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Risk assessment of marine LNG operations

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1. Introduction

The safety and reliability of LNG transfer operations is a major concern for LNG operating companies. LNG hazards have a high potential financial impact in addition to shutdown and failure of delivery. The LNG industry has developed and refined its practices gradually over the past 30 years, achieving very good results. Risk assessment/management of LNG marine terminal operations is an essential tool, however, for maintaining the industry's record for safe operations at LNG terminals.

This chapter presents various methodologies for the risk assessment of LNG transfer operations at the ship-shore interface of gas terminals. Hazards are identified as well as potential accident consequences. Various risk assessment approaches for modeling LNG accident scenarios at gas terminals are presented. These include qualitative risk matrices, multiple attribute utility models and a fuzzy inference system. LNG accident consequences (SIGTTO, 1999) involve multiple consequence classes such as personnel injuries, environmental pollution and loss of material assets. These consequences have different measurement scales and need to be combined in order to assess/rank risks arising from various hazardous scenarios. Fig. 1 shows the different consequence classes for an LNG ship accident while loading/offloading at the terminal (Elsayed et al., 2009).

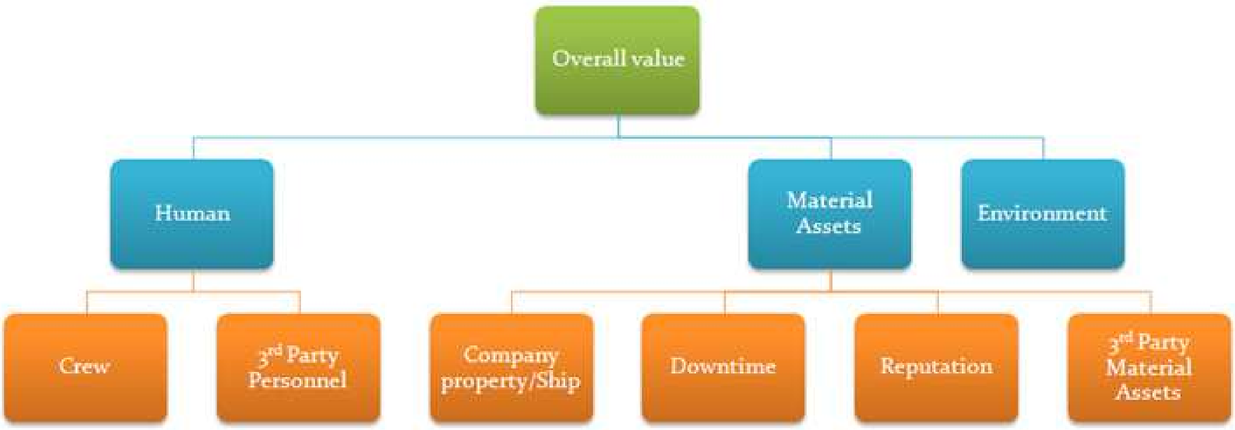

Fig. 1. Consequence classes resulting from hazardous sceanrios

2. Qualitative Risk Assessment

A standard qualitative risk assessment approach involves the evaluation of likelihood or probability of different accident scenarios (American Bureau of Shipping, 2000; HSE, 2002). Next an evaluation of the impact of the different accident scenarios with respect to the different consequence attributes is carried out. A risk matrix is often used in this approach. A risk matrix combines the likelihood of an event with its consequence severity into a risk level. Table 1 shows a sample qualitative assessment of the probabilities of occurrence of an LNG ship accident while loading/unloading at the terminal. Probabilities are assigned letters such as A, B, C, D and E corresponding to a linguistic scale: `frequent', `probable', `occasional', `remote' and `improbable' likelihoods. An indicative quantitative frequency range is associated with each probability level.

Level	Description	Indicative Frequency (per vessel year)	Definition
A	Frequent	>0.5	Will occur frequently
B	Probable	0.05-0.5	May occur several times
C	Occasional	0.005-0.05	Likely to occur during lifetime
D	Remote	0.0005-0.005	Unlikely to occur during lifetime
E	Improbable	< 0.0005	So unlikely event it may never be experienced

Table 1. Definition of likelihood levels

Table 2 shows a similar qualitative assessment of LNG accident consequence categories. Consequences are assigned numbers such as 1, 2, 3 and 4 corresponding to `minor', `major', 'critical' and `catastrophic' severity level. An indicative descriptive linguistic range is associated with each consequence attribute and severity level.

Consequence Class	**1**	**2**	**3**	**4**
	Minor	**Major**	**Critical**	**Catastrophic**
Crew	Minor injury	Serious injury	One fatality	Several fatalities
3rd Party personnel	No injury	Minor injury	Serious injury	Fatalities
Environmental	Negligible pollution	Pollution reportable to regulatory authorities Minor release	Pollution reportable to regulatory authorities Major release	Pollution reportable to regulatory authorities Uncontrolled pollution
Ship damage	Minor damage	Moderate damage	Major damage	Loss of ship
Downtime	Negligible	One day	One week	More than one week
Reputation	Negligible	Affected localy	Affected nationaly	Loss of reputation
3rd party assets	No effect	Minor damage	Major damage	Extensive damage

Table 2. Definition of severity levels of accident consequences

Table 3 shows an example of the risk matrix used by ship classification societies. The risk matrix combines likelihood and severity into an output linguistic risk level for each scenario and consequence attribute. These linguistic risk values are then combined to give an overall linguistic risk value for each accident scenario being evaluated. Output risk level are denoted linguistically as `low', `medium' or `high' (Skramstad & Musaeus, 2000).

		SEVERITY			
		1	2	3	4
LIKELIHOOD	A	M	H	H	H
	B	M	M	H	H
	C	L	M	M	H
	D	L	L	M	M
	E	L	L	L	L

Table 3. Example of a qualitative risk matrix

3. Multiple Attribute Utility Risk Model

A multiple attribute risk assessment approach using utility theory is presented in this section (Elsayed et al., 2009). Multiple attribute risk assessment based on utility theory has many advantages. Most importantly, it allows LNG operating companies to identify/rank operational risks and to express their expectations about the consequences of various hazardous scenarios. It also provides insights into how the uncertainty of their expectations affects the ranking of risk scenarios. In addition, multiple attribute risk assessment provides a systematic method for evaluating an organization's risks using the best available hazard information. As operating companies gain better hazard/consequence information, the risk models can be easily updated with new input data and the marginal effect on risk assessment can be measured. The value of a multiple attribute risk assessment is not only in the numbers produced, but also in the insights that operating companies gain during sensitivity analyses and each refinement step of the assessment.

3.1 Modelling Consequences Using Utility Functions

Utility is a number measuring the attractiveness of a consequence, the higher the utility, the more desirable the consequence, the measurement sometimes being made on a probability scale (Clemen, 1997; Lindley, 1992;). Different people and/or organizations have different risk attitudes and thus are willing to accept different levels of risk (Oliver & Marshall, 1997). Some are prone to taking risks while others are more conservative and tend to avoid risk. Individuals who are unwilling to risk a substantial part of their assets even for positive expected return are said to be risk averse. Those willing to take a risky venture for a negative expected return are said to be risk seeking. Finally, an individual can be risk neutral. Risk neutrality is reflected by a utility curve that is a simple straight line. A decision maker that has a constant aversion to risk, is referred to as constantly risk-averse decision maker. In this work, the constant risk aversion utility model is adopted. This is to reflect the fact that LNG accident consequences are acute in nature with very severe consequences and LNG ship operators are constantly averse in taking accident risks. An example of a utility function is the exponential utility function with constant risk aversion and can be expressed as:

$$u(x) = \frac{e^{-b(x - x_{\min})} - 1}{e^{-b(x_{\max} - x_{\min})} - 1} \tag{1}$$

Where x_{max} and x_{min} are best (most preferred) and worst (least preferred) values of the consequence attribute and b is a coefficient of risk aversion. In order to model the consequence classes shown in Fig.1, seven utility functions are needed corresponding to the seven consequence attributes. Each utility function is constructed such that the most preferred value x_{max} for the consequence of interest would be 'minor' or 'negligible' consequence on a qualitative scale and would correspond to a utility value of 1. Whereas the least preferred value would correspond to 'catastrophic', corresponding to a utility value of 0.

3.2 Probabilistic Multiple Attribute Utility Risk Model

A probabilistic multiple attribute risk model can be used for modeling situations during LNG ships loading/offloading at the LNG ship/terminal interface where risks needs to be assessed and ranked in terms of severity. Various resulting hazard consequences are taken into account, and a systematic and consistent evaluation of various risk alternatives is carried out to determine most/least severe risk alternative. These include environmental pollution, injuries/fatalities to crew or 3rd party personnel and material assets such as ship damage, down time, reputation and third party material assets.

Multiple attribute utility theory is then used to combine the effects of different consequences into a unified utility measure. According to the maximum expected utility (MEU) concept (Chen & Hwang, 1992), a maximum risk alternative is selected such that:

$$R_{\max} = \min_{1 \le i \le M} \sum_{j=1}^{N} k_{ij} u_j \tag{2}$$

R_{max} = maximum risk alternative.
M = number of risk alternatives or hazards.
N = number of consequences.
k_{ij} = weight of importance of the jth consequence.
u_j = measure of consequence, utility, of the ith consequence in terms of jth risk alternative

This semi-quantitative approach assigns a numeric expected utility value for each risk scenario thus allowing the ranking of various hazardous scenarios. Software tools can be used to implement the abovementioned risk model.

4. Fuzzy Risk Assessment

4.1 Modelling of Probabilities and Consequences as Fuzzy Sets

In many engineering situations there is pervasive fuzzy information, *i.e.* information that is vague/qualitative, linguistic and/or imprecise (Bellman & Zadeh, 1970; Chen & Hwang, 1992; Zadeh, 1965; Zadeh, 1975; Zimmerman, 1976; Zimmerman, 1987). This is often the case when trying to assess accident probabilities/consequences that are not known a priori and/or difficult to quantify mathematically (Elsayed et al., 2008). The assignment of accident probabilities is usually based on reliability methods and/or historical failure data. Reliability methods require knowledge of the relevant physical process and the specification of a limit state function (Elsayed & Mansour, 2003). In many cases, historical failure data can be lacking and/or unreliable. When historical failure data is available, it can be supplemented with expert judgment (Cooke, 1996). These approaches however are not sufficient to predict accident probabilities under all relevant circumstances. This is due to lack of knowledge of physical conditions and processes, change of industry practice over the years, and lack/unreliability of data. Hence, predictions of accident probabilities are often associated with significant uncertainties. In fact it is because of these uncertainties that many risk assessment tools avoid absolute probability values all together and stick to relative probabilities (American Gas Association, 1990).

LNG accident consequences (Elsayed et al., 2009; Gyles, 1992; Skramstad & Musaeus, 2000; McGuire & White, 1999) vary from personnel injuries to environmental pollution and loss of material assets. These consequences are imprecise in nature, each with its own measurement scale, and cannot be added mathematically. They may however be defined linguistically or on a qualitative scale. In this section, a new approach for the risk assessment of LNG carriers using a fuzzy inference system FIS is adopted. The main advantage of the use of the fuzzy inference system is its ability to handle imprecise data. The approach uses the concept of a pure fuzzy logic system. A fuzzy rule base is constructed to follow the logic used by the risk assessor when using the traditional qualitative risk matrix approach. The fuzzy inference engine uses these rules to determine a mapping from probability and consequences, modeled as fuzzy sets, to a fuzzy output set of risk values. In doing so, it is implied that probabilities/consequences used in the risk assessment process have an inherent degree of uncertainty.

4.2 Fuzzy inference System

Fuzzy inference is the process of mapping from a given input set to an output set using fuzzy logic. Membership functions, fuzzy logic operators and *if-then* rules are used in this process. The fuzzy inference system FIS is known in the literature by a number of names, such as fuzzy-rule-based system, fuzzy expert system or simply a fuzzy system (Kandel, 1992). The basic advantage of such system is its tolerability to linguistic/imprecise data. In this work, the Mamdani and the Sugeno fuzzy inference methods are adopted (Mathworks, Inc., 2006). In the Mamdani type of inference, the output membership functions are fuzzy sets. These are in turn defuzzified to obtain a crisp output risk value for each consequence alternative.

In the Sugeno method of fuzzy inference, output membership functions are either linear or constant. A typical rule in a Sugeno fuzzy model has the form:

$$If\ Input\ 1 = x\ and\ Input\ 2 = y, then\ Output\ is\ z = ax + by + c \tag{3}$$

Where a, b and c are the consequence parameters of the rule. The output level *zi* of each rule is weighted by the firing strength wi of the rule. For example, for an AND rule with Input 1 = *x* and Input 2 = *y*, the firing strength is

$$w_i = AndMethod(F_1(x)F_2(y)) \tag{4}$$

where *F*1,2 *(.)* are the membership functions for inputs 1 and 2.
The final output of the system is the weighted average of all rule outputs, computed as

$$Final\ Output = \frac{\sum_{i=1}^{N} w_i z_i}{\sum_{i=1}^{N} w_i} \tag{5}$$

where *N* is the number of rules.
Fig 2 shows the structure of the Mamdani fuzzy inference system FIS used for the assessment of a risk value for each consequence class or attribute.

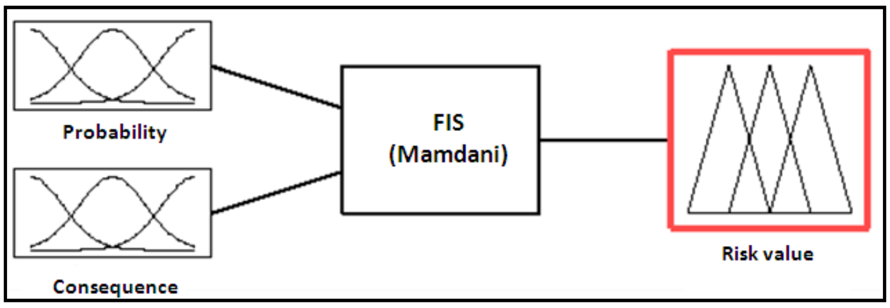

Fig. 2. Fuzzy inference system for the assessment of risk values

Fig. 3 shows a Sugeno FIS including two input variables x, y, and one output variable z.

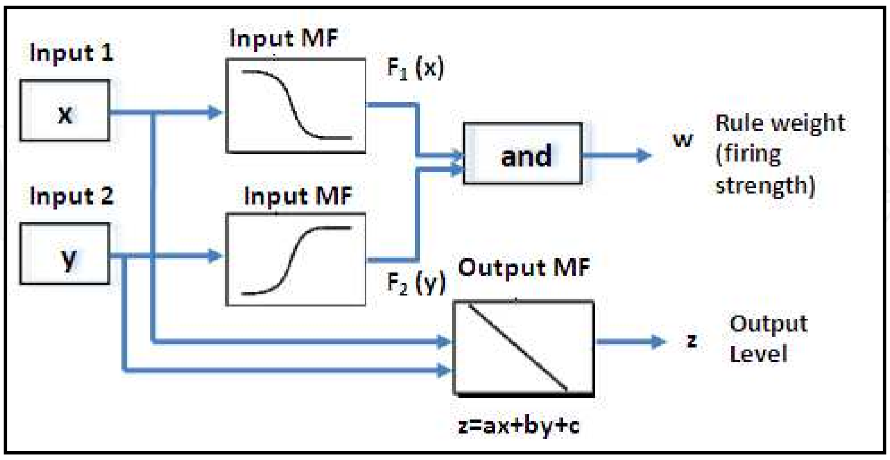

Fig. 3. Fuzzy inference process – Sugeno s method

5. Case Study: Assessment of LNG Risks during Loading/offloading at Terminals

A case study is used to demonstrate the above mentioned approaches for an LNG carrier loading at the terminal. Six hazardous scenarios are evaluated during LNG loading/offloading at the terminal (Elsayed, 2009). These are summarized in Table 4. As seen from Table 4, each consequence is denoted by a letter followed by a number. The letters (C,P,E,S,D,R,M) correspond to the consequence class for e.g. (crew, 3rd party personnel, environment, ship, downtime, reputation and 3rd party material assets). The numbers (1, 2, 3, and 4) correspond to the degree of severity of the consequence, for e.g. 'minor', 'major', 'critical' and 'catastrophic') on a qualitative scale.

Haz id	Hazard Description	Likelihood	Consequences
1	**Leak on the cargo system:** unignited release – continuos flow. This comprises all leak sizes that cannot easily be stopped by operatioal routines to a rupture in apipe. Potential consequences is brittle fracture of hull or secondary structure. Frost burns for personnel. No consequences to 3rd party anticipated.	Occasional (C)	C2, P1, E1, S2, D3, R3, M1
2	**Release of liquid nitrogen**: can give local effects to steel due to low temperature. Possible frost burn for personnel.	Occasional (C)	C2, P1, E1, S2, D2, R1, M1
3	**Release of bunker oil during loading operation**. Very low risk of fire and personnel injuries. The oil may mess up nearby quays affecting 3rd party assets.	Occasional (C)	C1, P1, E3, S1, D2, R3, M2
4	**Fire in the engine room**. Since always manned during this operational mode, the escalation potential is considered low. The event is considered not to affect 3rd party. All fires will have to be reported terminal, thus local reputation is affected.	Remote (D)	C3, P1, E1, S2, D3, R3, M1
5	**Accomodation fires**. The crew present in the accomodation most likely quickly extinguishes these fires. It is considered to be less likely to occur than fire in the engine room, but still a remote probability. If developing to a large fire more crew members may be affected by the accident, than for an engine room fire. 3rd party not likely to be affected.	Remote (D)	C3, P1, E1, S2, D3, R3, M1
6	**Fires on open deck.** Ignited cargo release. The consequences depend on the release size and the development of the event, including shutdown. Early ignition gives smaller consequences than late ignition. Most likely there is a flash fire which burn back to a smaller fire at the release location (jet or diffusive, depending on pressure in the system and if the release hits obstructions or not). Wether the fire may escalate to the LNG tanks depend on the possibility to shut down fuel to the fire.	Remote (D)	C4, P3, E1, S3, D4, R3, M2

Table 4. Hazards considered during LNG loading/offloading at terminal

5.1 Qualitative Risk Assessment Results

Table 5 provides a summary of the calculated qualitative risk values for the six hazardous scenarios and seven consequence attributes. As can be as seen the various consequence attributes are assigned linguistic risk values (low, medium, high) using the qualitative risk matrix outlined above. These consequences are then combined to provide an overall linguistic risk value for each accident scenario.

	Leak on the cargo system	Release of liquid nitrogen	Release of bunker oil	Fire in engine room	Accommodation Fires	Fires on open deck
Crew	Medium	Medium	Low	Medium	Medium	Medium
3rd party personnel	Low	Low	Low	Low	Low	Medium
Environment	Low	Low	Medium	Low	Low	Low
Ship	Medium	Medium	Low	Low	Low	Medium
Downtime	Medium	Medium	Medium	Medium	Medium	Medium
Reputation	Medium	Low	Medium	Medium	Medium	Medium
3rd party material assets	Low	Low	Medium	Low	Low	Low
Final rating	Medium	Low	Medium	Low	Low	Medium

Table 5. Summary of calculated qualitative risk values for six hazardous scenarios and seven consequence attributes.

5.2 Multiple Attribute Utility Risk Assessment Results

A software tool has been written using a decision analysis software suite (Treeage, 2006) to implement the abovementioned risk model. Fig. 4 shows the risk model used for modeling of the LNG carrier loading/offloading at the terminal. Emanating from the hazard node are the six accident scenarios. These are ‘leak on the cargo system’, ‘release of liquid nitrogen’, ‘release of bunker oil’, ‘fire in the engine room', ‘accommodation fires’ and ‘fires on open deck’. Each hazard is associated with a probability level. An overall consequence for each scenario is measured by seven consequences (crew, third-party personnel, environment, ship, down time, reputation and third-party material assets). Each consequence is modeled using a utility function. Formulated in this way, the optimum or minimum risk alternative corresponds to the highest maximum expected utility (MEU). The decision analysis software DATA (Decision Analysis by Treeage) was used for the modeling of the risk model. Sensitivity of hazardous scenarios to various model variables can also be carried out. Fig. 5 shows the output of the risk model for the six hazardous scenarios. The risk model shows the most severe scenario, ‘Fire on Open Deck’, in this case corresponding to minimum total expected utility (MTEU) value of 0.00406. The program windows interface shows a red color, which indicates the most severe scenario.

Fig. 6 shows a snapshot of a one-way sensitivity analysis with respect to ‘occasional probability’. As can be seen the recommendations of the risk model are not affected by the change in the probability level within the range considered (0.005–0.05)

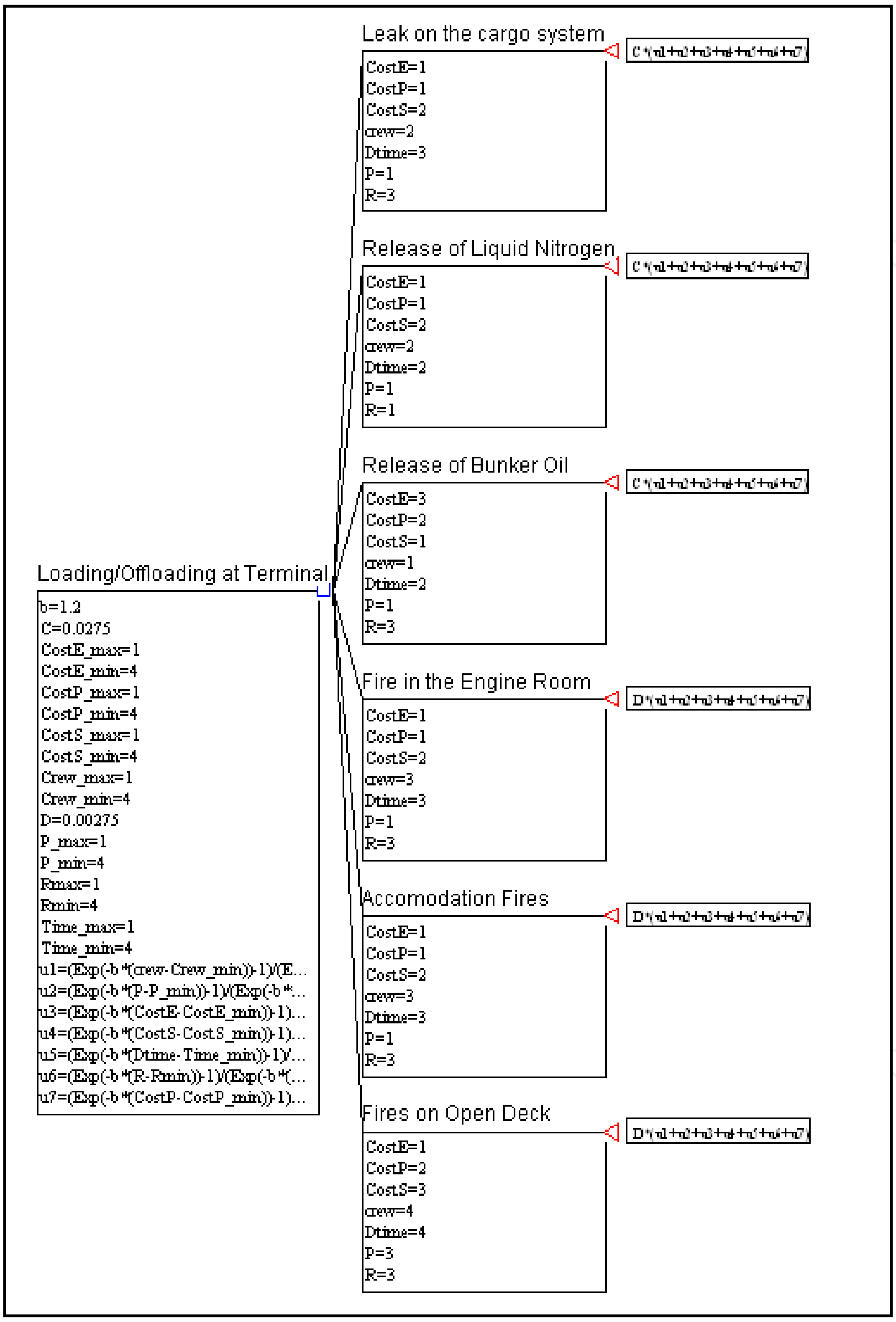

Fig. 4. Basic framework for risk model for LNG loading/offloading at terminal using multiple attribute utility theory

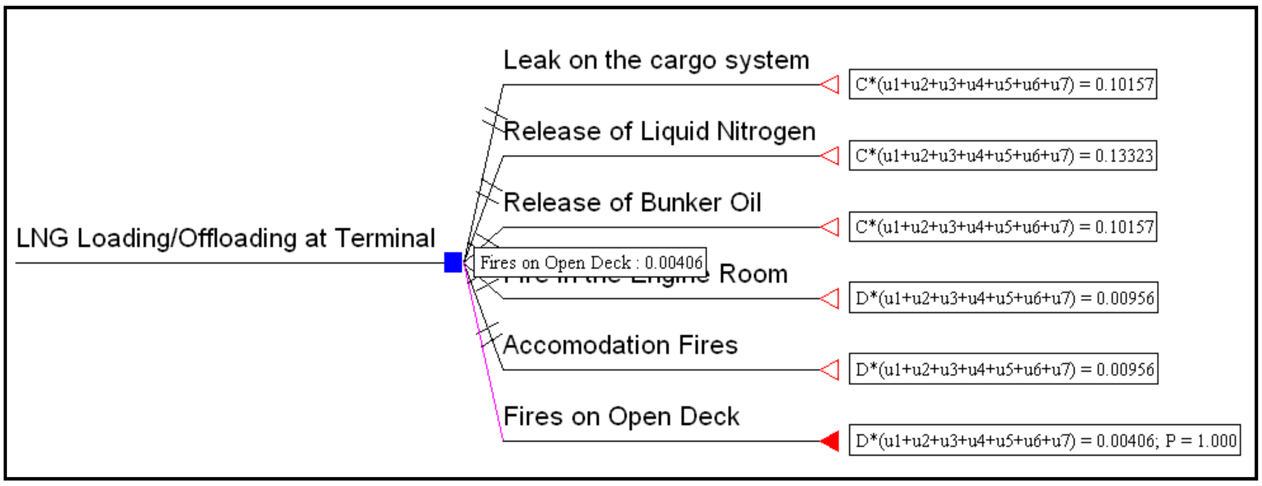

Fig. 5. Risk model showing most severe scenario 'fires on open deck', corresponding to minimum total expected utility

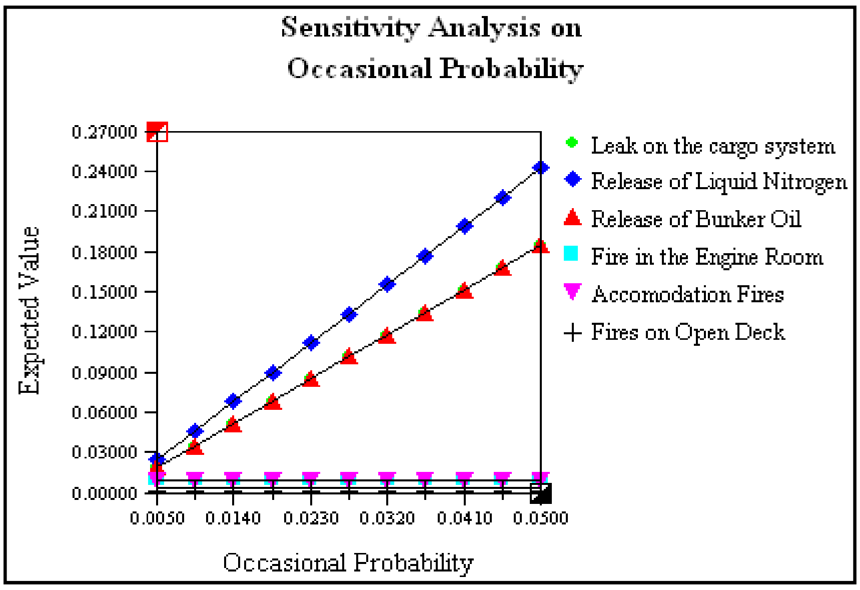

Fig. 6. Sensitivity analysis on 'occasional probability'.

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5.3 Fuzzy Risk Assessment Results

5.3.1 Determination of Membership Functions and Rule Base

In order to adopt this approach for risk assessment, probabilities of accident scenarios as well as accident consequences are modeled as fuzzy sets. In doing so, it is implied that probabilities/consequences are by themselves uncertain or at least a degree of uncertainty is associated with their values. Several approaches for building and adapting membership functions exist (Zhou et al., 1997). In this work, a fixed center-based membership function approach using the symmetric Gaussian membership function was adopted. One membership function is assigned to each value of the fuzzy variable. The Gaussian membership function depends on two parameters and is given by:

$$f(x,\sigma,c) = e^{\frac{-(x-c)^2}{2\sigma^2}} \tag{6}$$

Where c is the mean value and σ is the standard deviation. Membership functions are centered, each at the mid-value of the numeric interval associated with each fuzzy variable. For example for 'remote probability' the Gaussian membership functions is centered on the average value of the interval (0.005-0.0005) which would correspond to a mean value c=0.00275, as shown in Table 6. The standard deviation parameters σ for the Gaussian functions were chosen such that membership function curves are completed with the minimum and maximum points of the interval associated with each of the fuzzy variables (Zhou et al., 1997). With these membership functions each input value will belong to no more than two fuzzy sets. Fig. 7 shows the membership functions for the probability of occurrence and consequences respectively modeled as fuzzy sets. Probabilities of occurrence are represented by fuzzy sets whose ranges are chosen to coincide with the indicative frequency ranges shown in Table 1. Similarly, accident consequences are represented by fuzzy sets whose ranges are chosen to coincide with the indicative severity levels shown in Table 2. Figure 8 shows the membership functions for the resulting risk value. A scale of 1 to 10 was adopted to represent output risk values. As can be seen, the use of fuzzy sets allows representation of linguistic terms, such as 'frequent', 'probable', 'occasional', 'remote' and 'improbable' for likelihoods. Consequences are also represented linguistically as 'minor', 'major', 'critical' and 'catastrophic'. Finally output risk values are denoted as 'low', 'medium' and 'high'. Table 6 summarizes the membership type and parameters adopted in the developed fuzzy inference system FIS.

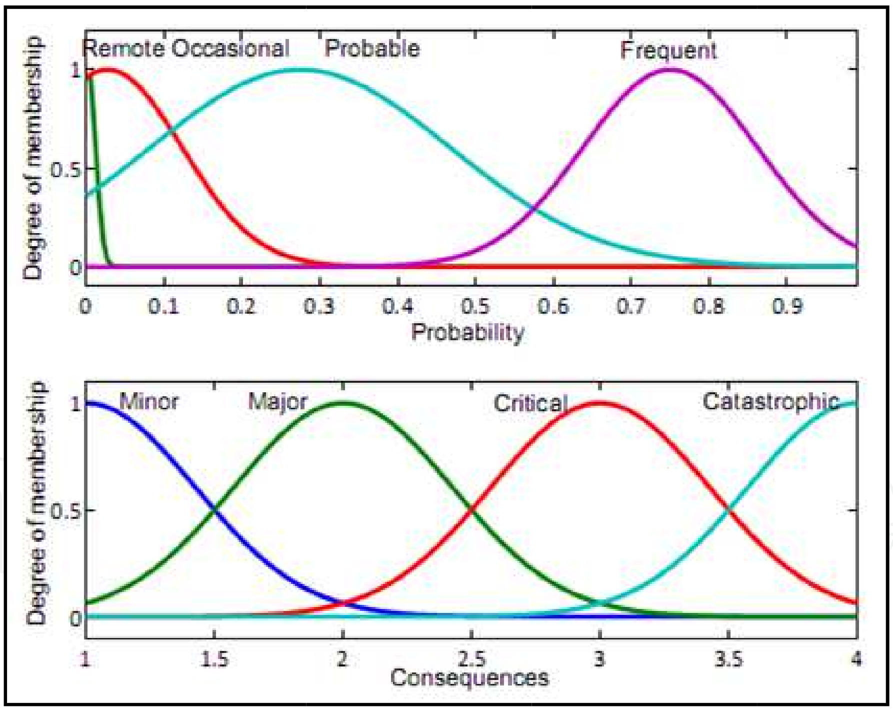

Fig. 7. Membership functions for probability of occurrence and consequence severity levels

Table 6. Membership type and parameters in the fuzzy inference system.

Variable	Value/Range	Membership Type	Membership parameters (σ,c)
Probability –' frequent'	> 0.5	Gauss	(0.11,0.75)
Probability – 'probable'	0.5-0.05	Gauss	(0.19,0.275)
Probability – 'occasional'	0.05-0.005	Gauss	(0.09,0.0275)
Probability- 'remote'	0.005 -0.0005	Gauss	(0.009,0.00275)
Probability- 'improbable'	< 0.0005	Gauss	(0.0009,0.000275)
Consequence- 'catastrophic'	4	Gauss	(0.4247,4)
Consequence- 'critical'	3	Gauss	(0.4247,3)
Consequence- 'major'	2	Gauss	(0.4247,2)
Consequence- 'minor'	1	Gauss	(0.4247,1)
Risk – 'high'	10	Gauss	(1.911,10)
Risk – 'medium'	5.5	Gauss	(1.911,5.5)
Risk – 'low'	1	Gauss	(1.911,1)

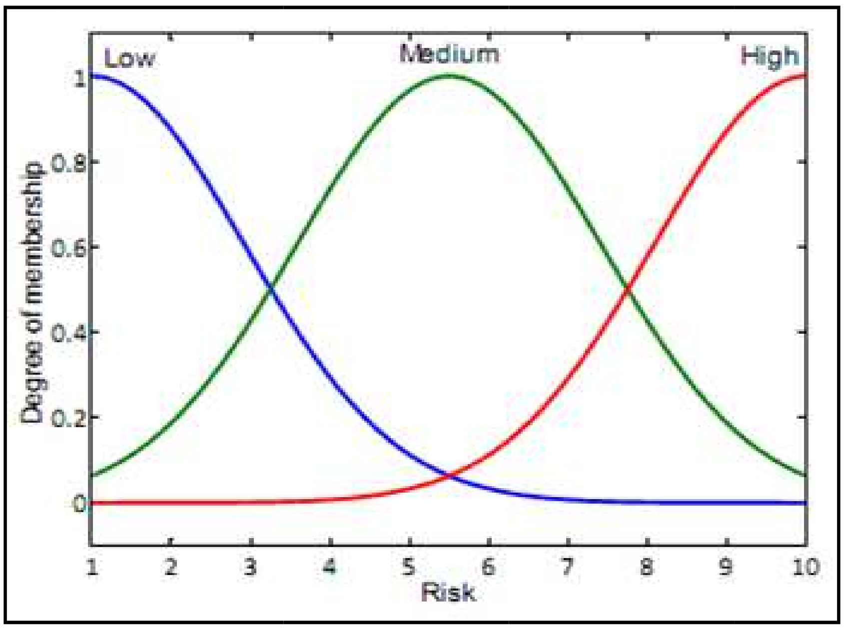

Fig. 8. Membership functions for risk values

The mapping between probability, consequences and final risk value is accomplished by the use of fuzzy *if-then* rules. For a single attribute risk problem, a total of twenty *if-then* rules can be used in the fuzzy inference system FIS to provide the mapping between probability, consequence and the computed risk value. The rules are designed to follow the logic of the risk assessor when using the qualitative risk matrix approach outlined earlier. First twelve rules of the developed system are listed below.

Rule 1: if (Probability is Frequent) and (Consequence is Minor) then Risk is Medium.
Rule 2: if (Probability is Frequent) and (Consequence is Major) then Risk is High.
Rule 3: if (Probability is Frequent) and (Consequence is Critical) then Risk is High.
Rule 4: if (Probability is Frequent) and (Consequence is Catastrophic) then Risk is High.
Rule 5: if (Probability is Probable) and (Consequence is Minor) then Risk is Medium.
Rule 6: if (Probability is Probable) and (Consequence is Major) then Risk is Medium.
Rule 7: if (Probability is Probable) and (Consequence is Critical) then Risk is High.

Rule 8: if (Probability is Probable) and (Consequence is Catastrophic) then Risk is High.
Rule 9: if (Probability is Occasional) and (Consequence is Minor) then Risk is Low.
Rule 10: if (Probability is Occasional) and (Consequence is Major) then Risk is Medium.
Rule 11: if (Probability is Occasional) and (Consequence is Critical) then Risk is Medium
Rule 12: if (Probability is Occasional) and (Consequence is Catastrophic) then Risk is High.

As can be seen, the first four rules represent the first row in the qualitative risk matrix given in Table 3. The second row in the matrix is represented by the next four rules *i.e.* rules 5-8 and so on. For the qualitative risk matrix given in Table 3, (Skramstad & Musaeus, 2000), the numbers of rows is five and the number of columns is four, *i.e.* a total of twenty rules are needed for modeling the logic embedded in this matrix. As such, the total number of rules needed to construct the fuzzy inference engine can be expressed as:

$$N = m \times n \tag{7}$$

where N = number of fuzzy *if-then* rules
m = number of rows in qualitative risk matrix.
n = number of columns in qualitative risk matrix.

These rules provide the mapping for each hazardous scenario for only one consequence attribute.

5.3.2 Application to Hazardous Scenarios

Often LNG risk assessment problems involve multiple consequence attributes for each hazardous scenario, such as material assets, human life and/or environmental pollution. These consequences are combined to provide an overall risk value for each accident scenario. In this work, a fuzzy risk index FRI is used to combine the various consequence attribute risks into a unified risk measure. The fuzzy risk index FRI value is an average aggregation operator for each accident scenario can be calculated by (Yager, 1988)

$$FRI = \frac{(\sum_{i=1}^{N} k_i Risk_i)/N}{\sum_{i=1}^{N} k_i} \tag{8}$$

where N = number of consequences.
k_i = weight factor for each consequence.
$Risk_i$ = calculated fuzzy risk value for each consequence attribute.

The weighting factors k_i reflects the attribute's relative importance. Fig. 9 shows the structural hierarchy and information storage for the fuzzy inference system used. The FIS structure contains various substructures which in turn contain variable names, membership function definitions and computation method.

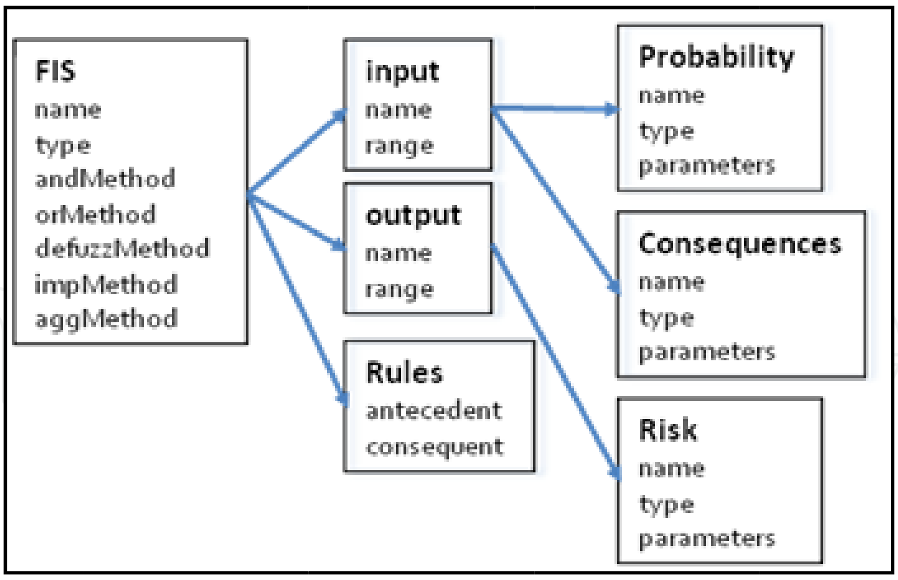

Fig. 9. Fuzzy inference system structural hierarchy

Figures 10 and 11 show the resulting output surface envelopes for both the Mamdani/Sugeno methods for two fuzzy inputs, probability and consequence as well as the fuzzy output risk. A zero-order Sugeno model was adopted for computation of final risk values.

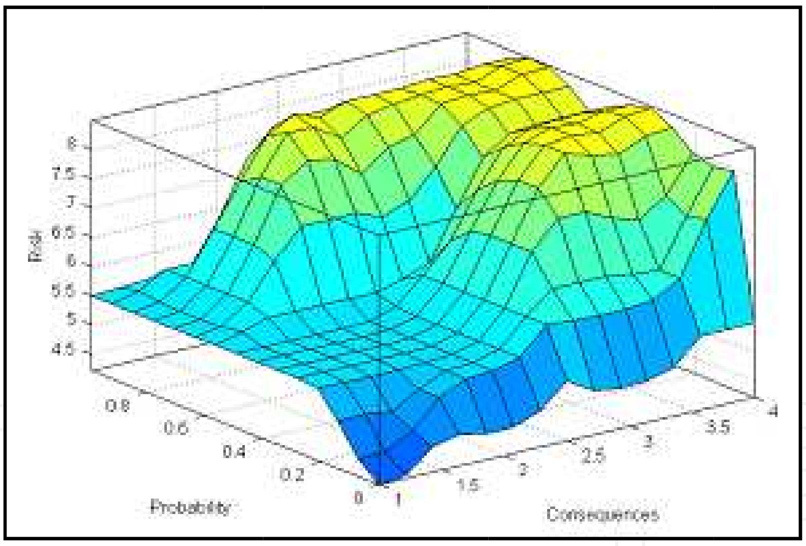

Fig. 10. Output risk surface envelope (Mamdani) for two fuzzy inputs: probability and consequence.

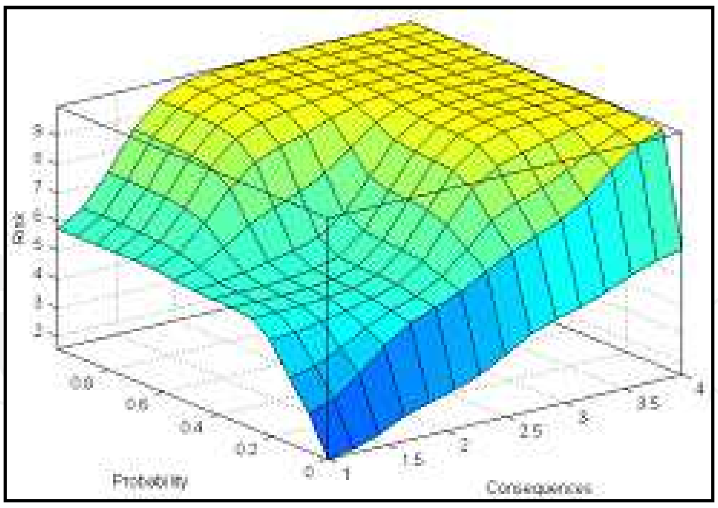

Fig. 11. Output risk surface envelope (Sugeno) for two fuzzy inputs: probability and consequence

Table 7 provides a summary of the calculated fuzzy risk values for the six scenarios and seven consequence attributes. Both the Mamdani/Sugeno methods of inference were used in the calculation of final risk output values. Table 8 shows a comparison between qualitative and fuzzy risk assessment results for the six scenarios considered. Figures 12 and 13 show the Sugeno fuzzy risk values for material assets and crew respectively. Figures 14 and 15 show the Mamdani fuzzy risk values for material assets and crew respectively.

	Leak on the cargo system		Release of liquid nitrogen		Release of bunker oil		Fire in engine room		Accommoda tion Fires		Fires on open deck	
	M	S	M	S	M	S	M	S	M	S	M	S
Crew	5.50	5.30	5.50	5.30	4.35	2.51	5.76	6.06	5.76	6.06	6.31	7.83
3^rd^ party personnel	4.35	2.51	4.35	2.51	4.35	2.51	4.23	1.80	4.23	1.80	5.76	6.06
Environment	4.35	2.51	4.35	2.51	5.84	6.92	4.23	1.80	4.23	1.80	4.23	1.80
Ship	5.50	5.30	5.50	5.30	4.35	2.51	4.67	3.56	4.67	3.56	5.76	6.06
Downtime	5.84	6.92	5.50	5.30	5.50	5.30	5.76	6.06	5.76	6.06	6.31	7.83
Reputation	5.84	6.92	4.35	2.51	5.84	6.92	5.76	6.06	5.76	6.06	5.76	6.06
3rd party material assets	4.35	2.51	4.35	2.51	5.50	5.30	4.23	1.80	4.23	1.80	4.67	3.56
Final rating	5.10	4.57	4.83	3.70	5.10	4.57	4.95	3.88	4.95	3.88	5.54	5.60

Table 7. Summary of calculated fuzzy risk values for six hazardous scenarios and seven consequence attributes. (M=Mamdani method, S=Sugeno method).

Id	Hazard	Qualitative risk value	*Mamdani* fuzzy risk value	*Sugeno* fuzzy risk value
1	Leak on the cargo system	Medium	5.1073	4.5706
2	Release of liquid nitrogen	Low	4.8437	3.7091
3	Release of bunker oil	Medium	5.1073	4.5706
4	Fire in engine room	Low	4.9524	3.8820
5	Accommodation fires	Low	4.9524	3.8820
6	Fires on open deck	Medium	5.5461	5.6054

Table 8. Comparison between qualitative and fuzzy risk values for six hazardous scenarios.

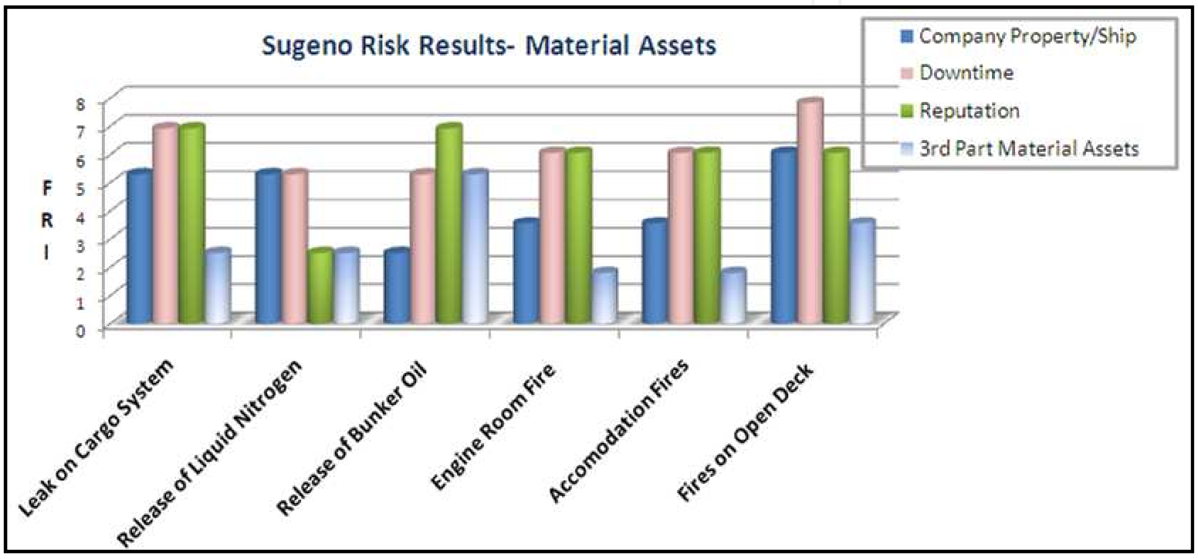

Fig. 12. Sugeno fuzzy risk values for material assets

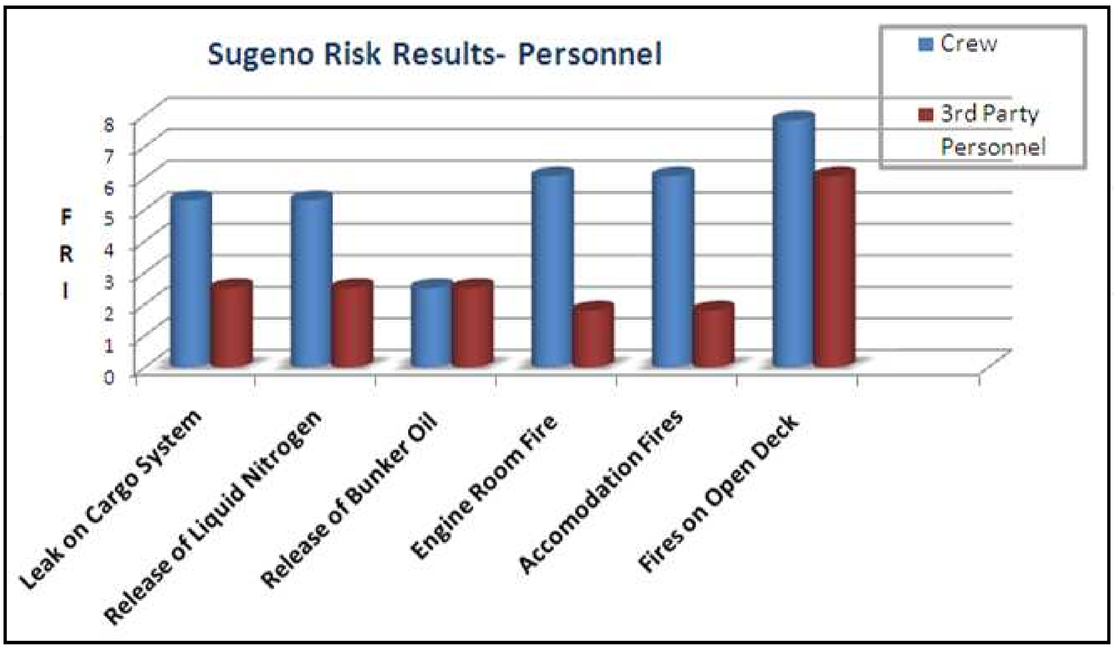

Fig. 13. Sugeno fuzzy risk values for personnel

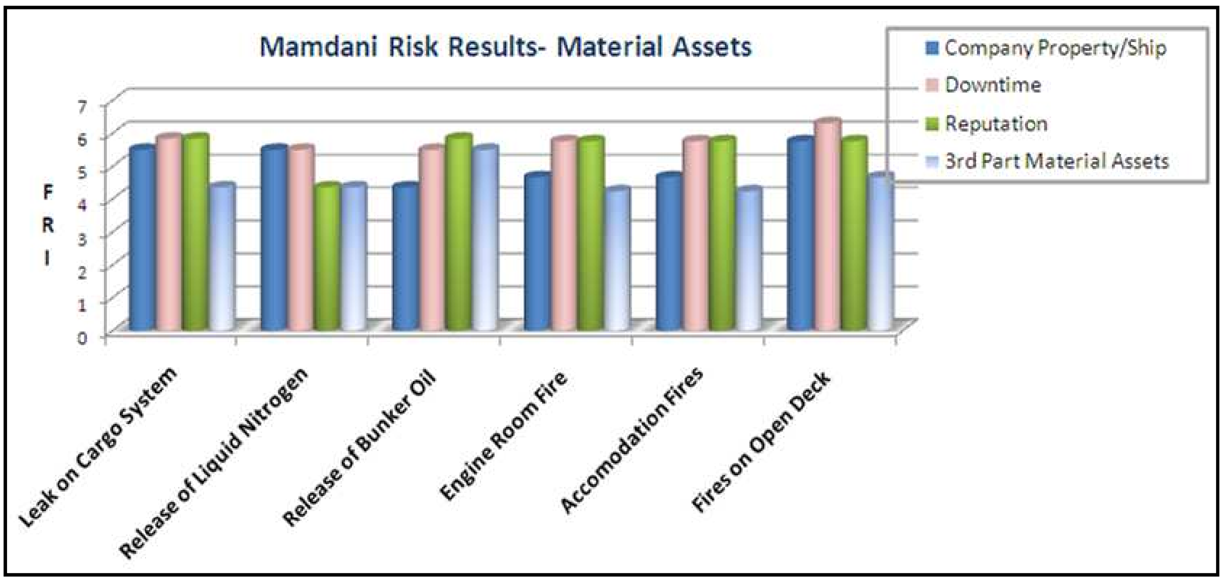

Fig. 14. Mamdani fuzzy risk values for material assets

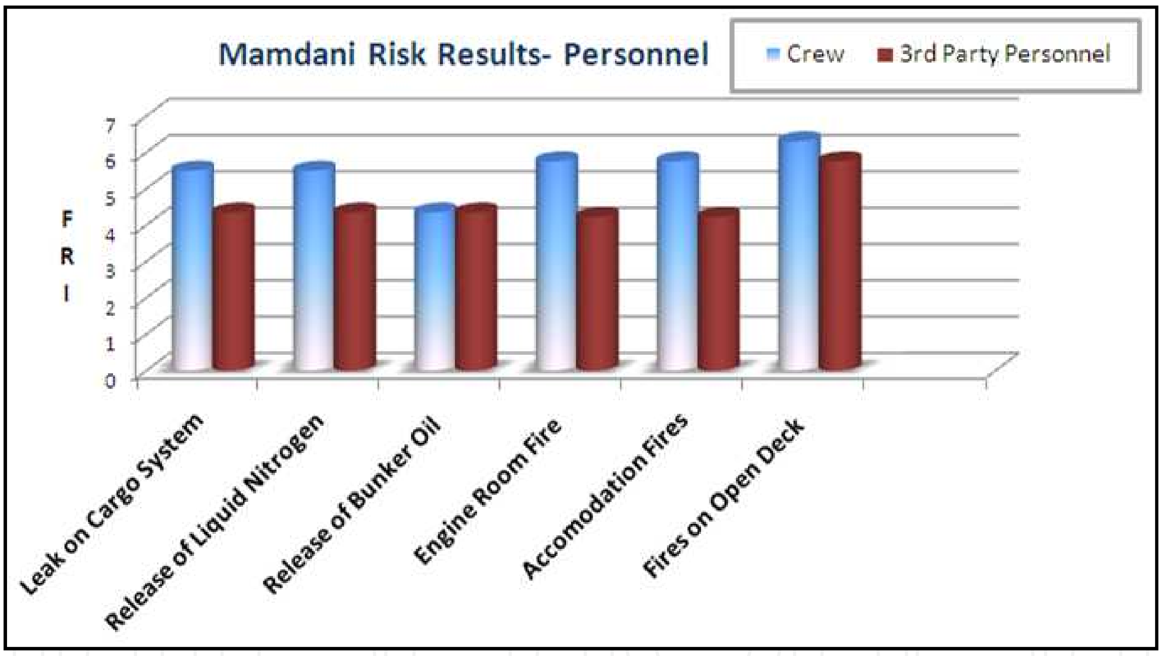

Fig. 15. Mamdani fuzzy risk values for personnel

As can be seen in Table 4, scenarios 1 and 3 are expected to have equal risk values. Both scenarios have a probability level of 'occasional' and the same combined overall consequence level of (3 ‘minor’, 2 ‘major’ and 2 ‘critical’). As can be seen in Table 7, the computed fuzzy risk values for these two scenarios are indeed equal. Same situation applies to scenarios 4 and 5. Their corresponding computed fuzzy risk values provided in Table 7 are also equal. Table 9 provides a comparison between risk results for crew obtained using a qualitative risk matrix approach (Skramstad & Musaeus, 2000) and those using a fuzzy risk index measure. Scenarios are ranked from least severe to most severe with respect to risks to crew members. As can be seen, the same ranking is obtained using both methods for the six hazardous scenarios under consideration.

Hazard	Qualitative risk values	*Mamdani* fuzzy risk value	*Sugeno* fuzzy risk value
Release of bunker oil	Low	4.35	2.51
Leak on the cargo system	Medium	5.50	5.30
Release of liquid nitrogen	Medium	5.50	5.30
Fire in engine room	Medium	5.76	6.06
Accommodation fires	Medium	5.76	6.06
Fires on open deck	Medium	6.31	7.83

Table 9. Comparison between fuzzy risk results and qualitative risk values for crew

6. Conclusion

Various methodologies for the risk assessment of LNG transfer operations at the ship-shore interface of gas terminals were presented. These include a qualitative risk matrix approach, a multiple attribute utility model and a fuzzy inference system. The use of multiple attribute utility theory in risk assessment of LNG operations allows the ranking of risk alternatives based on a unified utility measure. A maximum risk alternative is selected to minimize the overall expected utility. This methodology allows modeling of the decision maker's attitude towards risk, i.e., risk aversion/neutral and/or risk taker. Available software tools allow ranking of risk alternatives and sensitivity analyses to be carried out to assess the sensitivities of the risk model's recommendations to various modeling variables.

An approach for the assessment of multiple attribute risk using fuzzy set theory was also presented. The developed methodology is an alternative to qualitative risk assessment matrices currently used in many industries and by ship classification societies. A three dimensional risk envelope or surface is generated and used for computation of risk values as replacement to the traditional risk matrix.The use of fuzzy sets and a fuzzy inference engine is suited for handling imprecision often associated with accident likelihood and consequence data. The total number of rules needed to construct the fuzzy inference engine is the product of the number of rows and the number of columns for the corresponding qualitative risk matrix. The proposed approach improves upon existing qualitative methods and allows the ranking of risk alternatives based on a unified measure. A fuzzy risk index was adopted for aggregation of multiple consequences into a unified measure. Both the Mamdani and Sugeno type inference methods were adopted. Results show that while the Mamdani method is intuitive and well suited to human input, the Sugeno method is computationally more efficient and guarantees continuity of the final risk output surface. It was also found that computed risk results using a fuzzy risk index measure are consistent with those obtained using a qualitative risk matrix approach. The use of a fuzzy inferene system provides more output information than the traditional risk matrix approach. Such approach is applicable to other ship operating modes such as transit in open sea and/or entering/leaving port

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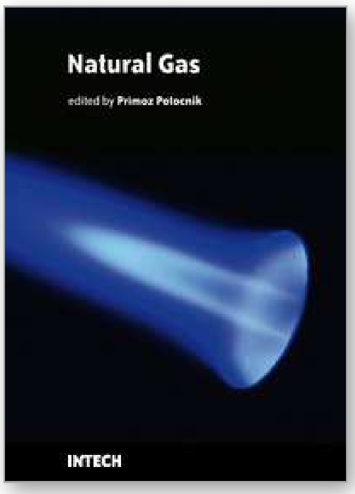

Natural Gas

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The contributions in this book present an overview of cutting edge research on natural gas which is a vital component of world's supply of energy. Natural gas is a combustible mixture of hydrocarbon gases, primarily methane but also heavier gaseous hydrocarbons such as ethane, propane and butane. Unlike other fossil fuels, natural gas is clean burning and emits lower levels of potentially harmful by-products into the air. Therefore, it is considered as one of the cleanest, safest, and most useful of all energy sources applied in variety of residential, commercial and industrial fields. The book is organized in 25 chapters that cover various aspects of natural gas research: technology, applications, forecasting, numerical simulations, transport and risk assessment.

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