshore oil and gas industry. An FPSO is similar in appearance to a ship but is designed quite differently. It carries on board all the necessary production and processing facilities normally associated with a fixed oil and gas platform, with the storage tanks for the crude oil recovered from the wells on the seabed below. FPSOs with ship-shape hulls accounted for more than half of the floating production systems worldwide. Currently, there are 15 FPSO and FPS units operating on the UK Continental Shelf (UKCS) and 70 worldwide. In the UK, crude oil is normally transported to shore using shuttle tankers specially designed for the harsh weather conditions found offshore Britain. Shuttle tankers equipped with a bow-loading system are connected to FPSOs or storage facilities by mooring hawser and loading hose through which cargo is off-loaded. In order to keep the tanker on station at a safe distance away from the FPSO or storage facility while loading, shuttle tankers are equipped with emergency shut down and dynamic positioning (DP) systems. The process of loading from the stern of the FPSO to the bow of the shuttle tanker is known as "tandem loading" [26].

Tandem loading/offloading is a complex marine operation. It is with high risk due to the close proximity required between the two large vessels. Problems include excessive motion of the shuttle tanker as it follows the FPSO, DP operator error, and abnormal interaction between the DP and power management systems (PMS) on board each vessel. The consequences of these problems vary from excessive fuel consumption to incidents that may cause personnel loss, environment pollution or damage to the vessel. In the North Sea, for instance, several recent contact incidents between FPSO/FSU (Floating Storage Unit) and shuttle tanker have demonstrated a high possibility of contact between vessels in tandem offloading [2][9]:

- Emerald FSU: Impact by shuttle tanker Navion Clipper, UK, 28.02.1996
- Gryphon FPSO: Impact by shuttle tanker Futura, 26.07.1997
- Captain FPSO: Impact by shuttle tanker Aberdeen, 12.08.1997
- Schiehallion FPSO: Impact by shuttle tanker Nordic Savonita, 25.09.1998
- Norne FPSO: Impact by shuttle tanker Knock Salliea, 05.03.2000

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As a result of the consequences of the accidents, the UK Health and Safety Executive (HSE) has set a target to reduce shuttle tanker "loss of station keeping events" by 25 percent in the near future, against a baseline of seven events per shuttle tanker per year. In the UK, all operating companies must prepare a Safety Case to demonstrate that the company has in place safety management systems; has identified hazards and reduced the associated risks to as low as is reasonably practicable; has put management controls in place; has a safe refuge for personnel in the event of an emergency; and has made provisions for safe evacuation and rescue [25].

To reduce the likely occurrence of accidents, it is essential that scenarios involving the potential loss of operational control are assessed at an early stage in the design of new facilities, in order to optimise technical and operational solutions. However, the operation of tandem loading/offloading is associated with a high level of uncertainty because it usually operates in a changing environment in which both technical and human and organisational malfunctions may contribute to a range of possible accidents. An efficient and effective safety assessment method, therefore, is needed to model the system safety of offshore and marine engineering systems. Particularly in the safety assessment of FPSOs, there is a need to understand the operational safety levels of FPSOs in relation to different types of failures, so that preventive measures can be taken at the early stages of system design [5][11][12].

Traditional ship/platform collision risk models may not be effective for tandem offloading operations. They often model the risk of a system in terms of the probability of occurrence of each hazard and its possible consequences. This brings difficulties in circumstances where there is a lack of information/past experience, or there is ill-defined situation. Furthermore, offshore quantitative risk analyses generally focus more on technical aspects, and less so on operational aspects. This leads to a hardware-centred risk control approach, which may not be effective in the face of risks in complex marine operations. There is therefore a clear need to develop a proper collision risk model in the first place for FPSO-tanker offloading, and to analyse the risk involved in this safety-critical operation.

A novel safety assessment framework for collision risk analysis for FPSO and tanker offloading operations is presented in this paper. The collision risk caused by various technical malfunctions is modelled by using fuzzy reasoning and evidential synthesis approaches. This framework concentrates on the risk evaluation of the major hazards threatening the FPSO and provides a means for screening the safety implications, which would influence the development of the early design concept. This will be suitable for carrying out safety assessment associated with incomplete safety information in the initial design stages or a system with high level of innovation.

In the following, Section 2 presents the offshore safety considerations and safety assessment methods. Section 3 describes the proposed novel safety framework using fuzzy reasoning and evidential synthesis approaches. A case study of collision risk assessments for FPSO-tanker during tandem offloading operation caused by various technical malfunctions is described in Section 4. Section 5 provides the conclusions of the paper.

2. Offshore safety consideration and safety assessment methods

In the maritime industry, quite a few recent serious accidents including the Capsize of the Herald of Free Enterprise and the Exxon Valdez tragedy have shocked the public and attracted great attention to safety. The studies on how similar accidents may be prevented have been actively carried out at both the national and international levels [18]. After Lord Carver's report on the investigation of the capsize of the Herald of Free Enterprise was published in 1992, the UK Maritime & Coastguard Agency (MCA) quickly responded and in 1993 proposed to the International Maritime Organization (IMO) that formal safety assessment should be applied to ships to ensure a strategic control of safety and pollution prevention [11][12][13]. The guidelines for the application of formal safety assessment have been recently approved for rule/regulation making purposes by the IMO. At the moment, one of the major concerns on the practical application of formal ship safety assessment is associated with the simplification of the approach and the study of trial test cases. These are used to produce more detailed guidelines to facilitate its application while the human and organisational elements that significantly influence quality, safety, etc., also need to be addressed in detail accordingly. In the UK offshore industry, the UK Offshore Operators Association (UKOOA) recently published the industrial guidelines on a framework for risk related decision support [16]. The framework could be usefully applied to a wide range of situations. In particular, it provides a sound basis for evaluating the various options that need to be considered at the feasibility and concept selection stages of a project. It can also be combined with other formal decision making aids such as Analytical Hierarchy Processing (AHP) [16].

As far as FPSO safety is concerned, the HSE recently completed a report to present accident and incident statistics to compare FPSOs' records with those of other fixed installations on the UKCS between 1996 and 2002 (see Table 1) [5]. It revealed that FPSO related incidents account for about 20% of the total incidents. The results show that, broadly, 33% of these "FPSO specific" incidents were attributed to risers/swivels or turrets, 22% arise from offloading systems, 15% relate to adverse weather including wave loading and motion related incidents, 11% arise from collision, potential collision and stability incidents, 10% arise from marine systems, and 9% arise from mooring and station keeping incidents. The total population engaged in offshore operations has decreased from over 30,000 people in the early 1990's to around 23,000 in 2002. In contrast, the FPSO/FSU population has increased to represent about 5% of the total.

Table1 1: Analysis of FPSO/FSU Incident Data 1996-2002

	96/97	97/98	98/99	99/00	00/01	01/02	Total	%
Riser/Tuuret/Swivel	5	3	4	7	6	1	26	33
Vessel SW/COW/Vent	2	1	0	2	1	2	8	10
Offloading System	2	1	4	4	2	4	17	22
Moorings/DP	0	0	1	2	1	3	7	9
Collision/Stability	0	5	2	2	0	0	9	11
Motion related Incident	2	0	4	5	0	1	12	15
FPSO/FSU Specific	11	10	15	22	10	11	79	
Total Incidents	46	78	78	77	81	62	422	
%FPSO Incidents	24	13	19	29	12	18	19	

Source: [5]

In recent years (1999-2002) the incident rate shows a downward trend for both FPSO and all installation types. FPSOs now have the same incident rate as for other installations; whilst in earlier years the rate of dangerous occurrences on FPSOs was higher. In summary, HSE is encouraged by the improved performance for FPSOs, demonstrating that lessons have been learnt as the new technology is introduced, and that the FPSO has a similar incident rate to other installations.

Although FPSOs are becoming more common, operational safety performance may still be considered somewhat unproven, especially when compared to fixed installations. Furthermore, floating installations are more dependent on the continued operation of some of the marine control systems, during a critical situation. There is accordingly a need to understand the aspects of operational safety for FPSOs, in order to enable a proactive approach to safety, particularly in the following areas:

- Turret operations and flexible risers
- Simultaneous marine and production activities
- Vessel movement/weather exposure
- Production, ballasting and offloading

In the above areas, accidents are often initiated by errors induced by human and organisational factors (HOF), technical (design) failures or a combination of both. To reduce the risk, some predictive risk and reliability techniques have been used in the North Sea offshore industry for almost 20 years, and have contributed to the reduction of the incidence rate of severe accidents. These techniques have traditionally focused more on technical aspects of design, construction and operation, than on human and organisational aspects. Some efforts have also been devoted to modelling operational safety. These models are mainly descriptive, not predictive, and are thus not very effective in determining how to prevent accidents.

The analysis techniques that are being applied include the following [18][19]:

- Task analysis
- Action error mode analysis
- Fault tree analysis
- Event tree analysis
- Risk influencing factor analysis

Apart from the above traditional methods, many authors also proposed different models based on up-to-date mathematical and control theories such as non-probabilistic theories, fuzzy control theory, and

Dempster-Shafer theory of evidence [1][21]. Coolen & Newby, for instance, studied Bayesian modelling with imprecise prior probabilities [4]. An extension of the standard Bayesian approach based on the theory of imprecise probabilities and intervals of measures was developed to reflect expert opinions using prior distributions. The highlight of their work is at the synthesis approach of the opinions of several experts. Karwowski & Mital investigated modelling of risk using approximate reasoning and fuzzy sets [7]. Linguistic variables were used to assess the risk of an event and hazardous events were modelled using fuzzy set theory [8]. Fuzzy set theory was used for uncertainty analysis [3]. Regardless of their strengths none of these approaches can systematically measure both qualitative and quantitative factors, and structure complex problems in the circumstances of lack of information and past experience, or ill-defined situation with a large number of criteria, attributes and alternatives. Therefore, based on the literature review, this paper explores the potential application of fuzzy reasoning and evidential synthesis mechanisms, to the uncertainty analysis of offshore safety assessment based on imprecise and uncertain information obtained from a panel of experts.

3. Offshore safety assessment framework

The architecture of the offshore safety assessment framework is depicted in Figure 1. The proposed system consists of four principal components: fuzzification module, knowledge base module, fuzzy inference module, and synthesis module. As can be seen, fuzzy reasoning is the key mechanism in the proposed system. In fact, fuzzy reasoning mimics human reasoning procedure by using fuzzy set theory and fuzzy logic in an environment of uncertainty and imprecision [23][24]. It is based on fuzzy expert system implying a collection of fuzzy membership functions and rules. The fuzzification module performs a scale mapping that changes the range of values of input variables into corresponding universe of discourse, and fuzzification that converts non-fuzzy (crisp) input data into suitable linguistic values. The knowledge base consists of database and fuzzy rule base. The database is a set of fuzzy membership functions. The fuzzy rule base consists of a set of linguistic fuzzy associative rules written in the IF-THEN form. The fuzzy associative rules help in the decision making process. After the approximate reasoning module is triggered with rules from the fuzzy rule base, it can infer the fuzzy output from fuzzified inputs. The fuzzy output is then taken as input of synthesis module, which is based on an evidential reasoning mechanism. The synthesis module is designed to deal with multi-attributes and multi-experts decision making problems. The details of the proposed assessment framework are depicted in the following sections.

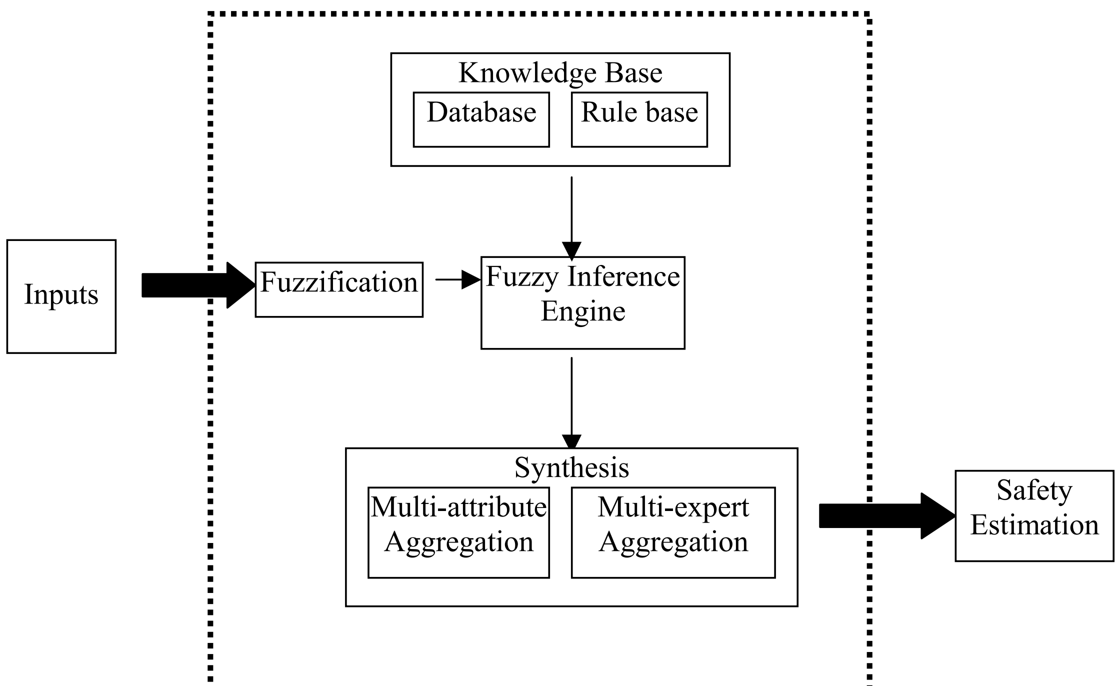

Figure 1 Offshore safety assessment framework

Fuzzification module

At the early concept design stages, a panel of safety experts is asked to identify a set of criteria for safety assessment. Based on the consensus of a brainstorming session, some attributes are identified to assess the safety level of a maritime or offshore system on a subjective basis e.g. *failure rate, consequence severity and failure consequence probability* [14][15].

- ***Failure rate*** refers to the failure frequencies in a certain time period, which directly represents the numbers of failures anticipated during the design life span of a particular system or an item. To estimate ***failure rate***, Seven linguistic variables are used in this research to describe failure rate: "*very low*", "*low*", *"reasonably low"* "*average*", *"reasonably frequent",* "*frequent*" and "*highly frequent*".
- ***Consequence severity*** refers to the magnitude of possible consequences, which is ranked according to the severity of the failure effects. Five linguistic variables are used to describe consequence severity: "*negligible*", "*marginal*", "*moderate*", *"critical"* and "*catastrophic*" to estimate consequence severity.
- ***Failure consequence probability*** refers to the occurrence likelihood of the accident, which may be estimated as *"Highly unlikely", "unlikely", "reasonably unlikely", "likely", "reasonably likely", "highly likely", and "definite".*

Four levels of linguistic variables i.e. *"poor", "fair", "average", and "good"* which are defined as safety expressions are used for modelling ***safety estimate***. It is worth noting that a reasonable estimation of the value of each attribute must be based both on the hard statistic data, and the soft data from experts' subjective judgements based on their direct/indirect operational experiences. To handle those hard and soft data, the attributes must be expressed with fuzzy values to characterise their uncertainty. If *L, C, E, and S* represent the fuzzy sets of ***failure rate***, ***consequence severity,*** ***failure consequence probability***, and ***safety estimate*** respectively, the linguistic variables of the fuzzy model are:

$$L = \{L_1, ..., L_i, ..., L_7\}$$

$$C = \{C_1, ..., C_j, ..., C_5\}$$

$$E = \{E_1, ..., E_p, ..., E_7\}$$

$$S = \{S_1, ..., S_q, ..., S_4\}$$

where L_i, C_j, and E_q are inputs of failure rate, consequence severity and failure consequence probability respectively, whilst S_q is the level of safety estimation:

$$L_i = \{x, \mu_{L_i}(x) \big| x \in L_i \subset U_1\} \qquad i = 1, ..., 7$$

$$C_j = \{y, \mu_{C_j}(y) \big| y \in C_j \subset U_2\} \qquad j = 1, ..., 5$$

$$E_p = \{z, \mu_{E_p}(z) \big| z \in E_p \subset U_3\} \qquad p = 1, ..., 7$$

$$S_q = \{\zeta, \mu_{S_q}(\zeta) \big| \zeta \in S_q \subset V\} \qquad q = 1, ..., 4$$

Knowledge base

The knowledge base stores the available knowledge about the problem. It acts as the repository of the problem specific knowledge on which the inference process reasons from an observed input to an associated output. In this research, the knowledge base consists of two parts: database and rule base. The database is a set of membership functions. Linguistic variables are described by different types of membership functions as decided according to the situation of the case of interest. In this research the fuzzy membership function is of the following four forms:

- A single deterministic value with 100 % certainty.
- A closed interval defined by an equally likely range.
- A triangular distribution defined by a most likely value, with lower and upper least likely values.
- A trapezoidal distribution defined by a most likely range, with lower and upper least likely value.

The selection of the form of membership function by each expert is dependent upon subjective judgment based on the level of ambiguity and uncertainty associated with the case as perceived by a particular expert. Some examples of attributes being represented linguistically could be*: the failure rate is very low, the consequence severity is catastrophic, the failure consequence probability is frequent.* The fuzzy membership functions are generated utilising the linguistic categories identified in the knowledge acquisition and consisting of a set of overlapping curves. Figure 2 shows an example of three fuzzy partitions comprised by seven, five, and seven membership functions respectively.

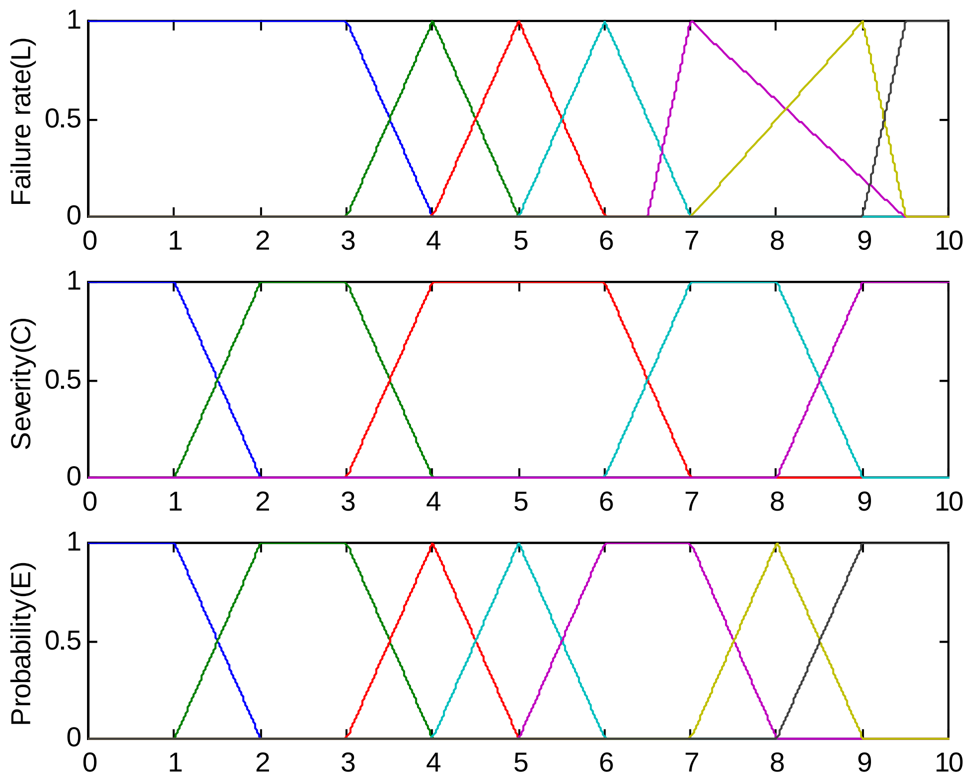

Figure 2 Fuzzy set definition for the three input variables

A rule base is a set of linguistic rules written in the IF-THEN form and joined by the fuzzy operators. Multiple rules can be fired simultaneously for the input. For example, the k^{th} rule can be explained as:

R^k : IF ***failure rate*** is frequent AND ***consequence severity*** is catastrophic AND ***failure consequence probability*** is likely, THEN ***safety estimate*** is poor.

Rule base can be presented by different structures. The form of the list of rules is the most common one, a sample of the 245 rules (seven membership functions in L, five membership functions in C, and seven membership functions in E produce $7 \times 5 \times 7$ =245 rules) in the rule base that are used in this study can be seen in [15].

Fuzzy inference engine

The inference engine is designed to derive the fuzzy outputs from the inputs fuzzy sets according to the relation defined through fuzzy rules. The Mamdani Min Implication operator is used in this study [10]. Specifically, a fuzzy *IF-THEN* rule is interpreted as a fuzzy relation between input set and output set with the membership function. The k^{th} rule, for example, is explained as

R^k : IF x is L_i^k AND y is C_j^k and z is E_p^k, THEN ζ is S_q^k with a belief degree of $\mu_{S_q^k}(\varsigma)$

where x, y, and z are input variables, ζ is output variable, and L_i^k, C_j^k, E_p^k, and S_q^k are fuzzy sets for x, y, z, and ζ respectively. Given inputs of the form:

x is $L^{'}$, y is $C^{'}$, z is $E^{'}$.

where $L^{'}$, $C^{'}$ and $E^{'}$ are fuzzy subsets of U_1, U_2, and U_3, the contribution of the k^{th} rule to a Mamdani model's output is a fuzzy set whose membership function is computed by:

$$\mu_{S_q^{k'}}(\varsigma) = (\alpha_L^k \wedge \alpha_C^k \wedge \alpha_E^k) \wedge \mu_{S_q^k}(\varsigma)$$

where α_L^k is the match degree between x and k^{th} rule condition about x; α_C^k is the match degree between y and k^{th} rule condition about y; α_E^k is the match degree between x and k^{th} rule condition about z. "$\wedge$" denotes the " min " operator. The final output of the model is the aggregation of outputs from fired rules using the max operator:

$$\mu_S(\varsigma) = \{\underset{N_1}{Max}(\mu_{S_1}^{N_1}(\varsigma)), \underset{N_2}{Max}(\mu_{S_2}^{N_2}(\varsigma)), \underset{N_3}{Max}(\mu_{S_3}^{N_3}(\varsigma)), \underset{N_4}{Max}(\mu_{S_4}^{N_4}(\varsigma))\}$$

Each $N_q (q = 1,2,3,4)$ is the number of fired rules leading to $S_q (q = 1,2,3,4)$.

Thus the output S (a fuzzy set) is generated as:

$$S(S_{the \cdot event}) = \{(\alpha^1, S_1), (\alpha^2, S_2), (\alpha^3, S_3), (\alpha^4, S_4)\}$$

where α^q (q = 1, 2, 3 or 4) is equal to $\underset{N_q}{Max}(\mu_{S_q}^{N_q}(\varsigma))$ and represents the extent to which the safety of the event belongs to the qth safety expression. Then the safety estimate is normalised according to the expression given as follows:

$$S\left(S^{'}_{the \cdot event}\right) = \left\{(\frac{\alpha^1}{D}, S_1), (\frac{\alpha^2}{D}, S_2), (\frac{\alpha^3}{D}, S_3), (\frac{\alpha^4}{D}, S_4)\right\},$$

where $D = \sum_{n=1}^{4} \alpha^n$.

Evidential synthesis

The synthesis module consists of multi-attribute synthesis and multi-expert synthesis. The experts and attributes may carry different weights when synthesizing the safety of the system. The weight of an element in a synthesis level may be judged on a subjective basis in terms of its contribution to the safety of the associated element in the upper level. For example, the safety associated with tandem loading/offloading operations is evaluated by the failure of CPP, thrusters, FPS, and DP systems within a panel of experts. The technique that is used to carry out the multi-attributes and multi-experts synthesis is the evidential reasoning approach which is based on the principle that if more pieces of evidence (each may carry different weight) support a hypothesis then it is more likely that it is true [18][20][21]. The kernel of this approach is an evidential reasoning algorithm developed on the basis of the Dempster-Shafer (D-S) theory. The Dempster-Shafer theory is also known as the theory of belief functions. It is based on two ideas: the idea of obtaining degrees of belief for one question from subjective estimations for a related question, and Dempster's rule for combining such degrees of belief when they are based on independent pieces of evidence. Therefore, the evidential reasoning approach has the advantage of synthesizing safety estimates without loss of any data and also that uncertainties in safety estimates are handled in a rational manner. To illustrate the idea of obtaining degrees of belief from synthesis of subjective estimates, two experts synthesis procedure is depicted below (details can be found in [21]).

Let S be the safety estimate synthesized from the two safety estimates S_1 and S_2 provided by two experts:

$$S = \{(\alpha^1, "poor"), (\alpha^2, "Fair"), (\alpha^3, "Average"), (\alpha^4, "Good")\}$$

$$S_1 = \{(\alpha_1^1, "poor"), (\alpha_1^2, "Fair"), (\alpha_1^3, "Average"), (\alpha_1^4, "Good")\}$$

$$S_2 = \{(\alpha_2^1, "poor"), (\alpha_2^2, "Fair"), (\alpha_2^3, "Average"), (\alpha_2^4, "Good")\}$$

Suppose the normalized relative weights of two safety experts in the safety evaluation process are given as ω_1 and ω_2 (where $\omega_1 + \omega_2 = 1$) and ω_1 and ω_2 can be estimated by using established methods such as simple rating methods or more elaborate methods based on the pair-wise comparisons.

Suppose m_1^i and m_2^i (i = 1, 2, 3 or 4) are probability masses (or weighted belief degrees) to which the estimates S_1 and S_2 support the hypothesis that the safety evaluation is confirmed to the *i*-th safety expression, that is

$$m_1^i = \omega_1 \times \alpha_1^i, \; m_2^i = \omega_2 \times \alpha_2^i, \text{ (i = 1, 2, 3 or 4)}$$

Let $H_1 = 1 - \omega_1 \sum_{m=1}^{4} \alpha_1^m$ and $H_2 = 1 - \omega_2 \sum_{m=1}^{4} \alpha_2^m$

H_1 and H_2 are regarded as remaining probability masses unassigned to any of the linguistic safety expressions. The terms H_1 and H_2 can be decomposed as follows:

$$H_1 = \bar{H}_1 + \tilde{H}_1 \text{ and } H_2 = \bar{H}_2 + \tilde{H}_2$$

where $\bar{H}_1 = 1 - \omega_1$ and $\bar{H}_2 = 1 - \omega_2$ represent the roles which other experts can play in the assessment while

$$\tilde{H}_1 = \omega_1 (1 - \sum_{m=1}^{4} \alpha_1^m) = \omega_1 [1 - (\alpha_1^1 + \alpha_1^2 + \alpha_1^3 + \alpha_1^4)]$$

and

$$\tilde{H}_2 = \omega_2 (1 - \sum_{m=1}^{4} \alpha_2^m) = \omega_2 [1 - (\alpha_2^1 + \alpha_2^2 + \alpha_2^3 + \alpha_2^4)]$$

represent the possible incompleteness in the estimates S_1 and S_2.

Suppose $\alpha^{i}_{U(2)}$ (*i*=1, 2, 3, or 4) represents the combined probability mass to which the safety evaluation is confirmed to the ***i***-th safety expression as a result of the synthesis of the judgements provided by experts #1 and #2. Suppose $H_{U(2)}$ represents the remaining belief degree unassigned to any of the safety expression as a result of the synthesis. The evidential reasoning algorithm can then be stated as follows:

$$K_{U(2)} = [1 - \sum_{T=1}^{4} \sum_{R=1 R \neq T}^{4} m_1^T m_2^R]^{-1}$$

$$\alpha^{i}_{U(2)} = K_{U(2)}(m_1^i m_2^i + m_1^i H_2 + H_1 m_2^i)$$

$$\bar{H}_{U(2)} = K_{U(2)}(\bar{H}_1 \bar{H}_2)$$

$$\tilde{H}_{U(2)} = K_{U(2)}(\tilde{H}_1 \tilde{H}_2 + \tilde{H}_1 \overline{H}_2 + \overline{H}_1 \tilde{H}_2)$$

After the above aggregation, the combined degree of belief α^i and the normalized remaining belief $H_{U(2)}$, which represents the incompleteness in the overall assessment, are generated by assigning $\bar{H}_{U(2)}$ back to the four safety expressions using the following normalization process:

$$\alpha^i = \alpha^{i}_{U(2)} / (1 - \bar{H}_{U(2)}) \text{ ; i=1, 2, 3, or 4}$$

$$H_{U(2)} = \tilde{H}_{U(2)} / (1 - \bar{H}_{U(2)})$$

The above process can be repeated if more estimates need to be synthesised at one level or between different levels in a hierarchical framework. Finally the safety evaluation associated with the failure event can then be presented in the following form:

S(*S*$_{the\ event}$) = {(α^1 , "*poor*"), (α^2 , "*fair*"), (α^3 , "*average*"), (α^4 , "*good*")}

It is worth mentioning that the order in which safety estimates are synthesised does not make any difference in terms of the final synthesis using the above algorithm. The evidential reasoning algorithm has the advantage that in theory the total unassigned belief decreases as more safety estimates are synthesized.

4. Case Study: Collision Risk of FPSO & Shuttle Tanker During Tandem Offloading Operation

In this section, a case study is presented to demonstrate the application of the proposed methodology for conducting safety assessment. The study assesses the risk of collision of FPSO and shuttle tanker during tandem offloading operation. For simplicity but without loss of generality, the following are assumed.

- Risks associated with only technical failures are assessed.
- Four major types of technical failures are considered. They are controllable pitch propeller (CPP) failure, thruster failure, position reference system (PRS) failure and dynamics positioning system failure (DP).
- There are three given input variables, namely ***failure rate (L)***, ***consequence severity (C)***, and ***failure consequence probability (E)***.
- Each input parameter (i.e., ***failure rate***, ***consequence severity***, and ***failure consequence probability***) will be fed into the proposed safety model using one of the four fuzzy membership functions discussed in Section 3.

The selection of the membership functions is dependent upon the level of ambiguity and uncertainty associated with the case as perceived by each expert. The safety estimate of each technical failure i.e. CPP failure, thrusters failure, PRS failure, and DP system failure, is assessed by five experts separately. The qualitative assessments provided by the five experts in terms of ***failure rate***, ***consequence severity***, and ***failure consequence probability*** are depicted in Table 2.

Table 2: Expert judgments of the three input parameters using appropriate membership functions to address different levels of uncertainty for technical failure caused by malfunction of the CPP, thrusters , PRS and DP

Technical failures	Expert	Shape of membership function	Failure Rate	Consequence Severity	Failure Consequence Probability
CPP	# 1	Triangular	(6.5, 8, 9.5)	(7.5, 8.5, 9.5)	(5.5, 7, 8.5)
	# 2	Triangular	(5.5, 7.5, 9)	(7, 8.5, 10)	(5, 7.5, 9.5)
	# 3	Closed interval	[6, 8]	[7, 9]	[6.5, 9]
	# 4	Trapezoidal	{5.5, 6.5, 9, 10}	{5.5, 7, 8, 10}	{5, 7, 8, 8.5}
	# 5	Single deterministic	7.75	8.25	7.6
Thrusters	# 1	Triangular	(6, 7, 7.5)	(6.5, 7, 8)	(4.5, 5.5, 6)
	# 2	Triangular	(6, 6.5, 8)	(7, 8, 9)	(6, 7.5, 8)
	# 3	Closed interval	[5.5, 5.5, 7.5, 7.5]	[6, 6, 8, 8]	[6, 6, 8, 8]
	# 4	Trapezoidal	{5, 6, 7, 8}	{5, 7, 8, 9}	{5, 6, 7, 9}
	# 5	Single deterministic	7.15	7.95	7.25
PRS	# 1	Triangular	(6.5, 7, 7.5)	(8, 8.5, 9)	(5.5, 7, 8)
	# 2	Triangular	(6, 7.5, 8)	(7.5, 8, 9.5)	(5, 6, 7)
	# 3	Closed interval	[6.5, 6.5, 8, 8]	[7, 7, 7.5, 7.5]	[6.5, 6.5, 7.5, 7.5]
	# 4	Trapezoidal	{6, 7, 8, 9}	{5, 7, 8, 8.5}	{6, 7, 8, 9}
	# 5	Single deterministic	7.5	7.2	7.1
DP	# 1	Triangular	(7, 7.5, 8)	(7.5, 8.5, 9)	(6, 7, 7.5)
	# 2	Triangular	(6.5, 7, 8)	(6.5, 7, 8.5)	(5.5, 6, 7)
	# 3	Closed interval	[7, 7, 9, 9]	[7.5, 7.5, 9.5, 9.5]	[7, 7, 8, 8]
	# 4	Trapezoidal	{6.5, 7, 7.5, 8}	{6, 6.5, 7, 8}	{6.5, 7, 7.5, 9}
	# 5	Single deterministic	7.95	8.25	7.9

<u>Fuzzification</u>

For demonstration purposes, only the risk assessment made by the five experts on collision risk caused by CPP failure is described here. Expert # 1 used a triangular form of membership function to address the inherent uncertainty associated with the data and information available while carrying out the assessment on the three input parameters. The ***failure rate*** is described triangularly as (6.5, 8.0, 9.5) on the fuzzy scale as shown in Figure 3. The most likely value is 8.0, and 6.5 and 9.5 are the lower and upper least likely values respectively. As can be seen in Figure 3, the triangle has four non-zero intersection points with *"average", "reasonably frequent", "frequent", and "highly frequent"*, respectively. That means the input variable has membership degrees of 0.2 in the "*Average*", 0.75 in the *"Reasonably frequent"*, 0.715 in the *"Frequent"* and 0.25 in the "*Highly frequent*", respectively.

As for the ***failure severity***, it is described triangularly as (7.5, 8.5, 9.5), with 8.5 as the most likely value, 7.5 and 9.5 the lower and upper least likely values. It has membership degrees of 0.75 in the "*Critical*" and 0.75 in the "*Catastrophic*". The ***failure consequence probability*** is triangularly represented as (5.5, 7.0, 8.5), with 7.0 as its most likely value, 5.5 and 8.5 its lower and upper least likely values. It has its membership degrees of 0.2 in the "*Likely*", 1.0 in the *"Reasonably likely"*, 0.6 in the *"Highly likely"* and 0.2 in the "*Definite*", respectively. In the same way, the membership degrees provided by the other four experts can be obtained. The results are shown in Table 3. Similarly the assessments made by the five experts on collision risk caused by malfunction of thrusters, PRS, and DP are given in Appendix A.

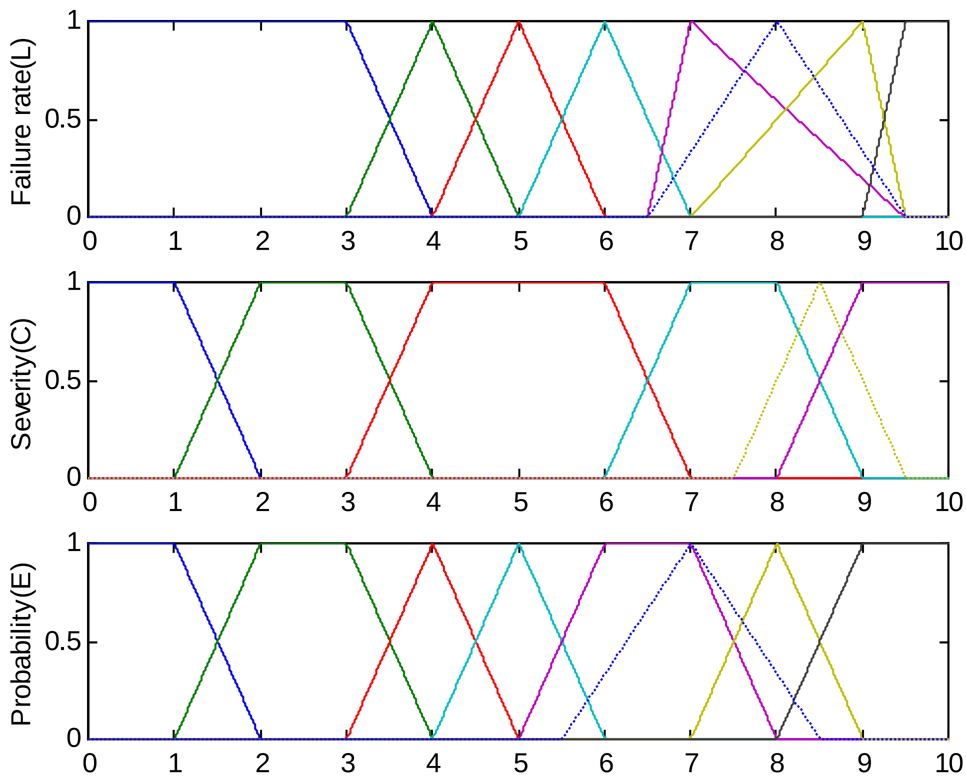

Figure 3 Results of inputs fuzzification

Table 3: The evaluation of safety estimate made by each expert according to CPP caused technical failures

Technical failure	Input variables	Linguistic class	Membership function from experts				
			# (1)	# (2)	# (3)	# (4)	# (5)
CPP	L	L1					
		L2					
		L3		0.166		0.25	
		L4	0.2	0.5	1	0.75	
		L5	0.75	0.899	1	1	0.7
		L6	0.715	0.571	0.5	1	0.375
		L7	0.25			0.666	
	C	C1					
		C2					
		C3				0.6	
		C4	0.75	0.8	1	1	0.75
		C5	0.75	0.8	1	0.666	0.25
	E	E1					
		E2					
		E3					
		E4	0.2	0.285		0.333	
		E5	1.0	0.875	1	1	0.4
		E6	0.6	0.833	1	1	0.6
		E7	0.2	0.5	1	0.333	

Fuzzy Inference

To illustrate the fuzzy inference process, we take rule #130 (as shown below) as an example:

Rule # 130: *IF the **failure rate** is <u>average</u> AND the **consequence severity** is <u>critical</u> AND the **failure consequence probability** is <u>likely</u> THEN the **safety estimate** is <u>fair</u>*

Because ***failure rate*** at (6.5, 8, 9.5) corresponds to μ_L = *0.20* for the "*average*" membership function, ***consequence severity*** at (7.5, 8.5, 9.5) corresponds to μ_C = *0.75* for the "*critical*" membership function, and ***failure consequence probability*** at (5.5, 7, 8.5) corresponds to μ_E = *0.20* for the "*likely*" membership function, in applying Rule # 130 the three different pieces of the antecedent (***failure rate*** is "*average*", ***consequence severity*** is "*critical"* and ***failure consequence probability*** is *"likely"*) yield the fuzzy membership values ($\mu_{L,130}, \mu_{C,130}, \mu_{E,130}$) = *(0.20, 0.75, 0.20)*..

In this manner, each input variable is fuzzified over all the qualifying membership functions required by the rules. The antecedents of the rules are then evaluated. The fuzzy AND operator ($\mu_r = Min(\mu_{L,r}, \mu_{C,r}, \mu_{E,r})$) simply selects the minimum of the three values, that is, *0.20*.

In this evaluation, 245 rules are considered [14]. As explained previously, when modelling collision risk caused by CPP failure, expert #1 uses a triangular form of membership function to address failure rate and therefore it has four non-zero values i.e. four intersection points with *"average", "reasonably frequent", "frequent", and "highly frequent"*, respectively. Similarly, for consequence severity there are two such non-zero values (two intersection points with "critical" and "catastrophic") and for failure consequence probability four such non-zero values (four intersection points with "likely", "reasonably likely", "high likely", and "definite"). Therefore 32 rules (4×2×4=32) are fired contributing to the actual evaluation process in this particular case (rule #130, #131, #132, #133, #137, #138, #139, #140, #165, #166, #167, #168, #172, #173, #174, #175, #200, #201, #202, #203, #207, #208, #209, #210, #235, #236, #237, #238, #242, #243, #244, and #245 are fired). The list of the 32 fired rules can be seen in Table 4. Figure 4 gives a graphic demonstration of the active rules with values.

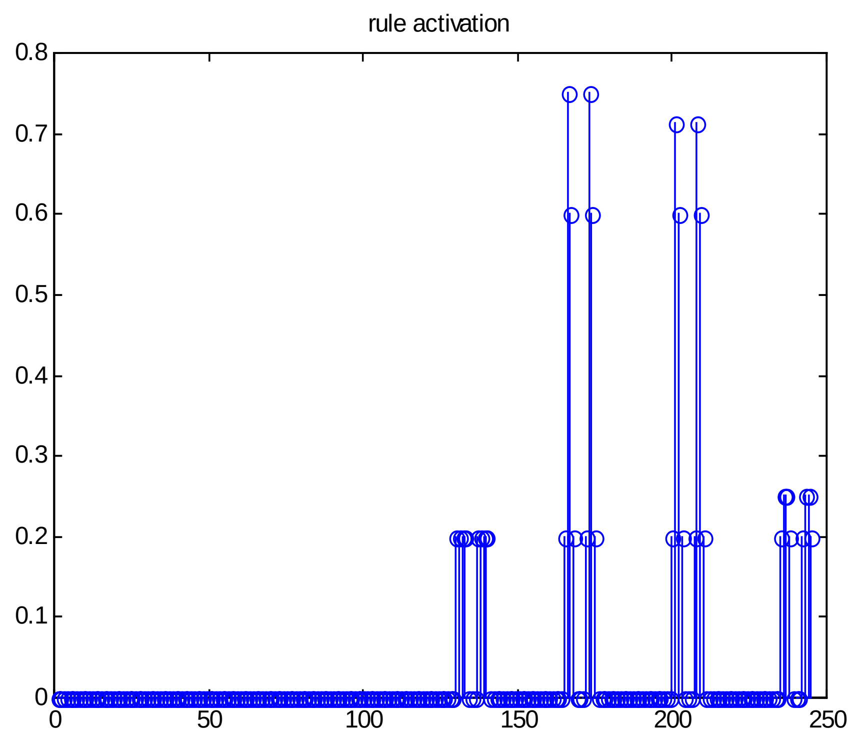

Figure 4 Graphic demonstration of active rules

Table 4: Safety estimate under the Controllable Pitch Propeller (CPP) failure by expert # 1

Rule #	Failure rate	Consequence severity	Failure severity probability	MIN-operator	Safety estimate
130	0.2	0.75	0.2	0.2	'fair'
131	0.2	0.75	1.0	0.2	'fair'
132	0.2	0.75	0.6	0.2	'poor'
133	0.2	0.75	0.2	0.2	'poor'
137	0.2	0.75	0.2	0.2	'fair'
138	0.2	0.75	1.0	0.2	'poor'
139	0.2	0.75	0.6	0.2	'poor'
140	0.2	0.75	0.2	0.2	'poor'
165	0.75	0.75	0.2	0.2	'fair'
166	0.75	0.75	1.0	0.75	'poor'
167	0.75	0.75	0.6	0.6	'poor'
168	0.75	0.75	0.2	0.2	'poor'
172	0.75	0.75	0.2	0.2	'poor'
173	0.75	0.75	1.0	0.75	'poor'
174	0.75	0.75	0.6	0.6	'poor'
175	0.75	0.75	0.2	0.2	'poor'
200	0.7	0.75	0.2	0.2	'fair'
201	0.7	0.75	1.0	0.7	'poor'
202	0.7	0.75	0.6	0.6	'poor'
203	0.7	0.75	0.2	0.2	'poor'
207	0.7	0.75	0.2	0.2	'poor'
208	0.7	0.75	1.0	0.7	'poor'
209	0.7	0.75	0.6	0.6	'poor'
210	0.7	0.75	0.2	0.2	'poor'
235	0.25	0.75	0.2	0.2	'fair'
236	0.25	0.75	1.0	0.25	'poor'
237	0.25	0.75	0.6	0.25	'poor'
238	0.25	0.75	0.2	0.2	'poor'
242	0.25	0.75	0.2	0.2	'poor'
243	0.25	0.75	1.0	0.25	'poor'
244	0.25	0.75	0.6	0.25	'poor'
245	0.25	0.75	0.2	0.2	'poor'

The fuzzy sets that represent the outputs of each rule are then combined into a single fuzzy set. All 32 rules that have been placed together to demonstrate the output of each rule are combined, or aggregated, into a single fuzzy set whose membership function is described in terms of belief degrees to the four safety expressions ("poor", "fair", "average", and "good"). As can be seen in Table 4, no belief degrees to "good" and "average" are given by expert #1 at all. Safety estimate "fair" appears 6 times in terms of rules #130, #131. #137, #165, #200 and #235, respectively. Thus:

$$(Max(0.2,0.2,0.2,0.2,0.2,0.2),\text{"}fair\text{"})=(0.2,\text{"}fair\text{"})$$

Safety estimate "poor" in Table 4 appears 26 times in terms of rule #132, #133, #138, #139, #140, #166, #167, #168, #172, #173, #174, #175, #201, #202, #203, #207, #208, #209, #210, #236, #237, #238, #242, #243, #244 and #245. Thus

$$\begin{aligned}(Max(&0.2,0.2,0.2,0.2,0.2,0.75,0.6,0.2,0.2,0.75,0.6,0.2,\\ &0.7,0.6,0.2,0.2,0.7,0.6,0.2,0.25,0.25,0.2,0.2,0.25,0.25,0.2)\text{ , "poor"))}\\ &=(0.75,\text{ "poor")}\end{aligned}$$

Therefore, the safety estimate assessed by Expert # 1 under CPP failure is as follows:

$$S(S_{the\cdot event})=\{(0.75,\text{"}poor\text{"});(0.20,\text{"}fair\text{"});(0,\text{"}average\text{"});(0,\text{"}good\text{"})\}$$

Then the safety estimate is normalised as ***safety estimate*** = {(0.79, "*poor*"), (0.21, "*fair*"), (0.0, "*average*"), (0.0, "*good*")}. The output can be interpreted in such a way that the safety estimate of the system is "*fair*" with a belief degree of *0.21* and "*poor*" with a belief degree of *0.79*.

Similar computation is performed on safety assessments provided by the other four experts under the CCP caused technical failure. Safety assessment related to the failures caused by the thrusters, PRS, and DP can be modelled in a similar way by taking into account the judgements provided by the five experts. The assessment results are shown in Table 5.

Table 5: Safety estimate by each expert on collision risk between FPSO & shutter tanker due to different technical failures

	Expert	Failure rate	Consequence severity	Failure consequence probability	Safety estimate				Safety estimate (normalised)			
					Poor	Fair	Average	Good	Poor	Fair	Average	Good
CPP	# 1	(6.5, 8, 9.5)	(7.5, 8.5, 9.5)	(5.5, 7, 8.5)	0.75	0.2			0.79	0.21		
	# 2	(5.5, 7.5, 9.0)	(7, 8.5, 10)	(5, 7.5, 9.5)	0.80	0.5			0.60	0.40		
	# 3	[6, 8]	[7, 9]	[6.5, 9]	1.0	1.0			0.5	0.5		
	# 4	{5.5,6.5,9,10}	{5.5, 7, 8, 10}	{5, 7, 8, 8.5}	1.0	0.75	0.25		0.5	0.35	0.15	
	# 5	7.75	8.25	7.6	0.6				1.0			
Thrusters	# 1	(6, 7, 7.5)	(6.5, 7, 8)	(4.5, 5.5, 6)	0.66	0.75	0.25		0.4	0.45	0.15	
	# 2	(6, 6.5, 8)	(7, 8, 9)	(6, 7.5, 8)	0.75	0.67			0.55	0.45		
	# 3	[5.5, 5.5, 7.5, 7.5]	[6, 6, 8, 8]	[6, 6, 8, 8]	1.0	1.0	0.5		0.4	0.4	0.2	
	# 4	{5, 6, 7, 8}	{5, 7, 8, 9}	{5, 6, 7, 9}	1.0	1.0	0.5		0.4	0.4	0.2	
	# 5	7.15	7.95	7.25	0.75				1			
PRS	# 1	(6.5, 7, 7.5)	(8, 8.5, 9)	(5.5, 7, 8)	0.67	0.333			0.65	0.35		
	# 2	(6, 7.5, 8)	(7.5, 8, 9.5)	(5, 6, 7)	0.88	0.5			0.65	0.35		
	# 3	[6.5, 6.5, 8, 8]	[7, 7, 7.5, 7.5]	[6.5, 6.5, 7.5, 7.5]	1.0	0.5			0.65	0.35		
	# 4	{6, 7, 8, 9}	{5, 7, 8, 8.5}	{6, 7, 8, 9}	1.0	0.67			0.6	0.4		
	# 5	7.5	7.2	7.1	0.80				1.0			
DP	# 1	(7, 7.5, 8)	(7.5, 8.5, 9)	(6, 7, 7.5)	0.75				1.0			
	# 2	(6.5, 7, 8)	(6.5, 7, 8.5)	(5.5, 6, 7)	1.0	0.33			0.75	0.25		
	# 3	[7, 7, 9, 9]	[7.5, 7.5, 9.5, 9.5]	[7, 7, 8, 8]	1.0				1.0			
	# 4	{6.5, 7, 7.5, 8}	{6, 6.5, 7, 8}	{6.5, 7, 7.5, 9}	1.0	0.6			0.6	0.4		
	# 5	7.95	8.25	7.9	0.62				1.0			

Multi-expert safety synthesis

The multi-expert synthesis is carried out by using the evidential reasoning approach discussed in Section 3. For demonstration purposes, details on how to synthesize the safety evaluation made by the five experts under CPP failure are given here. From Table 5, we have

α_1 = (0.79, 0.21, 0, 0); α_2 = (0.6, 0.4, 0, 0); α_3 = (0.5, 0.5, 0, 0); α_4 = (0.5, 0.35, 0.15, 0); α_5 = (1.0, 0, 0, 0)

Suppose the weights of the five experts are equal.

(ω_1 ω_2 ω_3 ω_4 ω_5)= (0.2, 0.2, 0.2, 0.2, 0.2) where each ω_i (i=1,2,3,4,5) is the weight of the *i*-th expert.

Using the formula given in Section 3, the basic probability masses for m_1 are given by:

$$m_1^1 = 0.2\times 0.79 = 0.16;\ m_1^2 = 0.2\times 0.21 = 0.04;\ m_1^3 = 0.2\times 0 = 0;\ m_1^4 = 0.2\times 0 = 0$$

$$\bar{H}_1 = 1 - 0.2 = 0.8; \qquad \tilde{H}_1 = 0.2\times (1 - (0.79 + 0.21 + 0 + 0)) = 0;$$

$$H_1 = \bar{H}_1 + \tilde{H}_1 = 0.8 + 0 = 0.8$$

For m_2, the basic probability masses are given by:

$$m_2^1 = 0.2\times 0.6 = 0.12;\ m_2^2 = 0.2\times 0.4 = 0.08;\ m_2^3 = 0.2\times 0 = 0;\ m_2^4 = 0.2\times 0 = 0$$

$$\bar{H}_2 = 1 - 0.2 = 0.8; \qquad \tilde{H}_2 = 0.2\times (1 - (0.6 + 0.4 + 0 + 0)) = 0$$

$$H_2 = \bar{H}_2 + \tilde{H}_2 = 0.8 + 0 = 0.8$$

For m_3, the basic probability masses are given by:

$$m_3^1 = 0.2\times 0.5 = 0.1;\ m_3^2 = 0.2\times 0.5 = 0.1;\ m_3^3 = 0.2\times 0 = 0;\ m_3^4 = 0.2\times 0 = 0$$

$$\bar{H}_3 = 1 - 0.2 = 0.8; \qquad \tilde{H}_3 = 0.2 \times (1 - (0.5 + 0.5 + 0 + 0)) = 0$$

$$H_3 = \bar{H}_3 + \tilde{H}_3 = 0.8 + 0 = 0.8$$

For m_4, the basic probability masses are given by:

$$m_4^1 = 0.2 \times 0.5 = 0.1;\ m_4^2 = 0.2 \times 0.35 = 0.07;\ m_4^3 = 0.2 \times 0.15 = 0.03;\ m_4^4 = 0.2 \times 0 = 0$$

$$\bar{H}_4 = 1 - 0.2 = 0.8; \qquad \tilde{H}_4 = 0.2 \times (1 - (0.5 + 0.35 + 0.15 + 0)) = 0$$

$$H_4 = \bar{H}_4 + \tilde{H}_4 = 0.8 + 0 = 0.8$$

For m_5, the basic probability masses are given by:

$$m_5^1 = 0.2 \times 1.0 = 0.2;\ m_5^2 = 0.2 \times 0 = 0;\ m_5^3 = 0.2 \times 0 = 0;\ m_5^4 = 0.2 \times 0 = 0$$

$$\bar{H}_5 = 1 - 0.2 = 0.8; \qquad \tilde{H}_5 = 0.2 \times (1 - (1.0 + 0 + 0 + 0)) = 0$$

$$H_5 = \bar{H}_5 + \tilde{H}_5 = 0.8 + 0 = 0.8$$

The combined probability masses are given by

$$\begin{aligned} K_{U(2)} &= \{1 - [(m_1^1 m_2^2 + m_1^1 m_2^3 + m_1^1 m_2^4) \\ &\qquad + m_1^2 m_2^1 + m_1^2 m_2^3 + m_1^2 m_2^4 \\ &\qquad + m_1^3 m_2^1 + m_1^3 m_2^2 + m_1^3 m_2^4) \\ &\qquad + m_1^4 m_2^1 + m_1^4 m_2^2 + m_1^4 m_2^3)]\}^{-1} \\ &= \{1 - [(0.16 \times 0.024 + 0.16 \times 0 + 0.16 \times 0) + \\ &\qquad + (0.04 \times 0.12 + 0.04 \times 0 + 0.04 \times 0) + 0 + 0]\}^{-1} \\ &= \{0.99616\}^{-1} = 1.0039 \end{aligned}$$

$$\begin{aligned} \alpha_{U(2)}^1 &= K_{U(2)} (m_1^1 m_2^1 + m_1^1 H_2 + H_1 m_2^1) \\ &= K_{U(2)} (0.16 \times 0.12 + 0.16 \times 0.8 + 0.8 \times 0.12) = 0.2432 \times K_{U(2)} = 0.2441 \end{aligned}$$

$$\begin{aligned} \alpha_{U(2)}^2 &= K_{U(2)} (m_1^2 m_2^2 + m_1^2 H_2 + H_1 m_2^2) \\ &= K_{U(2)} (0.04 \times 0.08 + 0.04 \times 0.8 + 0.8 \times 0.08) = 0.0992 \times K_{U(2)} = 0.0996 \end{aligned}$$

$$\begin{aligned} \alpha_{U(2)}^3 &= K_{U(2)} (m_1^3 m_2^3 + m_1^3 H_2 + H_1 m_2^3) \\ &= K_{U(2)} (0 \times 0 + 0 \times 0.8 + 0.8 \times 0) = 0 \end{aligned}$$

$$\begin{aligned} \alpha_{U(2)}^4 &= K_{U(2)} (m_1^4 m_2^4 + m_1^4 H_2 + H_1 m_2^4) \\ &= K_{U(2)} (0 \times 0 + 0 \times 0.8 + 0.8 \times 0) = 0 \end{aligned}$$

$$\begin{aligned} \tilde{H}_{U(2)} &= K_{U(2)} (\tilde{H}_1 \tilde{H}_2 + \tilde{H}_1 H_2 + H_1 \tilde{H}_2) \\ &= K_{U(2)} (0 \times 0 + 0 \times 0.8 + 0.8 \times 0) = 0 \end{aligned}$$

$$\begin{aligned} \bar{H}_{U(2)} &= K_{U(2)} (\bar{H}_1 \bar{H}_2) = \\ &= K_{U(2)} (0.8 \times 0.8) = 0.64 \times K_{I(2)} = 0.6425 \end{aligned}$$

The process is carried on to calculate:

$$\alpha^{1'}_{U(3)}, \alpha^{2'}_{U(3)}, \alpha^{3'}_{U(3)}, \alpha^{4'}_{U(3)}, K_{U(3)}, \bar{H}_{U(3)}, \tilde{H}_{U(3)}$$

$$\alpha^{1'}_{U(4)}, \alpha^{2'}_{U(4)}, \alpha^{3'}_{U(4)}, \alpha^{4'}_{U(4)}, K_{U(4)}, \bar{H}_{U(4)}, \tilde{H}_{U(4)}$$

$$\alpha^{1'}_{U(5)}, \alpha^{2'}_{U(5)}, \alpha^{3'}_{U(5)}, \alpha^{4'}_{U(5)}, K_{U(5)}, \bar{H}_{U(5)}, \tilde{H}_{U(5)}$$

Finally, the combined degrees of belief are calculated as follows.

$$\alpha^1 = \frac{\alpha^1_{U(5)}}{1-\bar{H}_{U(5)}} = 0.7242 \qquad \alpha^2 = \frac{\alpha^2_{U(5)}}{1-\bar{H}_{U(5)}} = 0.2528$$

$$\alpha^3 = \frac{\alpha^3_{U(5)}}{1-\bar{H}_{U(5)}} = 0.0230 \qquad \alpha^4 = \frac{\alpha^4_{U(5)}}{1-\bar{H}_{U(5)}} = 0$$

$$H_U = \frac{\tilde{H}_{U(5)}}{1-\bar{H}_{U(5)}} = 0$$

Table 6 shows the synthesised results of multi-expert safety assessments on collision risk between FPSO & shutter tanker due to technical failures caused by the CPP, thrusters, PRS and DP .

Table 6: Safety synthesis on collision risk between FPSO & shutter tanker due to different technical failures

Technical failures	Safety synthesis			
	Poor	Fair	Average	Good
CPP	0.7242	0.2528	0.0230	0
Thrusters	0.5819	0.3244	0.0938	0
PRS	0.7521	0.2479	0	0
DP	0.9081	0.0919	0	0

<u>Multi-attribute safety synthesis</u>

Similarly, the safety assessments based on each of the 4 types of technical failures, as shown in Table 6, can be synthesised to generate the overall safety estimate for the FPSO & shutter tanker operation due to different technical failures. From multi-expert synthesis (see Table 6), we have

CPP = (0.7242, 0.2528, 0.0230, 0); thrusters = (0.5819, 0.3244, 0.0938, 0); PRS = (0.7521, 0.2479, 0, 0); DP = (0.9081, 0.0919, 0, 0);

Again, suppose the weights of the above attributes are equal.

$(\omega_1\ \omega_2\ \omega_3\ \omega_4)$= (0.25 0.25,0.25,0.25) where each ω_i (i=1,2,4,5) is the weight of the *i*-th attribute.

Using the evidential reasoning method, the final safety synthesis can be calculated. The windows-based and graphically designed Intelligent Decision System (IDS), which has been developed based on the evidential reasoning approach [21], is used to synthesize the four attributes and generate the safety estimates. Figure 5 shows the IDS results of multi-attribute safety synthesis by the panel of five experts on the four types of anticipated technical failures, which may cause collision between FPSO and shuttle tanker. The result produced is as follows:

Overall safety assessment due to technical failures = *{ 0.7884, 'poor'; 0.1898, 'fair'; 0.0218, 'average'; 0, 'good' }*.

This means that with a belief degree of 78.84% safety level is “poor”, 18.98% “fair”, and 2.18% “average”. It is worth noting that in this case, the four system caused technical failures lead to a “poor” safety level of high belief degrees, 72.42% for CPP, 58.19% for thrusters, 75.21% for PRS, and 90.81% for DP respectively. The final synthesised result (a belief degree of 78.84% to “poor”) provides a consistent judgement in line with the assessments.

The synthesised results can be used for decision making purposes. For example, the results presented in Table 6 indicate the levels of collision risk between FPSO and shuttle tank associated with each of the four systems in terms of technical failures. Because failure of DP results in the highest level of poor safety, design efforts should be directed to reduce the DP related failure. The result shown in Figure 5 gives an overall profile of collision risk between FPSO and shuttle tank due to technical failure of CPP, thrusters, PRS and DP.

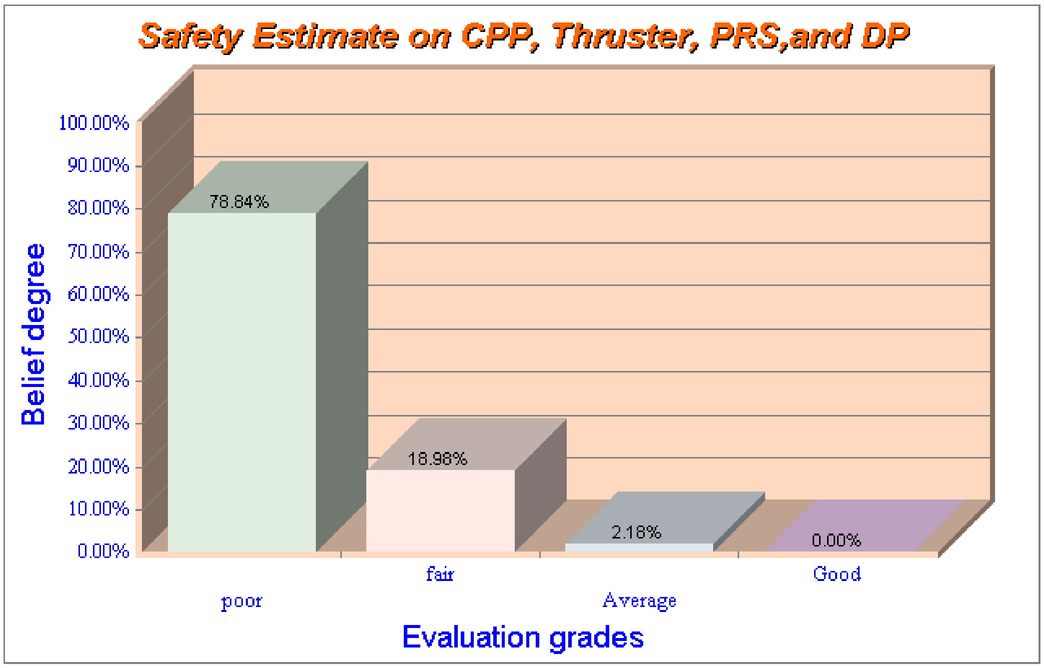

Figure 5 Graphic demonstration of the final safety estimate by evidential synthesis

5. Conclusions

The proposed framework can be used to assess the safety level of offshore systems at the early design stages. In the framework, expert judgements are transferred into fuzzy numbers to represent their intrinsic uncertainty. Fuzzy logic allows one to quantify vague or qualitative ideas, which are common in multi-attributes and multi-experts assessment problems. In the assessment process, the safety attributes are evaluated using linguistic values. The use of linguistic values with multi-possible boundaries (e.g. most likely value, upper and lower likely value) provides the decision maker with a high degree of flexibility to make the most reasonable judgement. Most importantly, the fuzzy reasoning process generates a safety estimate represented by a belief structure, which provides more informed outcome for decision making purposes. Overall, the proposed multi-attributes and multi-experts decision-making methodology can be a useful tool for offshore safety assessment problems where there is incomplete information, the attributes are of varying degrees of importance, or the values of the basic attributes are uncertain. The method described provides a supplement to concepts and methodologies already in use for offshore safety assessment.

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References

1. Apostolakis G. E., Guedes Soares C., Kondo S., Mancini G., “Are reliability and risk assessment ready for fuzzy methods?”, Reliability Engineering & System Safety, Vol.42, 1993, 65.

2. Chen, H., Moan, T., “Collision risk analysis of FPSO-tanker offloading operation”, 21st International Conference on Offshore Mechanics & Arctic Engineering, 23-28, June 2002, Oslo, Norway.
3. Chun M. H., Ahn K. I., “Assessment of the potential applicability of fuzzy set theory to accident progression event trees with phenomenological uncertainties”, Reliability Engineering & System Safety, Vol.37, 1992, 75-85.
4. Coolen F. P. A., Newby M. J., “Bayesian reliability analysis with imprecise prior probabilities”, Reliability Engineering & System Safety, Vol.43, 1994, 75-85.
5. FPSO/FSUs Green Water and Wave Slam Incident Analysis. BOMEL Limited on Behalf of the BOMEL Consortium. Report C902\01\012R, Rev B, January 2001
6. Health & Safety Executive, Analysis of accident statistics for floating monohull and fixed installation, 2003
7. Karwowski W., Mital A., “Potential applications of fuzzy sets in industrial safety engineering”, Fuzzy Sets and Systems, Vol.19, 1986, 105-120.
8. Keller A. A., Kara-Zaitri C., “Further applications of fuzzy logic to reliability assessment and safety analysis”, Micro. Reliab., Vol.29, 1989, 399-404.
9. Leonhardsen R. L., Ersdal G., Kvitrud, A. , “Experience and risk assessment of FPSOs in use on the Norwegian Continental Shelf ”, Proceedings of 11th ISOPE Conference, Vol. 1, Stavanger, Norway, 2001.
10. Mamdani, E. H., Assilian, S. , “An experiment in linguistic synthesis with a fuzzy logic controller ”, International Journal of Man-Machine Studies, Vol. 7, No. 1, 1975, 1-13.
11. MSA (Marine Safety Agency), Formal safety assessment MSC66/14, Submitted by the United Kingdom to IMO Maritime Safety Committee, 1993.
12. MSA (Marine Safety Agency), Formal safety assessment MSC66114, Submitted by the United Kingdom to IMO Maritime Safety Committee, 1996.
13. Sekimizu, K., “Current work at IMO on formal safety assessment”, Proceeding of Marine Risk Assessment: A Better Way to Manage Your Business, The Institute of Marine Engineers, London, 8-9 April 1997, 9-20.
14. Sii H. S., Wang J., Ruxton T., “A fuzzy-logic-based approach to subjective safety modelling for maritime products”, Journal of UK Safety and Reliability Society, Vol.21, No.2, 2001, 65-79.
15. Sii H. S., Ruxton T., Wang J., “A synthesis using fuzzy set theory and Dempster-Shafer based approach to compromise decision making with multiple attribute applied to risk control options selection”, Proceedings of the Institution of Mechanical Engineers Part E, IMechE Journal of Process Mechanical Engineering, Vol.212, 2001, 251-261.
16. UKOOA, Industry guidelines on a framework for risk related decision making, Published by the UK Offshore Operators Association, 1999.
17. Wang J., Yang. J. B., Sen P., “Safety analysis and synthesis using fuzzy set modelling and evidential reasoning”, Reliability Engineering & System Safety, Vol.47, No.3, 1995, 103-118.
18. Wang J., Yang. J. B., Sen P., “Multi-person and multi-attribute design evaluations using evidential reasoning based on subjective safety and cost analyses”, Reliability Engineering & System Safety, Vol.52, No.2, 1996, 113-129.
19. Wang J., “A subjective methodology for safety analysis of safety requirements specifications”, IEEE Transactions on Fuzzy Systems, Vol.5, No.3, 1997, 418-430.
20. Yang J. B., Singh M. G., "An evidential reasoning approach for multiple attribute decision making with uncertainty", IEEE Transactions on Systems, Man, and Cybernetics, Vol.24, No.1, 1994, 1-18.
21. Yang J. B., Xu D. L., “On the evidential reasoning algorithm for multiattribute decision analysis under uncertainty”, IEEE Transactions on Systems, Man, and Cybernetics, Part A: Systems and Humans, Vol.32, No.3, 2002, 289-304.
22. Zadeh, L., Fuzzy sets, Information and Control, Vol.8, 1965, 338-353.
23. Zadeh, L. A. (1973) “Outline of a new approach to the analysis of complex systems and decision processes ”, IEEE Transactions on Systems, Man, and Cybernetics, Vol. 3, 1973, 28-44.
24. Zadeh, L. A. (1975) The concept of a linguistic variables and its application to approximate reasoning I, II, III, Information science, Vol.8, 1975, 301-357.
25. http://www.ukooa.co.uk/issues/fpso/faq.htm (access date 18/11/2004)
26. http://www.freesafetycheck.co.uk/oil4.htm (access date 18/11/2004)

Appendix A: Safety assessments made by each expert under different technical failures (thrust, PRS, DP)

Technical failure	Input variables	Linguistic class	Membership function from experts				
			# (1)	# (2)	# (3)	# (4)	# (5)
Thrusters	L	L1					
		L2					
		L3			0.5	0.5	
		L4	0.5	0.666	1.0	1.0	
		L5	1	0.75	1.0	1.0	0.94
		L6	0.2	0.286	0.25	0.33	0.075
		L7					
	C	C1					
		C2					
		C3	0.333		1.0	0.666	
		C4	1.0	1.0	1.0	1.0	1.0
		C5		0.5		0.5	
	E	E1					
		E2					
		E3	0.25				
		E4	0.75			0.5	
		E5	0.666	0.799	1.0	1.0	0.75
		E6		0.666	1.0	0.666	0.25
		E7				0.333	
PRS	L	L1					
		L2					
		L3					
		L4	0.333	0.399	0.5	0.5	
		L5	1.0	0.875	1.0	1.0	0.8
		L6	0.1995	0.4	0.5	0.666	0.25
		L7					
	C	C1					
		C2					
		C3				0.666	
		C4	0.666	1.0	1.0	1.0	1.0
		C5	0.666	0.6		0.333	
	E	E1					
		E2					
		E3					
		E4	0.1999	0.5			
		E5	1.0	1.0	1.0	1.0	0.9
		E6	0.5		0.5	1.0	0.1
		E7				0.5	
DP	L	L1					
		L2					
		L3					
		L4		0.333		0.333	
		L5	0.8332	1.0	1.0	1.0	0.62
		L6	0.4	0.333	1.0	0.4	0.475
		L7					
	C	C1					
		C2					
		C3		0.333		0.666	
		C4	0.75	1.0	1.0	1.0	0.75
		C5	0.666	0.2	1.0		0.25
	E	E1					
		E2					
		E3					
		E4		0.333			
		E5	1.0	1.0	1.0	1.0	0.1
		E6	0.333		1.0	0.8	0.9
		E7				0.399	