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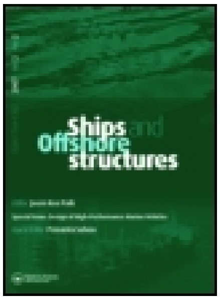

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Risk assessment of liquefied natural gas carriers using fuzzy TOPSIS

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Risk assessment of liquefied natural gas carriers using fuzzy TOPSIS

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An approach for the risk assessment of liquefied natural gas (LNG) carriers is proposed in this study. The approach is based on the use of the fuzzy technique of order preference by similarity to the ideal solution or fuzzy TOPSIS. In the proposed approach, probabilities and consequences of hazardous scenarios are represented by fuzzy sets to take into account imprecision associated with the subjective assignment of their values by experts. A case study for an LNG ship during loading and offloading at terminals is presented to illustrate the capability and effectiveness of the proposed fuzzy TOPSIS method and its difference from other qualitative techniques. Results show that the proposed approach is effective for handling imprecision often associated with subjective expert assessment of risk data. It gives more reasonable and robust risk ranking of the different hazardous scenarios. The proposed methodology is also applicable to other ship-operating modes such as transit in open sea and/or entering/leaving port.

Keywords: risk assessment; multiple risk consequences; liquefied natural gas carriers; fuzzy sets; fuzzy TOPSIS

1. Introduction

The safety in design and operation of liquefied natural gas (LNG) carriers is a major concern for LNG-tanker operating companies. LNG hazards have a high potential financial impact in addition to shutdown and failure of delivery (Elsayed et al. 2009). Risks associated with LNG transfer operations at the ship–shore interface of gas terminals are often difficult to estimate. Hazards and potential accident consequences during these operations are difficult to quantify. A number of different analysis techniques and models have been developed to aid in conducting risk assessments (ABS 2000). These range from simple qualitative methods to detailed quantitative risk analyses. The latter can be used if there is sufficient information to estimate quantitative failure frequency and/or associated accident consequences. Some authors have proposed to use neural networks (Wang et al. 2004; Wang and Elhag 2007) and neuro-fuzzy networks (Wang and Elhag 2008) for risk assessment. In this approach, a neural/neuro-fuzzy network is trained using a large data-set of expert assessment and risk data. The network can then be used to simulate a response to a different input. These approaches, however, used deterministic expert data. In this study, we propose to use a modified version of the fuzzy technique of order preference by similarity to the ideal solution or fuzzy TOPSIS. This approach has the advantage of efficiently modeling multiple attribute decision-making problems under fuzzy environment. Imprecision associated with the assignment of probability and consequence values can be incorporated. The fuzzy TOPSIS approach has been used in many multiple-attribute decision/risk assessment applications. Examples include bridge risk assessment (Wang and Elhag 2006), spread mooring system selection (Mentes and Helvacioglu 2012), combat response to oil spills selection (Krohling and Companharo 2011), risk evaluation of tunneling projects (Fouladgar et al. 2012), risk analysis of critical infrastructures (Yazdani and Aliddoosti 2012), for proposing competitive strategies in maritime transportation networks (Celik et al. 2009), selection of the best barrier for offshore wells (Seyed et al. 2012), risk assessment model selection in construction industry (Karmiazari et al. 2011) and for ranking alternatives (Ding 2011). In this study, we propose/investigate the use of the fuzzy TOPSIS approach for the risk assessment of LNG ships during loading and offloading at terminals.

2. Hazard identification

A hazard identification (HAZID) study was carried out by the European maritime research project (Safedor 2005). The study was coordinated by Germanischer Lloyd, the ship classification society, with partners from various sectors of the marine industry. Major accident hazards affecting LNG ships, during various modes of operation, were assessed as a first step to carrying out a risk assessment study. The following LNG ship operational modes were considered: loading, departing quay, manoeuvring, transit and navigation in coastal waters, transit in open sea, arriving in port, mooring and preparing for unloading, unloading, operation in ice conditions, maintenance and repairing on

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Table 1. LNG hazardous scenarios during loading/offloading at terminals (Safedor 2005).

HAZID number	HAZID	Likelihood	Consequences
1	Overloading: danger of overloading cargo tanks with effects on structure/equipments and possibly creating gas pockets on board.	(3.2)	*H*2.2, *E*2.2, *T*2.2, *R*2.2
2	LNG spill on deck to sea: faults in connections or pipes leading to spill.	(3.4)	*T*1.6
3	Filling liquid into compressor and boiler areas: during overloading, LNG overflows into neighbouring rooms causing damage to equipment/structure; caused by malfunction of equipment and human failure.	(2.3)	*H*2.5, *T*2.5
4	Fault in operational procedures: tanks are being filled too high due to commercial pressure, calculating that the boil-off rate will reduce the high level in the tanks after a while.	(2.6)	*H*2.6, *F*2.6
5	High movements in LNG transfer system: LNG transfer system is designed to withstand a certain movement and will break causing spillage if violated.	(3.4)	*T*1.8
6	Lack of communication with shore personnel: leads to overloading.	(3.4)	*H*2.0
7	Personnel failing in adjusting the moorings during loading/unloading: vessel must be kept in the right position and moorings must be adjusted accordingly with the ship being loaded/unloaded.	(3.0)	*H*2.2
8	External forces from wind, wave and tide: causes high movements in LNG transfer system.	(2.8)	*T*2.0
9	Fault in ballast system or fault operation of ballast system: causes high movements or displacement movements in LNG transfer system.	(2.6)	*T*2.2
10	Being struck by passing vessels: may cause high-rate spillage.	(1.8)	*H*4.2
11	Lack of crew competence and training: lack in this department may lead to all sorts of incidents.	(3.0)	*H*2.6
12	Roll-over: lack of stability during loading/unloading may lead to roll-over.	(1.4)	*H*3.8
13	Tank depressurising: working the pumps when the tank is empty will depressurise the tank and it may collapse, membrane will be damaged, sphere structure may buckle (Moss type), etc.	(2.8)	*F*3.6, *T*3.6
14	Overfilling other tanks: fault operation may pump LNG into other tanks leading to them overfilling with secondary effects.	(2.4)	*H*2.8, *F*2.8
15	Debris in tanks: during the first discharge after docking may lead to damage to cargo pumps as debris is left in tank or tank system following docking.	(3.4)	*F*2.4, *T*2.4
16	Clogging up pumps with ice cubes ice: clogging may result if water gets into the system causing ice formation. This may damage pumps and cause operational failure.	(2.8)	*F*2.4, *T*2.4
17	Clogging of filter: this fault is caused by different debris (foam, etc.) resulting in clogging filters and causing the operation to halt.	(3.2)	*F*2.2, *T*2.2
18	Situations on terminal causing back fire on ship: this may result in various technical and safety problems on this ship.	(1.8)	*H*4.0, *F*4.0, *T*4.0

board, training, emergency situations, docking and general hazards.

A typical membrane-type LNG tanker, namely a 138,000 m^3 LNG carrier, was used as case study. The risk register identified a total of 120 hazardous scenarios in 17 different operating conditions. A sample of 18 scenarios during LNG loading/unloading at terminals was chosen for this study. Table 1 summarises the 18 hazardous scenarios identified as major risk contributors during LNG loading/offloading operations (Safedor 2005).

As seen from Table 1, each hazardous scenario is associated with likelihood, defined numerically, and consequences. The likelihood of each hazardous scenario is expressed as a decimal number, which represents the average of the assessments of eight experts. During the HAZID meeting, the experts were asked to assess/rate the likelihood of each hazardous scenario, and its impact on five accident consequences on a qualitative scale based on Tables 2 and 3, respectively. Results of the eight assessments were then averaged and the final average probability/consequence values are provided in Table 1 for each scenario. Accident consequences are denoted by a letter followed by a number. The letters *H*, *E*, *F*, *T* and *R* correspond to the consequence classes for 'human safety', 'environmental', 'costs and finance', 'ship safety and technology' and 'reputation and disruption', respectively. The numbers 1, 2, 3, 4 and 5 correspond to the degrees of severity of the consequence, for example, 'minor', 'significant', 'severe', 'catastrophic' and 'disastrous', respectively, on a qualitative scale as shown in Table 3. It should be noted that the HAZID has been conducted based on a membrane-type 138,000 m^3 LNG carrier. There may be new hazardous scenarios if one considers a larger or smaller vessel or a Moss-type, spherical tank, vessel and the hazard register will need to be updated accordingly.

Table 2. Definition of probability index (Safedor 2005).

Probability index	Probability	Definition	Probability (per ship year)
8	Very frequent	Likely to happen once or twice a week on one ship.	100
7	Frequent	Likely to occur once per month on one ship.	10
6	Probable	Likely to occur once per year on one ship.	1
5	Reasonably probable	Likely to occur once per year in a fleet of 10 ships, i.e. likely to occur a few times during a ship's life.	0.1
4	Little probable	Likely to occur once per year in a fleet of 100 ships, i.e. likely to occur in the total life of a ship's life.	0.01
3	Remote	Likely to occur once per year in a fleet of 1000 ships, i.e. likely to occur in the total life of several similar ships.	0.001
2	Very remote	Likely to occur once per year in a fleet of 10,000 ships.	0.0001
1	Extremely remote	Likely to occur once in the lifetime (20 years) of a world fleet of 5000 ships.	0.00001

3. Qualitative risk assessment

The identified hazardous scenarios of the LNG vessel were assessed using a qualitative risk assessment approach. Table 2 shows the probability index used for the qualitative assessment of the probabilities of occurrence, while Table 3 shows the consequences index. The risk matrix in Table 4 was used to assign risk levels to each of the combinations of probability of occurrence and consequence of events. Risk is defined as

$$\text{Risk} = \text{probability} \times \text{consequence}. \tag{1}$$

Using a logarithmic scale,

$$\log(\text{Risk}) = \log(\text{probability}) + \log(\text{consequence}). \tag{2}$$

Overall scenario risk can be estimated as

$$\text{Risk}_i = P_i + (H_i + E_i + F_i + T_i + R_i)/5, \tag{3}$$

where P_i is the scenario probability and $(H_i, E_i, F_i, T_i, R_i)$ are the average expert assessment values for the scenario consequences 'human safety', 'environmental', 'costs', 'ship safety and technology' and 'reputation', respectively. Results of the qualitative assessments for the 18 hazardous scenarios considered are provided in Table 11.

4. Fuzzy TOPSIS model

The technique of order of preference by similarity to ideal solution TOPSIS is a multiple-attribute decision-making method. It was originally developed by Hwang and Yoon (1981). TOPSIS is based on the concept that the chosen alternative should have the shortest distance from a positive ideal solution and the longest distance from a negative ideal solution. A positive ideal solution is defined as a solution that maximises the benefit criteria and minimises the cost criteria simultaneously. A negative ideal solution is defined as a solution that maximises the cost criteria and minimises the benefit criteria simultaneously. In conventional qualitative assessment, experts give their judgments/ratings in linguistic-valued assessments such as 'minor', 'significant', 'severe' and 'catastrophic'. These are then transformed into crisp/precise value judgments as shown in Table 2.

In real-world problems, it is often difficult for an expert to determine a precise assessment, for example, the probability of a hazardous scenario, or the effect of a hazardous scenario on a certain accident consequence. In fuzzy TOPSIS approach, the concept of a linguistic variable or fuzzy set is used to represent the expert subjective ratings of accident probabilities and consequences. Linguistic variables are regarded as a natural representation of preferences/judgments of accident probabilities and consequences. Given a set of m hazardous scenarios, $S = \{S_i \mid i = 1, \ldots, m\}$, resulting in a set of n risk consequences, $C = \{C_j \mid j = 1, \ldots, n\}$, the set of fuzzy expert ratings of the ith scenario with respect to the jth consequence can be expressed as $\tilde{X} = \{\tilde{X}_{ij} | i = 1, \ldots, m; j = 1, \ldots, n\}$. The set of fuzzy weights of the consequences is denoted as $\tilde{W} = \{\tilde{w}_j | j = 1, \ldots, n\}$. The approach is carried out through the following steps (Triantaphyllou and Lin 1996; Wang and Elhag 2006).

Step 1: Construct a fuzzy multiple-consequence risk matrix.

$$\tilde{R} = \begin{array}{c} \\ S_1 \\ S_2 \\ \vdots \\ S_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \ldots & C_n \end{array} \\ \begin{bmatrix} \tilde{X}_{11} & \tilde{X}_{12} & & \tilde{X}_{1n} \\ \tilde{X}_{21} & \tilde{X}_{22} & & \tilde{X}_{2n} \\ \vdots & \vdots & & \vdots \\ \tilde{X}_{m1} & \tilde{X}_{m2} & \ldots & \tilde{X}_{mn} \end{bmatrix} \end{array}, \tag{4}$$

where $\tilde{X}_{ij}$ is the risk rating of the ith hazardous scenario S_i with respect to the jth risk consequence C_j. $\{\tilde{X}_{ij} \mid i = 1, \ldots, m; j = 1, \ldots, n\}$ are triangular fuzzy numbers given

Table 3. Definition of consequence index (Safedor 2005).

CI	Consequence	Human safety	Environment related	Cargo/monetary losses	Effect on ship	3rd Party assets	Equivalent fatalities
1	Minor	Single or minor injuries.	Negligible release – negligible pollution – no acute environmental or public health impact.	30,000 US$	Local equipment damage (repair on board possible, downtime negligible).	Minor damage	0.01
2	Significant	Multiple or severe injuries.	Minor release - minimal acute environmental or public health impact - small, but detectable environmental consequences.	300,000 US$	Non-severe ship damage (port stay required, downtime 1 day).	Significant damage	0.1
3	Severe	Single fatality or multiple severe injuries.	Major release - effects on recipients - short term disruption of the ecosystem.	3 million US$	Severe damage (yard repair required, downtime < 1 week).	Severe damage in vicinity of ship	1
4	Catastrophic	Multiple fatalities.	Severe pollution - medium-term effect on recipients - medium-term disruption of the ecosystem.	30 million US$	Total loss (of, e.g. a medium-sized merchant ship).	Extensive damage	10
5	Disastrous	Large number of fatalities.	Uncontrolled pollution - long-term effect on recipients - long-term disruption of the ecosystem.	300 million US$	Total loss (of, e.g. a large merchant ship).	Major public interest	100

by $\tilde{X}_{ij} = (a_{ij}, b_{ij}, c_{ij})$, and $\tilde{w}_j$ represents the weight of the jth risk criterion C_j.

Step 2: Construct a normalised fuzzy risk matrix.

$$\tilde{R} = \left[\tilde{r}_{ij}\right]_{m\times n,}\ i = 1, \ldots, m;\ j = 1, \ldots, n, \tag{5}$$

where $\tilde{r}_{ij} = (\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*})$ and $c_j^* = \max_i c_{ij}$ for maximisation objective. Since all consequences are cost attributes and are measured on the same scale, this step was omitted.

Step 3: Compute the weighted normalised fuzzy risk matrix $\widetilde{V}$.

$$\tilde{V} = \begin{bmatrix} \tilde{w}_1\tilde{r}_{11} & \tilde{w}_2\tilde{r}_{12} & & \tilde{w}_n\tilde{r}_{1n} \\ \tilde{w}_1\tilde{r}_{21} & \tilde{w}_2\tilde{r}_{22} & & \tilde{w}_n\tilde{r}_{2n} \\ \vdots & \vdots & & \vdots \\ \tilde{w}_1\tilde{r}_{m1} & \tilde{w}_2\tilde{r}_{m2} & \ldots & \tilde{w}_n\tilde{r}_{mn} \end{bmatrix}, \tag{6}$$

Table 4. Risk matrix (Safedor 2005).

		Consequence/Severity				
PI	Probability	1 Minor	2 Significant	3 Severe	4 Catastrophic	5 Disastrous
8	Very frequent	9	10	11	12	13
7	Frequent	8	9	10	11	12
6	Probable	7	8	9	10	11
5	Reasonably probable	6	7	8	9	10
4	Little probable	5	6	7	8	9
3	Remote	4	5	6	7	8
2	Very remote	3	4	5	6	7
1	Extremely remote	2	3	4	5	6

Table 5. Basic dimensions of the 138,000 LNG carrier (Safedor 2005).

Length overall (LOA)	284.40 m
Length between perpendiculars (LBP)	271.00 m
Breadth moulded	42.50 m
Depth moulded to main deck	25.40 m
Depth moulded to trunk deck	32.2 m
Design draft	11.40 m
Total loaded displacement – lower than	98,500 tonnes
Design speed	19.5 knots

where $\{\tilde{w}_1, \tilde{w}_2, \ldots, \tilde{w}_n\}$ are fuzzy weights of the different consequences and $[\tilde{v}_{ij}]_{m\times n,} i = 1, \ldots, m; j = 1, \ldots, n$.

All consequences were assigned equal deterministic weights in this study.

Step 4: The fuzzy positive ideal solution (FPIS) (S^*) and fuzzy negative ideal solution (FNIS) $\left(S^-\right)$ can be calculated as

$$S^* = \left(\bar{v}_{1,}^* \bar{v}_{2,}^*, \ldots, \bar{v}_n^*\right), \tag{7}$$

where $\overline{v}_j^* = \max_i\{\tilde{v}_{ij}\}, i = 1, \ldots, m; j = 1, \ldots, n$ and

$$S^- = \left(\bar{v}_{1,}^- \bar{v}_{2,}^- \ldots, \bar{v}_n^-\right). \tag{8}$$

where $\overline{v}_j^- = \min_i\{\tilde{v}_{ij}\}, i = 1, \ldots, m; j = 1, \ldots, n$.

Step 5: Calculate the distances from FPIS and FNIS.

$$d^* = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \quad \overline{v}_j^*), i = 1, \ldots, m, \tag{9}$$

$$d^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \quad \overline{v}_j^-), i = 1, \ldots, m. \tag{10}$$

The distance $d\ (\tilde{a}, \tilde{b})$ is the distance measurement between two fuzzy numbers $\tilde{a} = (a_1, a_2, a_3)$ and $\tilde{b} = (b_1, b_2, b_3)$ and can be calculated by the vertex method (Chen 2000) as

$$d\left(\tilde{a}\ ,\ \tilde{b}\right) = \left[\sqrt{\frac{1}{3}\left[(a_1 - b_1)^2 + (a_2 - b_2)^2 + (a_3 - b_3)^2\right]}\right]. \tag{11}$$

Step 6: Calculate the closeness coefficient, CC_i^*.

$$CC_i^* = \frac{d_i^-}{d_i^- + d_i^*}, \quad i = 1, 2, \ldots, m. \tag{12}$$

Step 7: Rank the preference order of hazardous scenarios according to closeness coefficient CC_i^*. A higher value of the closeness coefficient indicates a more risky scenario.

5. Case study

A case study for a 138,000 m^3 membrane-type LNG tanker loading/offloading at the terminal is used to demonstrate the proposed fuzzy risk assessment approach (Safedor 2005). A longitudinal and plan view of the LNG tanker is illustrated in Figure 1, while Table 5 summarises the principal particulars of the ship. The 18 hazardous scenarios, outlined earlier in Table 1, were evaluated using the proposed fuzzy TOPSIS method. Probabilities of the hazardous scenarios as well as accident consequences were represented as fuzzy

Table 6. Hazardous scenarios- fuzzy probabilities and consequences.

Hazard ID	HAZID	Fuzzy probability	Fuzzy consequences
1	Overloading	(2.2,3.2,4.2)	H(1.2,2.2,3.2) E(1.2,2.2,3.2) F(0.0,0.0,1.0) T(1.2,2.2,3.2) R(1.2,2.2,3.2)
2	LNG spill on deck to sea	(2.4,3.4,4.4)	H(0.0,0.0,1.0) E(0.0,0.0,1.0) F(0.0,0.0,1.0) T(0.6,1.6,2.6) R(0.0,0.0,1.0)
3	Filling liquid into compressor and boiler areas	(1.3,2.3,3.3)	H(1.5,2.5,3.5) E(0.0,0.0,1.0) F(0.0,0.0,1.0) T(1.5,2.5,3.5) R(0.0,0.0,1.0)
4	Fault in operational procedures	(1.6,2.6,3.6)	H(1.6,2.6,3.6) E(0.0,0.0,1.0) F(1.2,2.2,3.2) T(0.0,0.0,1.0) R(0.0,0.0,1.0)
5	High movements in LNG transfer system	(2.4,3.4,4.4)	H(0.0,0.0,1.0) E(0.0,0.0,1.0) F(0.0,0.0,1.0) T(0.8,1.8,2.8) R(0.0,0.0,1.0)
6	Lack of communication with shore personnel	(2.4,3.4,4.4)	H(1.0,2.0,3.0) E(0.0,0.0,1.0) F(0.0,0.0,1.0) T(0.0,0.0,1.0) R(0.0,0.0,1.0)
7	Personnel failing in adjusting the moorings during loading/unloading	(2.0,3.0,4.0)	H(1.2,2.2,3.2) E(0.0,0.0,1.0) F(0.0,0.0,1.0) T(0.0,0.0,1.0) R(0.0,0.0,1.0)
8	External forces from wind, wave and tide	(1.8,2.8,3.8)	H(0.0,0.0,1.0) E(0.0,0.0,1.0) F(0.0,0.0,1.0) T(1.0,2.0,3.0) R(0.0,0.0,1.0)
9	Fault in ballast system or fault operation of ballast system.	(1.6,2.6,3.6)	H(0.0,0.0,1.0) E(0.0,0.0,1.0) F(0.0,0.0,1.0) T(1.2,2.2,3.2) R(0.0,0.0,1.0)

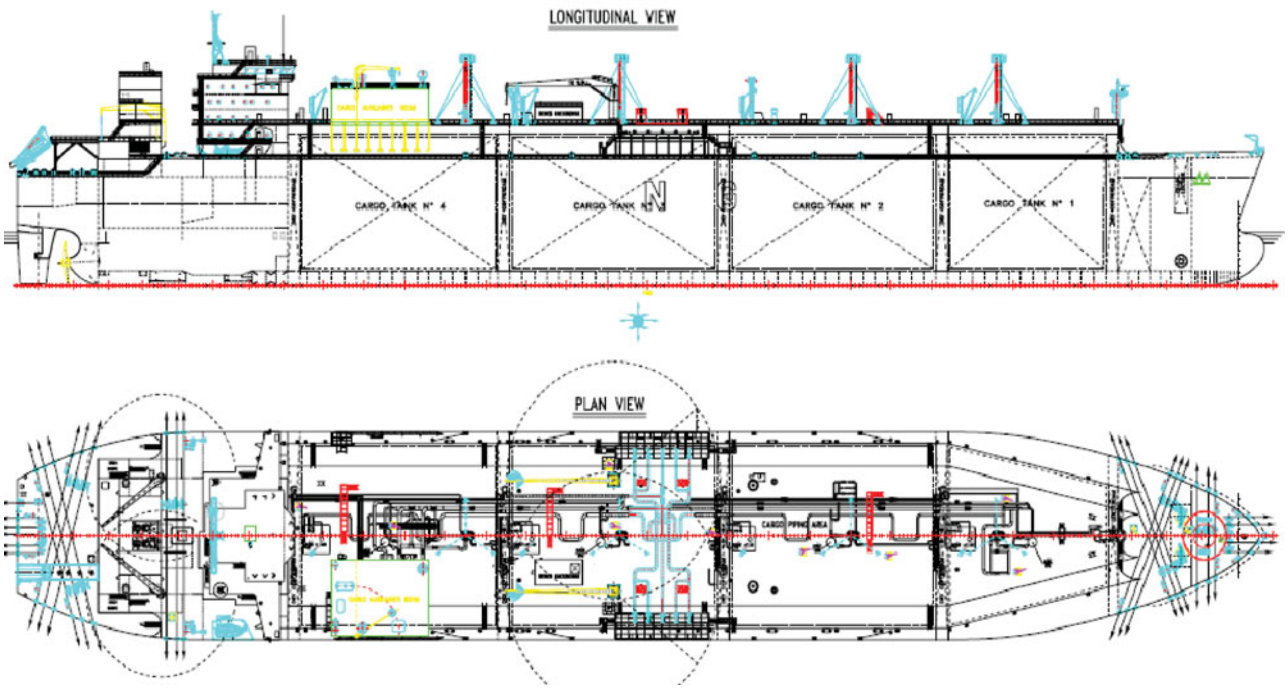

Figure 1. Principal particulars of the 138,000 m^3 LNG carrier (Safedor 2005). This figure is available in colour online.

sets (Elsayed 2009). Triangular membership functions, as shown in Figure 2, were adopted because of simplicity, convenience of mathematical operations and effectiveness in representing judgment distributions of multiple experts (Mentes and Helvacioglu 2012). A software tool was implemented using the Matlab program. Figure 2 shows the membership functions for the probability of occurrence and consequences modeled as fuzzy sets. Table 6 shows the first nine hazardous scenarios with probabilities and consequence values represented as fuzzy numbers. As seen from Table 1, scenario 1, overloading LNG cargo tanks, was assessed qualitatively by experts to affect consequences (H, E, T, R) but not cost and finance (F). Consequence F has a zero value for this scenario. In fuzzy environment, the consequence F is represented by the triangular fuzzy set, ‘close to zero,’ or (0,0,1). This implies that there might be some small, or close to zero, cost losses associated with scenario 1. Table 7 shows the fuzzy triangular membership function values and the fuzzy multiple-consequence risk matrix for the first nine hazardous scenarios. Columns of the fuzzy multiple-consequence risk matrix were not normalised since they represent cost attributes and are measured on the same scale. No weights were used to normalise the fuzzy risk matrix. The FPIS was calculated as

$$S^{*} = \{(4, 6, 8), (3.4, 5.4, 7.4), (4.4, 6.4, 8.4), (4.4, 6.4, 8.4), (3.4, 5.4, 7.4)\}.$$

The FNIS was calculated as

$$S^{-} = \{(1.6, 2.6, 4.6), (0.4, 1.4, 3.4), (0.4, 1.4, 3.4), (0.4, 1.4, 3.4), (0.4, 1.4, 3.4)\}.$$

Table 7. Fuzzy multiple-consequence risk matrix – $\tilde{R}$.

Hazard ID	H	E	F	T	R
1	(3.4,5.4,7.4)	(3.4,5.4,7.4)	(2.2,3.2,5.2)	(3.4,5.4,7.4)	(3.4,5.4,7.4)
2	(2.4,3.4,5.4)	(2.4,3.4,5.4)	(2.4,3.4,5.4)	(3.0,5.0,7.0)	(2.4,3.4,5.4)
3	(2.8,4.8,6.8)	(1.3,2.3,4.3)	(1.3,2.3,4.3)	(2.8,4.8,6.8)	(1.3,2.3,4.3)
4	(3.2,5.2,7.2)	(1.6,2.6,4.6)	(3.2,5.2,7.2)	(1.6,2.6,4.6)	(1.6,2.6,4.6)
5	(2.4,3.4,5.4)	(2.4,3.4,5.4)	(2.4,3.4,5.4)	(3.2,5.2,7.2)	(2.4,3.4,5.4)
6	(3.4,5.4,7.4)	(2.4,3.4,5.4)	(2.4,3.4,5.4)	(2.4,3.4,5.4)	(2.4,3.4,5.4)
7	(3.2,5.2,7.2)	(2.0,3.0,5.0)	(2.0,3.0,5.0)	(2.0,3.0,5.0)	(2.0,3.0,5.0)
8	(1.8,2.8,4.8)	(1.8,2.8,4.8)	(1.8,2.8,4.8)	(2.8,4.8,6.8)	(1.8,2.8,4.8)
9	(1.6,2.6,4.6)	(1.6,2.6,4.6)	(1.6,2.6,4.6)	(2.8,4.8,6.8)	(1.6,2.6,4.6)

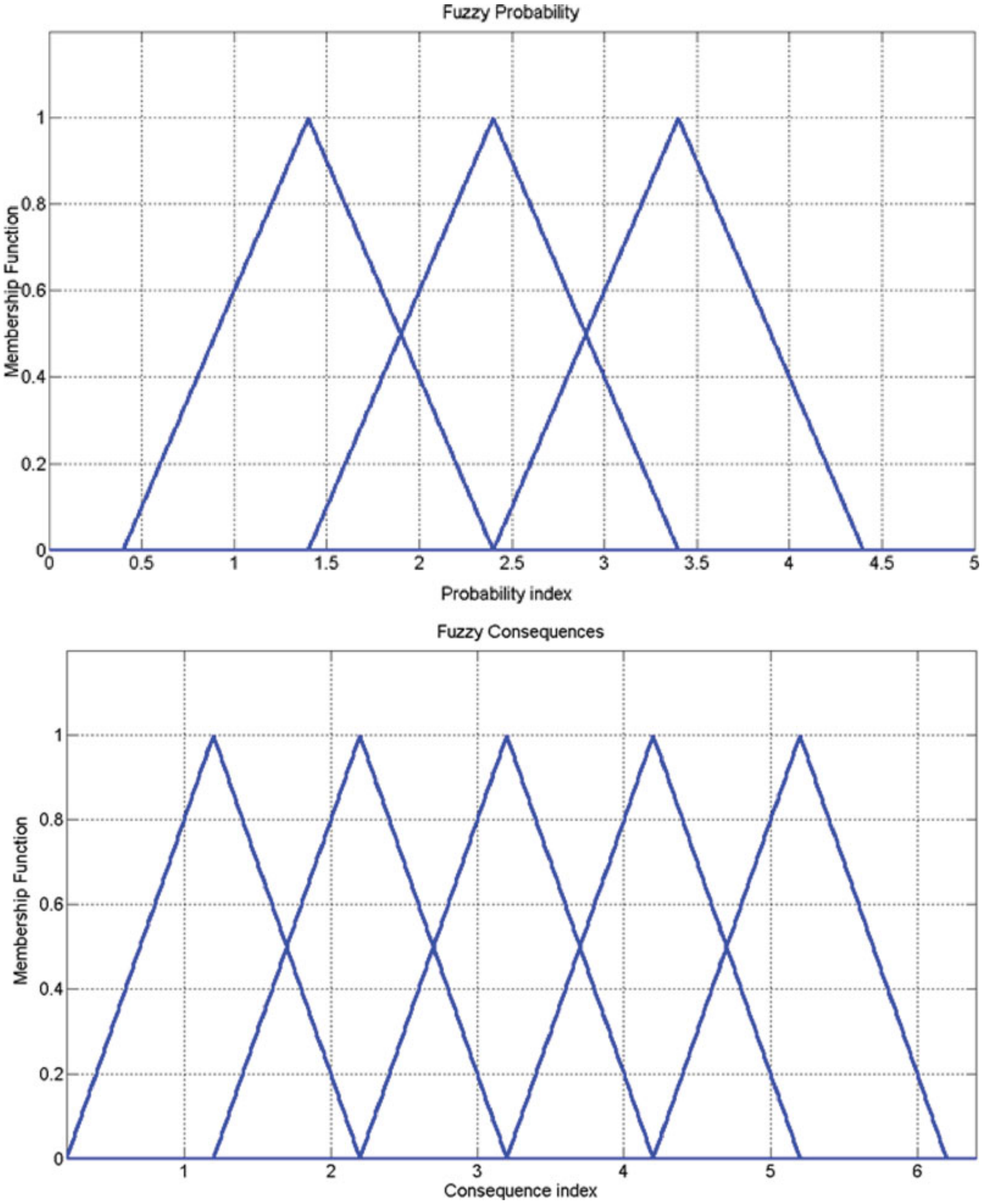

Figure 2. Membership functions for probability index and consequence index. This figure is available in colour online.

Separation distances from FPIS and FNIS, for the first nine hazardous scenarios, are shown in Tables 8 and 9, respectively.

6. Summary and discussion of results

Table 10 shows a summary of fuzzy TOPSIS risk ranking results. Separation distances from positive and negative ideal solutions are computed for the 18 scenarios. Table 11 provides a comparison between qualitative risk assessment and fuzzy TOPSIS risk assessment results for the 18 scenarios considered and 5 consequence attributes.

Table 8. Distance from FPIS – $d(\tilde{v}_{ij}, \overline{v}_j^*)$.

Hazard ID	*H*	*E*	*F*	*T*	*R*
1	0.6000	0.0000	2.9052	1.0000	0.0000
2	2.3152	1.7321	2.7080	1.4000	1.7321
3	1.2000	2.8065	3.7961	1.6000	2.8065
4	0.8000	2.5113	1.2000	3.4986	2.5113
5	2.3152	1.7321	2.7080	1.2000	1.7321
6	0.6000	1.7321	2.7080	2.7080	1.7321
7	0.8000	2.1197	3.1027	3.1027	2.1197
8	2.9052	2.3152	3.3005	1.6000	2.3152
9	3.1027	2.5113	3.4986	1.6000	2.5113

Table 9. Distance from FNIS – $d(\tilde{v}_{ij}, \overline{v}_j^-)$.

Hazard ID	H	E	F	T	R
1	2.5113	3.6968	1.8000	3.6968	3.6968
2	0.8000	2.0000	2.0000	3.3005	2.0000
3	1.9253	0.9000	0.9000	3.1027	0.9000
4	2.3152	1.2000	3.4986	1.2000	1.2000
5	0.8000	2.0000	2.0000	3.4986	2.0000
6	2.5113	2.0000	2.0000	2.0000	2.0000
7	2.3152	1.6000	1.6000	1.6000	1.6000
8	0.2000	1.4000	1.4000	3.1027	1.4000
9	0.0000	1.2000	1.2000	3.1027	1.2000

As can be seen from Table 11, 'overloading' of cargo tanks is the most severe scenario, while 'roll-over' due to lack of stability during loading/unloading is the least severe scenario. This is consistent with ranking results obtained using the qualitative method. Comparing the 2 ranking results, we find that 16 (out of 18) scenarios remain their ranking positions unchanged, while only 2 scenarios move their positions either up or down by 1 position.

In order to further assess the results, the degree of correlation between the two risk ranking results obtained by the two methods was calculated as

$$r = \frac{\operatorname{cov}(x, y)}{\sigma_x \sigma_y} = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n} (y_i - \bar{y})^2}} = 0.998, \tag{13}$$

where x = qualitative ranking results, y = fuzzy TOPSIS ranking results, $\bar{x}$ = mean value of x, $\bar{y}$ = mean value of y, $\operatorname{cov}(x, y)$ = covariance of x and y, σ_x = standard deviation of x and σ_y = standard deviation of y.

The high correlation coefficient value ($r = 0.998$) implies the effectiveness of using fuzzy TOPSIS method.

Figure 3 shows a comparison between qualitative and fuzzy risk values for the six most hazardous scenarios. Fuzzy TOPSIS closeness coefficient values were multiplied by 10, in order to plot the results for comparison purposes.

As can be seen, computed risk values using a fuzzy TOPSIS approach are consistent with those obtained using a qualitative risk matrix.

According to qualitative ranking, scenario S_{16}, 'clogging up pumps with ice cubes', has a higher rating than scenario S_2, 'LNG spill on deck to sea', that is, $S_{16} > S_2$, whereas in fuzzy TOPSIS, $S_2 > S_{16}$. Assessed qualitatively, S_2 affects only ship safety and technology – T consequence, as shown in Table 1. It has no effect on the consequences $\{H,E,F,R\}$. The qualitative consequence element of S_2 can be expressed as $\{H0,F0,T1.6,E0,R0\}$. When applying fuzzy sets, scenario S_2 affects all consequences, as shown in Table 6, including 'human safety' (H), 'environmental' (E), 'costs and finance' (F) and 'reputation and disruption' (R). Consequences are not processed to the risk picture as zero – no effect – but with the fuzzy number 'close to zero'. This effect gets added to the scenario probability resulting in an increase in the risk value of the scenario. The result is scenario S_2 outranking scenario S_{16}, that is, $S_2 > S_{16}$ with fuzzy TOPSIS values of $\text{Risk}_{S_2} = 0.5053$ and $\text{Risk}_{S_{16}} = 0.5015$, respectively. This shows that the fuzzy TOPSIS approach is capable of capturing uncertainty not realised by the simple qualitative method.

Table 10. Summary of fuzzy TOPSIS risk ranking.

Hazard ID	HAZID	Fuzzy TOPSIS			
		d^*	d^-	CC_i^*	Rank
1	Overloading	4.50	15.40	0.7737	1
2	LNG spill on deck to sea	9.88	10.10	0.5053	8
3	Filling liquid into compressor and boiler areas	12.20	7.72	0.3876	14
4	Fault in operational procedures	10.52	9.41	0.4722	10
5	High movements in LNG transfer system	9.68	10.29	0.5153	7
6	Lack of communication with shore personnel	9.48	10.51	0.5258	6
7	Personnel failing in adjusting the moorings	11.24	8.71	0.4366	13
8	External forces from wind, wave and tide	12.43	7.50	0.3763	15
9	Fault in ballast system or fault operation of ballast system	13.22	6.70	0.3364	16
10	Being struck by passing vessels	15.18	4.70	0.2364	17
11	Lack of crew competence and training	10.84	9.10	0.4565	11
12	Roll-over	17.57	2.31	0.1164	18
13	Tank depressurising	7.53	12.38	0.6216	3
14	Overfilling other tanks	11.11	8.81	0.4423	12
15	Debris in tanks	6.97	12.98	0.6505	2
16	Clogging up pumps with ice cubes	9.93	9.99	0.5015	9
17	Clogging of filter	8.36	11.59	0.581	5
18	Situations on terminal causing back fire on ship	8.00	11.89	0.5978	4

Table 11. Comparison between qualitative and fuzzy TOPSIS rankings.

Hazard ID	HAZID	Qualitative		Fuzzy TOPSIS	
		Value	Rank	Value	Rank
1	Overloading	4.96	1	0.7737	1
2	LNG spill on deck to sea	3.72	9	0.5053	8
3	Filling liquid into compressor and boiler areas	3.3	14	0.3876	14
4	Fault in operational procedures	3.64	10	0.4722	10
5	High movements in LNG transfer system	3.76	7	0.5153	7
6	Lack of communication with shore personnel	3.8	6	0.5258	6
7	Personnel failing in adjusting the moorings	3.44	13	0.4366	13
8	External forces from wind, wave and tide	3.2	15	0.3763	15
9	Fault in ballast system or fault operation of ballast system	3.04	16	0.3364	16
10	Being struck by passing vessels	2.64	17	0.2364	17
11	Lack of crew competence and training	3.52	11	0.4565	11
12	Roll-over	2.16	18	0.1164	18
13	Tank depressurising	4.24	3	0.6216	3
14	Overfilling other tanks	3.52	12	0.4423	12
15	Debris in tanks	4.36	2	0.6505	2
16	Clogging up pumps with ice cubes	3.76	8	0.5015	9
17	Clogging of filter	4.08	5	0.581	5
18	Situations on terminal causing back fire on ship	4.2	4	0.5978	4

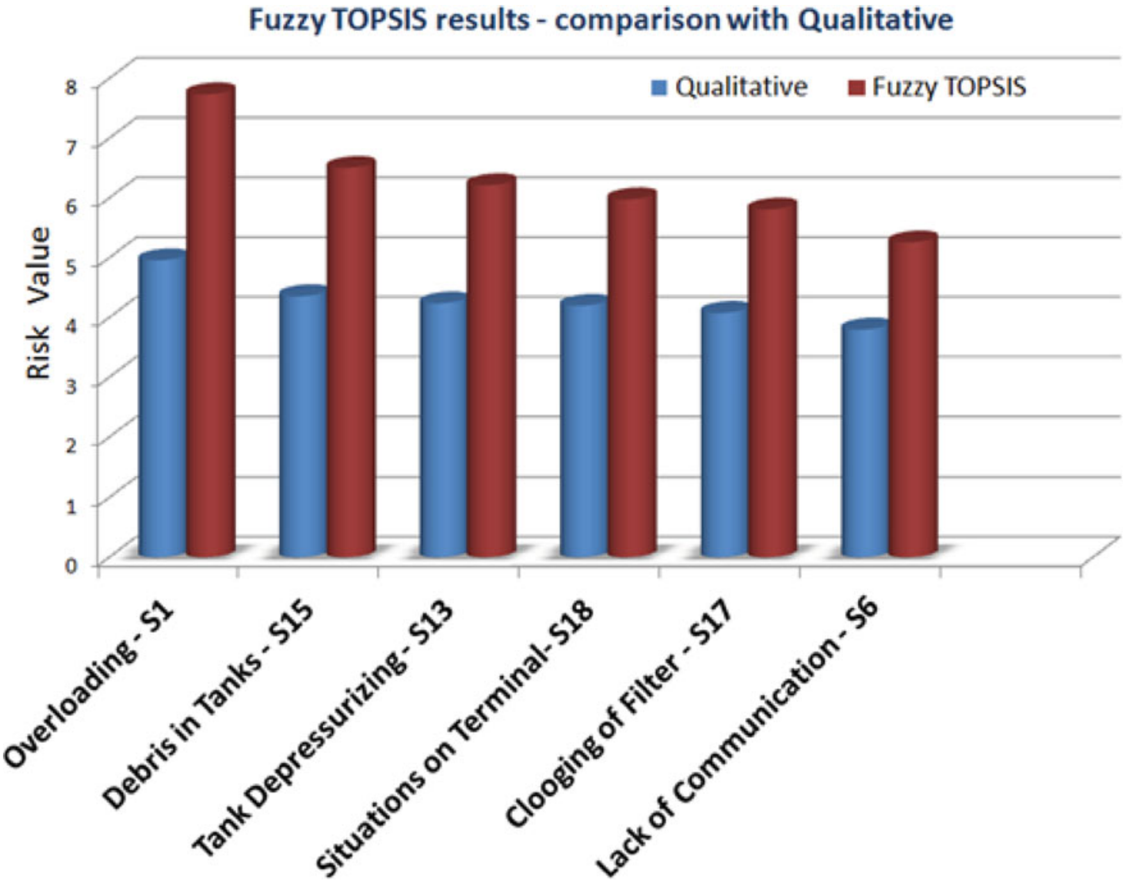

Figure 3. Comparison between fuzzy TOPSIS and qualitative results for six hazardous scenarios. This figure is available in colour online.

To further assess the results, we note that a fuzzy version of Equation (3) can be written as

$$\widetilde{\mathrm{Risk}}_i = \widetilde{P}_i + (\widetilde{H}_i + \widetilde{E}_i + \widetilde{F}_i + \widetilde{T}_i + \widetilde{R}_i)/5. \tag{14}$$

For scenario S_2, fuzzy probability and consequence values (Table 6) are given by $\widetilde{P}_2 = (2.4, 3.4, 4.4)$, $\widetilde{H}_2 = (0, 0, 1)$, $\widetilde{E}_2 = (0, 0, 1)$, $\widetilde{F}_2 = (0, 0, 1)$, $\widetilde{T}_2 = (0.6, 1.6, 2.6)$ and $\widetilde{R}_2 = (0, 0, 1)$. Using the arithmetic of triangular fuzzy numbers, the risk value of S_2 is calculated as $\widetilde{\mathrm{Risk}}_{S2} = (2.52, 3.72, 5.72)$.

Similarly, risk value of S_{16} can be calculated as $\widetilde{\mathrm{Risk}}_{S16} = (2.36, 3.76, 5.76)$. The centre of gravity, CoG, or geometric centre of a triangular fuzzy number (l, m, u) can be expressed as

$$\mathrm{CoG} = l + \frac{(u-l)+(m-l)}{3}, \tag{15}$$

where (l, m, u) are the lower, middle and upper values of the fuzzy triangular number. Comparing the two fuzzy risk numbers, CoG (S_2) = 3.9867and CoG (S_{16}) = 3.9600, that is, $S_2 > S_{16}$. This is the same result obtained using fuzzy TOPSIS and confirms that change in rank of the two scenarios (S_2 and S_{16}) is a direct result of incorporating uncertainties irrespective of the TOPSIS method.

7. Conclusions

The fuzzy technique for order preference by similarity to ideal solution, fuzzy TOPSIS, is one of the well-known multiple-criteria decision-making techniques. A framework approach for the risk assessment of LNG carriers using fuzzy TOPSIS was developed in this study.

Eighteen hazardous scenarios with five consequence attributes were evaluated and fuzzy positive and negative ideal solutions were determined. A final fuzzy score was computed for each scenario. The final risk ranking shows consistency between the results of the qualitative and the fuzzy TOPSIS risk assessment and both results are highly correlated. The classical qualitative method cannot deal with the expert ambiguity, uncertainty and vagueness, but instead handles such assessments as crisp value. Fuzzy TOPSIS has been shown effective in incorporating uncertainty and imprecision into various expert subjective ratings of accident probabilities and consequences. It is practical for representing judgment distributions of multiple experts. The fuzzy TOPSIS risk assessment method could serve as a promising analysis method for the improvement of risk-based approaches required by design codes.

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