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Risk Assessment of LNG Regasification Terminal Using Cascaded Fuzzy-LOPA

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Abstract

Natural gas has turned in to a major source of energy in Asian countries in recent times due to its perpetual growth of consumption in industries, automobiles, household and power plants. This is due to various technical and economic advantages of natural gas. Transportation of the natural gas is mainly done in liquid form (LNG). There are more than ten existing and above twenty under construction LNG terminals in Asia. In this paper, Layer of Protection Analysis (LOPA) is used for assessing the risks pertaining to LNG regasification terminals. During the development of hazard scenarios the economic loss is also considered in finding the degree of severity. To deal with the uncertainties of data in LOPA, Fuzzy logic is applied in two stages. The paper also shows how a better result is achieved to maintain Safety Integrity Level (SIL) to acceptable limits.

Keywords: *LNG Regasification Terminal, LOPA, Cascaded Fuzzy LOPA*

1. Introduction

The Natural gas has turned into a major source of energy in many countries due to its perpetual growth in consumption in industries, automobiles, power plants and households. It is a mixture of naturally occurring hydrocarbon gases with primary content as methane and a varying percentage of higher order alkanes. Small amount of carbon dioxide, nitrogen, hydrogen sulfide and helium may be present as impurities in this mixture. There are many technical as well as economic advantages for the natural gas which become the key points in the development of natural gas industry. Natural gas is a clean, versatile, and easily controllable source of energy. Moreover it is considered as the future energy in terms of a sustainable energy system. Today, 80% of global energy demand is provided by oil, coal and gas (fossil fuels) due to their abundance, affordability and availability (Kumar et al., 2011).

It has been projected that China, which today meets almost 90% of its power needs with coal, will see its energy demand for power generation more than double by the next century, surpassing U.S. demand by more than one-third. The natural gas industry is projected to be helpful in meeting this growing global energy demand(Kumar et al., 2011).

The natural gas is supplied, from the gas producing areas to the gas consuming areas, either by pipeline or in a container or tanker in liquid form. However, pipelines gas supplies have few limitations: (i) the construction and maintenance of underwater pipelines are difficult and is costly (ii) pipelines are a permanent fixture leading from a given gas field to a particular consuming area and, (iii) pipeline gas supplies are also affected by pipeline pressure differential (which changes the pipeline capacity) and seasonality of gas pipeline contracts. Meanwhile, natural gas in its liquid form called Liquefied Natural Gas (LNG) is ideally transported in cryogenic tankers by road, ships and rail wagons (Keyaerts, Hallack, Glachant, & D'haeseleer, 2011).

LNG is the cleanest form of natural gas and contains more than 90% methane therefore, LNG becomes synonyms to methane. Some significant properties and applications are highlighted here. It is colourless, odourless, nontoxic and no-corrosive. Its weight is less than one-half that of water. Some of its hazardous properties are flammability, freezing and asphyxia.

The density of LNG is approximately 0.41–0.5kg/L, depending on temperature, pressure and composition, compared to water at 1.0kg/L. The heat value depends on the source of gas that is used and the process that is used to liquefy the gas. The higher heating value of LNG is estimated to be 24MJ/L at -

164^{0}C. This value corresponds to a lower heating value of 21MJ/L.

LNG is produced by cooling natural gas to -161 ^{0}C to liquefy. This process reduces its volume by a factor of more than 600. The ability to convert natural gas to LNG, which can be shipped on specially built ocean-going ships, provides consumers with access to vast natural gas resources worldwide (Kumar et al., 2011).

2. Layer of Protection Analysis (LOPA)

The Layer of Protection Analysis (LOPA) is an important tool used within the process industries to tackle risk based issues and decisions in a simplified manner (Myers, 2013). LOPA is a risk assessment technique which is commonly used in the chemical process industry that can provide a detailed, semi-quantitative assessment of the risk and layers of protection associated with accident scenarios (Willey, 2014). The layers of protection help to prevent an initiating event from developing into an incident or to mitigate the consequence of an incident when it occurs. LOPA uses a relatively simple, scenario based approach that can be used to effectively address various risk related issues, which helps in providing a timely and cost-effective methodology to conduct analysis as an aid to decision making (Myers, 2013). It is effectively used to bring objectivity and a more consistent approach in addressing layer of protection and assessment of risk beyond that afforded in qualitative Process Hazard analysis (PHA) reviews. LOPA helps in generating additional information required for decision making with a higher degree of confidence rather than relying on the qualitative findings of a PHA. For a particular accident scenario, only one protection layer must work successfully in order to prevent the consequence (Center for Chemical Process Safety, 2001). However, since there is no Independent Protection Layer (IPL) which is perfectly effective, additional or sufficient protection layers must be provided to lower the risk levels of the accident scenario. A scenario in LOPA is defined as an unplanned event or sequence of events that could result in an undesirable consequence (Markowski & Sam Mannan, 2010)and it consist of at least two elements; an initiating event that starts the chain of events and a consequence that results if the chain of events continues without any interruptions(Markowski & Sam Mannan, 2010).

LOPA does not suggest which IPL is to be implemented or which designs to choose; rather it helps in a consistent basis of judging whether there are sufficient IPLs or if the scenario is not tolerable, suggestions for additional layers is done. LOPA assumes that accident scenario is represented by one typical pair of events: cause-consequence(Markowski & Mannan, 2009) and it takes place as a result of failure of independent protection layer (IPL) which forms a multilayer system (Markowski & Mannan, 2009). The calculation of the outcome frequency rate of particular scenario consequences is based on event tree analysis (Markowski and Mannan, 2009) as shown in figure 1.

2.1 Fuzzy Logic

The major purpose of developing fuzzy logic and fuzzy models is because the binary logic and probability theory are not enough to solve problems characterized by high uncertainty, complexity and ambiguity. Since the LOPA analysis involves a large number of parameters and the uncertainty associated with each variable is comparatively high, the application of Fuzzy can improve the final results.

Fig. 1 LOPA event tree

The fuzzification of risk using fuzzy LOPA helps in providing a better risk assessment of the plant compared to that of classical LOPA (Markowski and Mannan, 2008). Fuzzy logic is a multi-valued logic which deals with ambiguous, imprecise or missing information. Fuzzy logic or fuzzy sets theory was developed by Lofti Zadeh in 1960s. In this logic, the truth values of variables may be any real number between 0 and 1. With fuzzy logic propositions can be represented with degrees of truthfulness and falsehood. Fuzzy logic is considered as a better

method for sorting and handling information data and has proven to be an excellent choice for many control system applications since it mimics human control logic (Mure and Demichela, 2009).
Fuzzy set A, defined as a collection of objects called universal set X, represents a class of objects with a continuum of grades of membership. Such a set is characterized by the membership function, $\mu_A(x)$ which assigns to each object a grade of membership ranging between zero (non membership) and one (total membership). In that way a fuzzy set is the set of pair: $A=\{(x, \mu_A(x)); x€X\}$, where $\mu_A : X\rightarrow[0,1]$ is the membership function describing the degree of belonging to x in the set A. Figure 2 shows the differences between a classical set and a fuzzy set for ‘‘safe state’’(Markowski et al., 2009). Classical fuzzy set with its crisp, precisely determined boundary sharply dissevers safe state from unsafe one, whereas the fuzzy set shows smooth change from safe to unsafe state.

2.2 Cascaded Fuzzy LOPA

The main problem associated with doing LOPA in an industry is the unavailability of rate of failure of different protection layers which prevent the occurrence of scenarios. The uncertainness allied with the failure rates of protection layers are also a problem. The severity of the consequence is considered to be a constant unlike the frequency which changes with the activeness of independent protection layers. The above said disadvantages of classical LOPA are taken into account by the application of fuzzy logic. Fuzzy Logic is proved as the best tool to deal with all such types of uncertainty including lack of knowledge and vagueness. Fuzzy logic is a set of mathematical principles which deals with degrees of membership and degrees of truth. It reflects how people think and attempt to model our sense of words, our decision making and common sense (Markowski and Mannan, 2009).

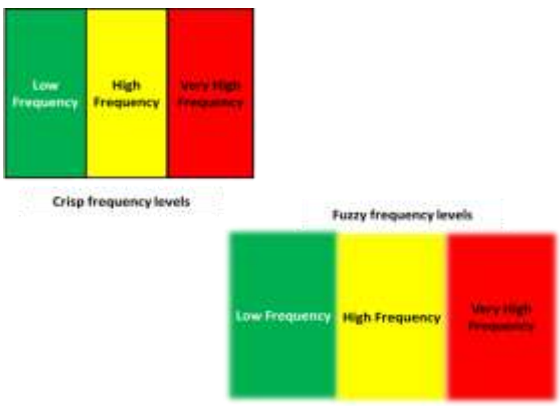

Fig 2. Classical set and fuzzy set for frequency levels

The fuzzy LOPA model applies three main sub systems: the two parallel that is Frequency Fuzzy Logic System, FLS (F), which calculates the fuzzy frequency of an incident scenario and the Severity Fuzzy Logic System, FLS (S), for the estimation of the severity of consequence for the incident scenario. Both systems provide inputs for the third sub-system that is the Risk Fuzzy Logic System, FLS (R), comprising the fuzzy risk matrix(Markowski & Mannan, 2009) . As a result of use of an appropriate fuzzy arithmetic and fuzzy reasoning, the final crisp risk index is obtained, which is used for further decision-making in risk management processes(Markowski & Mannan, 2009).

Fuzzification transforms the input crisp value to one or more fuzzy sets. These sets represent the perception of input variable. After that, the Fuzzy Inference System (FIS) processes the fuzzy input sets with the help of assigned *if-then-else* rules. The result is a fuzzy output from which the rules are weighted and averaged into one final crisp value (Markowski & Mannan, 2009) . Centroid method is used for defuzzification. It gives the center of area under the membership function curve.

Results of the final output data on risk index of LOPA with the use of fuzzy logic are more precisely determined in comparison to the classical LOPA results. The conventional risk matrix is simple to be implemented, but it leads to inconsistent possible results. Fuzzy logic has a positive impact when applied to conventional risk matrix for the risk determination process.

In this particular study fuzzy logic is applied for highly uncertain data to achieve accurate risk calculations. With the help of membership functions used, the fuzzy logic represents knowledge that can be both quantitative and qualitative in nature. Expert systems can be built based on fuzzy logic and can provide reasonably accurate outcomes useful in system analysis. The fuzzy set theory is based on the idea of membership. They allow the definition of vague concepts into mathematical structure. In traditional sets theory, whether an element belongs to a particular set or not is checked. In contrast, an element can belong to a set in some degree in fuzzy set theory. The degree is called membership and it takes values between 0 and 1. Among the different fuzzy set, the most important are the sets with membership functions that can be represented as mathematical functions (Hong, Pasman, Sachdeva, Markowski, & Mannan, 2016).Typical representations include Triangles, Gaussian and Trapezoids and are very useful in describing linguistic variables and qualitative data.

The process industries and plants are highly complex and involve different technologies and large numbers of apparatus and equipments. The more complex system the less precise information is available. The best method to deal with all the types of uncertainty including lack of knowledge, imprecision and vagueness associated with such complex systems is Fuzzy Logic. Fuzzy Layer of Protection Analysis (Fuzzy LOPA) presents a new approach to risk assessment and is based on two assumptions: Different effects of layer of protection functions on particular elements of the risks (frequency a severity of consequences), and the application of Fuzzy logic system which is composed of three elements: fuzzification, inference process and defuzzification (Markowski and Mannan, 2009).

Here fuzzy layer is applied in two layers. The total severity is found from the safety and economic severity levels. The crisp values of both safety severity and economic severity levels are fuzzified and fuzzy operation is carried out to get the total fuzzy severity. Then it is defuzzified to get the crisp value. Fuzzy operation is carried out between the fuzzy severity value and frequency fuzzy values to get a total fuzzy risk surface. The FIS engine defuzzifies the fuzzy risk values into the crisp values.

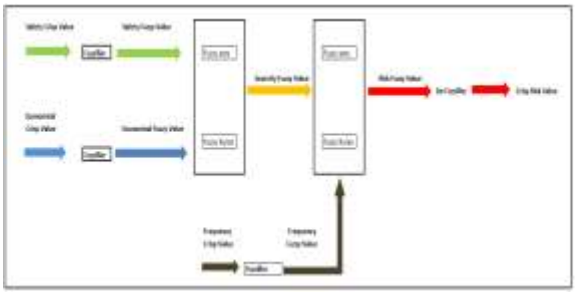

Fig 3. Fuzzy model's architecture

2.3 Cascaded Fuzzy LOPA Methodology

The Fuzzy LOPA methodology is developed into the following steps which are summarized as follows

Step 1: Study of process and process flow diagrams.
Step 2: Hazard and Operability Study (HAZOP).
Step 3: Identification of incidents and risks.
Step 4: Developing the scenarios.
Step 5: Identifying the initiating event of the scenario.
Step 6: Determining initiating event frequency.
Step 7: Identifying the Independent Protection Layer (IPL).
Step 8: Estimating Probability of Failure on Demand (PFD) for each IPL.
Step 9: Identify different economic and safety severity levels.
Step 10: Calculating the total severity using fuzzy logic.
Step 11: Estimating the risk using fuzzy logic.
Step 12: Analysis of risk.

The process involved in the LNG regasification plant is studied in detail from the flow diagram. After that a detailed HAZOP study is conducted. Then a cause consequence pairs are formulated with the help of HAZOP work sheet.

The OSHA compliance risk matrix can be used to rank different scenarios of the plant, if in case of too many scenarios present. This method helps to classify different scenarios according to their risk. Using this methodology, the scenarios with higher risks can be selected for the study. Once the scenarios are developed and selected for the fuzzy LOPA study, the next step carried out is to identify the initiating event of the scenarios and their initiating event frequency (per year). Then the Independent Protection Layers (IPL) of the scenarios is identified and the probability of failure on demand for the same is estimated. The failure data associated with each IPL is obtained either from the industry or from the respective failure data books and references.

Membership functions are assigned for different variables like frequency of failure, safety severity, economic severity, total severity and the risk associated with the scenario. Various types of membership functions used are triangular, trapezoidal, gaussian, and bell shaped. The gaussian membership function has been used for this study as it gives more precise and robust results when combined with overlapping descriptive ranges for the variables. The input variables like frequency and severity data are given to fuzzy inference system for fuzzification, which in turns provides a crisp output for risk after defuzzification. The IF-THEN rules are used to estimate risk in the fuzzy logic system.

3. Materials and Methods

The cascaded fuzzy LOPA methodology is applied to a liquefied natural gas regasification plant. A total of 25 cause consequence scenarios have been identified from the HAZOP study of the plant. From this a scenario with highest risk level is selected for the study. The initiating event and its frequency, protection layers and probability of failure on demand data were obtained from failure data books.

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Table 1 Selected accident scenarios with initiating events

Sl. No.	**Cause**	**Consequence**	**Initiating Event**	**Independent Protection Layers (IPLs)**
1	Accidental closure of control valve on the vapour return line	High pressure in LNG tank and vapour return line	Unplanned Valve closure	Pressure indicator High pressure switch Pressure safety valve Boil off compressor

Table 2 and 3 shows the initiating event frequency and Probability of failure on demand values respectively.

Table 2 Initiating event frequency

Sl. No	Initiating Event	Probability of occurrence
1	Closure of control valve on vapor return line	2.28E-02

Table 3 Probability of failure on demand of the IPLs

Sl. No.	Protective Leers	PFDs
1	Pressure Indicator	2.40E-02
2	High pressure switch	2.00E-02
3	Pressure Safety valve	5.12E-03
4	Boil off gas compressor	3.89E-01

Safety and economic severity levels are given in Fig 4 in the form of a matrix. Table 4 and 5 represents the criteria taken for different levels.

ECONOMIC SEVERIY					
	Catastrophic	Catastrophic	Catastrophic	Catastrophic	Catastrophic
	Very High	Very High	Very High	Very High	Catastrophic
	High	High	High	Very High	Catastrophic
	Moderate	Medium	Medium	High	Catastrophic
	Low	Low	Medium	High	Catastrophic
		Low	Moderate	High	Catastrophic
		SAFETY SEVERITY			

Fig 4. Risk matrix between economic and safety severity levels

Table 4. Economic severity ranges

Economic severity range	Qualitative criteria (USD)
Catastrophic	More than One Billion
Very high	100 Million- 1 Billion
High	10-100 Million
Moderate	1-10 Million
Low	Less than One Million

Table 5. Safety severity ranges

Safety severity range	Qualitative Criteria
Catastrophic	Potential for multiple life threatening injuries or fatalities
High	Potential for life threatening injuries or fatality
Moderate	Potential for any injury require physician's care
Low	Restricted to local vicinity, with potential injuries requiring not more than first aid.

The conditions applied using IF-THEN rules are as follows:

1. If (Safety Severity is Low) and (Economic Severity is Low) then (Total Severity is Low).
2. If (Safety Severity is Low) and (Economic Severity is Moderate) then (Total Severity is Medium).
3. If (Safety Severity is Low) and (Economic Severity is High) then (Total Severity is High).
4. If (Safety Severity is Low) and (Economic Severity is Very high) then (Total Severity is Very high).
5. If (Safety Severity is Low) and (Economic Severity is Catastrophic) then (Total Severity is Catastrophic).
6. If (Safety Severity is Moderate) and (Economic Severity is Low) then (Total Severity is Medium).
7. If (Safety Severity is Moderate) and (Economic Severity is Moderate) then (Total Severity is Medium).

8. If (Safety Severity is Moderate) and (Economic Severity is High) then (Total Severity is High).
9. If (Safety Severity is Moderate) and (Economic Severity is Very high) then (Total Severity is Very high).
10. If (Safety Severity is Moderate) and (Economic Severity is Catastrophic) then (Total Severity is Catastrophic).
11. If (Safety Severity is High) and (Economic Severity is Low) then (Total Severity is High).
12. If (Safety Severity is High) and (Economic Severity is Moderate) then (Total Severity is High).
13. If (Safety Severity is High) and (Economic Severity is High) then (Total Severity is Very high).
14. If (Safety Severity is High) and (Economic Severity is Very high) then (Total Severity is Very high).
15. If (Safety Severity is High) and (Economic Severity is Catastrophic) then (Total Severity is Catastrophic).
16. If (Safety Severity is Catastrophic) and (Economic Severity is Low) then (Total Severity is Catastrophic).
17. If (Safety Severity is Catastrophic) and (Economic Severity is Moderate) then (Total Severity is Catastrophic).
18. If (Safety Severity is Catastrophic) and (Economic Severity is High) then (Total Severity is Catastrophic).
19. If (Safety Severity is Catastrophic) and (Economic Severity is Very high) then (Total Severity is Catastrophic).
20. If (Safety Severity is Catastrophic) and (Economic Severity is Catastrophic) then (Total Severity is Catastrophic).

Total severity and frequency levels are given in Fig 6 in the form of a matrix. Table 6 represents the criteria taken for different frequency levels.

FREQUENCY						
	Very High	T	TNA	NA	NA	NA
	High	A	T	TNA	TNA	NA
	Moderate	A	A	T	TNA	NA
	Low	N	A	T	TNA	NA
	Unlikely	N	N	A	T	NA
		Low	Medium	High	Very High	Catastrophic
		TOTAL SEVERITY				

Fig 6. Risk matrix between severity and frequency levels

4. Results and Discussions

The fuzzy risk surface output obtained using MATLAB is shown in the figure 7. The comparison of the risk values of classical LOPA, fuzzy LOPA, cascaded LOPA, Cascaded Fuzzy LOPA for the selected accident scenario is given in the table 7. In traditional LOPA methodology the risk obtained is using the binary logic, where the element belongs to the particular set or not is checked, whereas in fuzzy LOPA which is a multi-valued logic the degrees of membership are checked.

Table 6. Frequency ranges

Very high	0.01-1
High	0.0001-0.01
Moderate	0.000001-0.0001
Low	0.00000001-0.000001
Unlikely	0.0000000001-0.00000001

Table 7 Comparison of risk indices of different methods

Method used	Initiating event frequency	Safety severity	Economic severity	Total severity	Estimated Rislk
Conventional LOPA	Low (4)	High (3)	_	_	Tolerable (3)
Fuzzy LOPA	-3.33 (log value)	2.55			3.24
Cascaded LOPA	Low (4)	High (3)	Very High	Very High	TNA (4)
Cascaded Fuzzy LOPA	-3.33 (log value)	2.55	3.52	3.57	3.5

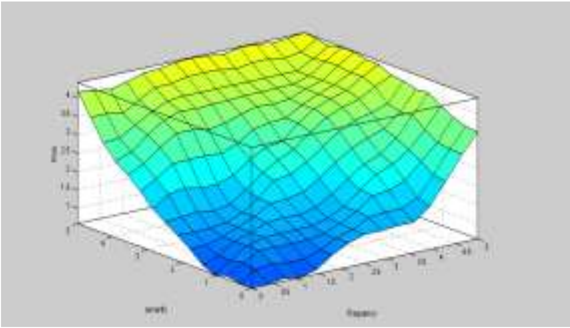

Fig 7. Fuzzy risk surface.

The above table 7 gives brief results obtained after the risk assessment using cascaded fuzzy LOPA methodology. Comparing these values, the fuzzy LOPA risk values are found to be more precise than compared to that of classical LOPA results. When economic severity is cascaded into this we get a higher value of risk. The risk values found can be directly linked with the safety integrity levels (SIL) and can be compared between scenarios. Also this methodology helps in suggesting more reliable protection layers and other monitoring systems to improve the safety of the plant.

6. Conclusions

A plant which deals with natural gas can have severe consequences. The risk associated with it should be calculated for bringing it down to an acceptable range. The methodology gives comparable risk values of classical LOPA and fuzzy LOPA which is helpful in analyzing the Independent Protection Layers. This is an easy, inexpensive and time saving method. The consideration of economic severity during the calculation severity gives light to the actual value of risk when compared to the situation in which only safety severity is considered. We can see that the risk is also higher when compared. The application of fuzzy logic helps to compare these risks in a more quantitative way. Furthermore, it makes the risk assessment method more reliable and these models can be readjusted easily to produce more accurate results. This methodology helps to take decisions to enhance safety and to reduce the economic losses by giving optimized number of protection layers between the initiating event and the consequence.

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