ISSN: 2414-1895 DOI: 10.6919/ICJE.202005_6(5).0010

Improved Fuzzy Bowtie LNG Ship Leakage Risk Assessment Method Based on BTS

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Abstract

In order to effectively prevent the leakage of LNG ships and reduce the consequences of the accident, a quantitative risk assessment method suitable for LNG ships was established. Combining the Bowtie model and fuzzy set theory, the BTS method is introduced to greatly reduce the subjectivity of the evaluation model. A fuzzy Bowtie model for the risk assessment of LNG ship leakage is constructed to quantitatively analyze the probability of each event and summarizes the items that need to be focused on in the prevention of LNG leakage . The results show that the risk assessment method based on the improved fuzzy Bowtie model based on BTS is applicable to the risk assessment of LNG ship leakage, and it improves the accuracy based on the transition from qualitative to quantitative assessment and provides decision support for related departments' safety management.

Keywords

LNG leakage;Bowtie model; Fuzzy set theory; BTS; Risk assessmen.

1. Introduction

As one of the cleanest energy sources in the world, LNG has huge advantages in reducing pollution and protecting the environment. It is mainly transported by ocean through LNG carriers, however, there are a lot of potential risks in LNG transportation. DNV and Lloyds have been tracking LNG ships for many years. According to historical data, from the 1960s to the beginning of the 21st century, there were about 190 LNG ship accidents, of which 10 were fire and explosion accidents of LNG ships. It can be seen that the probability of accidents of LNG ships is low, but the consequences of LNG leakage and fire and explosion accidents are far more serious than those of other ship types.[1]

A lot of experiments have been done by scholars to deal with the hazards that may be caused during the storage and transportation of LNG. Most of the large-scale LNG leak field tests used to study steam diffusion and pool fires were performed as early as the 1970s and 1990s[2-3], and they can often be used to develop and validate numerical models. Most of these studies focus on the mechanism of fire and explosion after the leakage. Understanding the physical and chemical properties of fire and explosion is effective to reduce the severity of the consequences of the accident, but it does not help reduce the frequency of LNG ship leakage accidents and cannot fully assess the risk.

The author will combine the Bowtie model and fuzzy set theory, and introduce the BTS method to reduce the subjectivity of the traditional fuzzy Bowtie model, establish an LNG ship leakage improvement fuzzy Bowtie model to analyze the probability of each accident consequence, in order to help quantitatively evaluate the risk of LNG ship leakage.

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2. Bowtie analysis and fuzzy set theory

2.1 Bowtie analysis

In the Bowtie analysis model, we take the top event as the core, analyze the possible cause that caused it (accident tree analysis), analyze the possible subsequent events after the top event occurs (event tree analysis), and then set the Barriers for prevention and control (Swiss cheese model). The Bowtie method can be used in risk assessment, risk management, and risk communication to better explain the status of specific risks and help people understand the relationship between risks and organizational events.

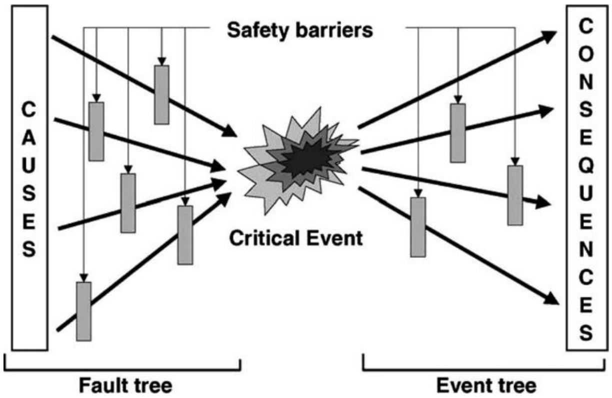

Fig1. Generic example of a bowtie form

There are limitations to the analysis of accident trees and event trees. There are two major reasons: First, as accident trees and event trees become larger, more bloated, and more complicated, they will lead to the application of this method. It is difficult for people to understand and use. Second, there are too many variables, disturbances, and unknown factors in the operating environment where the accident tree or event tree analysis is performed. For example, even the exact same device may have different failure rates when installed to different companies. How to deal with facilities and processes, how operators and managers make decisions cannot be quantified. The only way is to qualitatively manage such risks. The Bowtie method can be used for qualitative risk analysis of complex operating environments.

2.2 Fuzzy set theory

2.2.1Event Probability and Calculation Represented by Fuzzy Numbers

Based on the uncertainty of information, models, and human factors, the probability of an event occurring should not be expressed using exact values, so a triangular fuzzy number is used here to represent the probability value of the event [4] to quantify the ambiguity of the event. The triangular fuzzy number can be expressed by three parameters, denoted as A = (a, m, b), and its membership function is expressed by the formula:

$$\mu A(x)=\begin{cases}(x-a)/(m-a) & (a\le x\le m)\\ (b-x)/(b-m) & (m\le x\le b)\\ 0 & (\text{others})\end{cases} \tag{1}$$

Where A is the fuzzy set on the specified universe x; μA (x) refers to the membership function of x to the fuzzy set A; m is the mean of the fuzzy number A; The events are independent of each other. The AND gate fuzzy operator in the fault tree is:

$$\mathrm{Pand}=\left(\prod_{i=1}^{n} a_i,\prod_{i=1}^{n} m_i,\prod_{i=1}^{n} b_i\right) \tag{2}$$

The OR gate fuzzy operator is:

$$\mathrm{Por}=\left(1-\prod_{i=1}^{n}(1-a_i),\ 1-\prod_{i=1}^{n}(1-m_i),1-\prod_{i=1}^{n}(1-b_i)\right) \tag{3}$$

The fuzzy operator in the event tree is:

$$\mathrm{POEh}=\left(\prod_{i=1}^{n} a_i,\prod_{i=1}^{n} m_i,\prod_{i=1}^{n} b_i\right) \tag{4}$$

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Where i is a basic event; n is the number of events; h is a result event. The event risk is divided into 7 levels. The corresponding linguistic variables and fuzzy numbers refer to Table 1. The linguistic variables can directly express the relative importance of risk factors [5].

Table 1.Table of event risk levels represented by triangular fuzzy numbers

Risk Level	Language Variable	Triangular fuzzy number
1	very low	(0,0.025,0.05)
2	low	(0.045,0.125,0.2)
3	mid Lo	(0.15,0.275,0.4)
4	mid	(0.35,0.5,0.65)
5	mid high	(0.6,0.725,0.85)
6	high	(0.8,0.875,0.955)
7	very high	(0.95,0.975,1)

2.2.2Fuzzy number probabilistic

Because the obtained events are all represented by fuzzy numbers, in order to compare the magnitude of the risk, the fuzzy numbers need to be converted into corresponding probability values, that is, FPS (Fuzzy Possibility Score). In fuzzy set theory, this process is also called defuzzification. Here is the fuzzy maximum and minimum set method proposed by Chen and Hwang [6]. The minimum and maximum fuzzy sets defined by this method are:

$$\mu_{min}(x) = \begin{cases} 1-x & (0<x<1) \\ 0 & (\text{others}) \end{cases} \tag{5}$$

$$\mu_{max}(x) = \begin{cases} x & (0<x<1) \\ 0 & (\text{others}) \end{cases} \tag{6}$$

The possible left and right blur values of the fuzzy number are:

$$F_{AR} = sup_x[\mu_A(x) \wedge \mu_{max}(x)] \quad F_{AL} = sup_x[\mu_A(x) \wedge \mu_{\min}(x)] \tag{7}$$

Then the fuzzy probability value of the fuzzy number A is obtained by the following formula:

$$\text{FPS}=[F_{AR}+1-F_{AL}]/2 \tag{8}$$

Finally, in order to ensure the consistency between the true probability and the fuzzy probability of all events, the fuzzy possible value needs to be converted into a fuzzy failure probability FFR (Fuzzy Failure Rate) [7]:

$$\text{FFR} = \begin{cases} 1/10^k, \text{FPS} \neq 0 \\ 0, \ \text{FPS} = 0 \end{cases} \tag{9}$$

2.3 Debiasing of expert interval judgments

Where data is scarce or difficult to obtain, and incidents rarely or never happen, expert judgment is often the first choice. But under uncertain conditions, people usually rely on experience to make judgments, which leads to systematic biases such as overconfidence. In addition, experts are not independent individuals in actual conditions. They are often affected by other experts or environmental factors, making it difficult to make real judgments. Therefore, the de-biasing of expert judgment is an obstacle that must be faced when applying this method of expert judgment. The traditional fuzzy Bowtie model usually adopts the method of empowering experts to integrate the judgments of experts, which undoubtedly increases the subjectivity of the system again [8]. Based on this limitation and the BTS(Bayesian Truth Serum) method, the author proposes an improved fuzzy Bowtie model.

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2.3.1Bayesian Truth Serum

Drazen Pelec, a professor of psychology and cognitive science at the Massachusetts Institute of Technology, further developed this idea based on expert motivation research, and proposed the Bayesian Truth Serum (BTS) method [10], which is accurate using the expert's prediction information, when most people's opinions are wrong, they can choose 'close to an objective and true answer'. Compared with other methods that regard the majority as consensus, the BTS method is more scientific and reasonable. The BTS score consists of two parts: the information score (precision judgment) and the prediction score (precision judgment of others). The logic behind it is that if a person can predict the behavior of others, he already knows common sense. But if he behaves differently, then he must know something that others don't. Therefore, the behavior of these smart people can be treated as independent information.

2.3.2BTS score calculation

Experts can only choose one answer. Suppose the question has m options and the number of experts is n. Let $\boldsymbol{x_k^r} \in\{0,1\}$ represent whether expert r chooses option k, and use y=($\boldsymbol{y_1^r},\ldots,\boldsymbol{y_m^r}$) to represent expert's prediction of the probability of the answer. We can know from the definition of $\boldsymbol{y_k^r}(\boldsymbol{y_k^r} \geq \mathbf{0}$, $\sum_{k=1}^{m} \boldsymbol{y_k^r}$=1). The algorithm proceeds in the following four steps:

Step 1: Calculate the average of the real choice $\overline{\boldsymbol{x_k}}$ and the predicted geometric mean $\ln \overline{\boldsymbol{y_k}}$

$$\overline{\boldsymbol{x_k}} = \frac{1}{n}\sum_{r=1}^{n} \boldsymbol{x_k^r} \tag{10}$$

$$\ln \overline{\boldsymbol{y_k}} = \frac{1}{n}\sum_{r=1}^{n} \ln \boldsymbol{y_k^r} \tag{11}$$

Step 2: For each participant r, calculate its BTS score

$$\boldsymbol{u^r} = \sum_{k=1}^{m} \boldsymbol{x_k^r} \ln \frac{\overline{x_k}}{\overline{y_k}} + \sum_{k=1}^{m} \overline{\boldsymbol{x_k}} \ln \frac{y_k^r}{\overline{x_k}} \tag{12}$$

Step 3: For each option k, calculate its BTS score $\overline{\boldsymbol{u_k}}$

$$\overline{\boldsymbol{u_k}} = \frac{1}{n\overline{x_k}}\sum_{r=1}^{n} \boldsymbol{x_k^r}\, \boldsymbol{u^r} \tag{13}$$

Step 4: Select the option k that maximizes $\overline{\boldsymbol{u_k}}$

3. LNG ship leak analysis

3.1 Building a Bowtie Model

The top event in the Bow-tie model of this case is the LNG ship leak. The figure of the Bowtie model is shown in Figure 2. The description of each event in the model is shown in Table 2 and Table 3.

Table 2.Meaning of other symbols

Event number	Event name	Event number	Event name
M1	Hull structure damage	M8	Storm waves
M2	Damaged cargo tank	M9	Film rupture
M3	Defective discharge arm	M10	Low temperature insulation failure
M4	Crew error	M11	Cabin overpressure
M5	Weather impact	M12	Inert gas device failure
M6	Lightning strike	M13	Cabin overpressure
M7	Lightning rod failure	M14	Safety valve failure
M15	Inert gas generator failure	M22	Rotary joint failure
M16	Drying unit failure	M23	Hydraulic quick connector failure
M17	Cooling unit failure	M24	Broken pipe
M18	Combustion chamber failure	M25	Unable to rotate or damaged seal
M19	Washing tower failure	M26	Loose jaw
M20	Refrigeration device failure	M27	Failure of the pressing mechanism
M21	Leak in filling line		

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Table 3.Meaning of basic event symbols

Event number	Event name	Event number	Event name
X1	Ship collision	X10	LNG evaporates too fast
X2	Ship stranded	X11	Incorrect selection
X3	Mooring loose	X12	Damaged safety valve
X4	Lightning strikes the hull	X13	Incorrect oil selection
X5	No lightning rod installed	X14	Too little mixed air
X6	Lightning rod damaged	X15	Blocked scrubber duct
X7	Low hull wind resistance	X16	Temperature control system failure
X8	Weak hull structure	X17	Defective dryer
X9	Level gauge failure, overcharge	X18	No desiccant or desiccant failure
X19	Broken thermometer	X28	The service life of the pipeline is too long
X20	Evaporator damaged	X29	Substandard pipe material
X21	Damaged reservoir	X30	Unloading arm extended too long
X22	Compressor damaged	X31	Water vapor generated during operation
X23	Defective separator	X32	Failure of nitrogen purge system
X24	Damaged insulation	X33	Valve leak
X25	Insufficient selection of insulation material	X34	Flange faces are not tight
X26	Valve leak	X35	Electro-hydraulic control system is out of control
X27	Flange seal failure	X36	Damaged compression spring

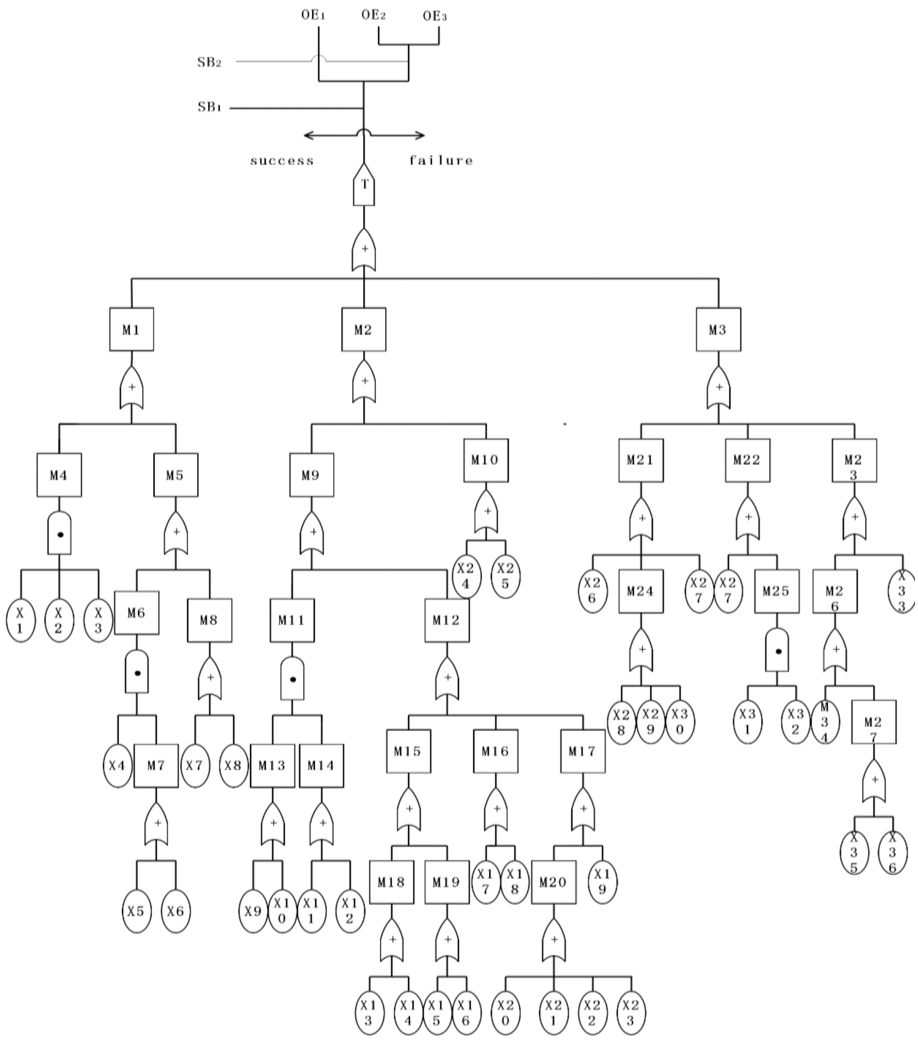

Fig 2.Fuzzy Bowtie model of LNG ship leakage

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3.2 Risk level

Using the BTS method, the question form is as follows:

The degree of "ship collision" is ( )

very low B. low C. medium low D. medium E. medium high F. high G. very high

In your opinion, the probability that others choose A, B, C, D, E, F, G is()、()、()、()、()、()、().

For the risk of "ship collision", the calculation results are shown in Table 4:

Table 4.BTS score of ship collision risk

Expert Number	Option	Predictions	BTS score
1	3	(0.05,0.05,0.15,0.25,0.15,0.15,0.2)	0.170945717994963
2	2	(0.1,0.15,0.25,0.15,0.15,0.1,0.1)	0.399643056185545
3	3	(0.1,0.15,0.2,0.2,0.15,0.1,0.1)	0.414111931521882
4	4	(0.15,0.15,0.2,0.2,0.15,0.1,0.05)	-0.73993681147356
5	5	(0.05,0.1,0.2,0.25,0.15,0.1,0.15)	-0.49333382841259
6	6	(0.05,0.05,0.2,0.2,0.1,0.25,0.15)	-0.40648476303335
7	3	(0.15,0.15,0.2,0.2,0.15,0.1,0.05)	0.385343724276703
8	7	(0.1,0.1,0.1,0.15,0.15,0.15,0.25)	-0.39470645946771
9	2	(0.25,0.2,0.15,0.15,0.15,0.05,0.05)	0.256931420621530
10	1	(0.25,0.2,0.2,0.15,0.1,0.05,0.05)	-0.35123693586041

Score of A：-0.351236935860416

Score of B：0.328287238403537

Score of C：0.323467124597849

Score of D：-0.739936811473567

Score of E：-0.493333828412597

Score of F：-0.406484763033354

Score of G：-0.394706459467716

Option B has the highest score, and the risk is considered to be low. By analogy, each risk occurrence level, FPS and FFR are shown in the following table:

Table 5.Evaluation table of each event

Number	Event Name	Comprehensive Level	FPS	FFR
X1	Ship collision	2	0.1508935	8.0772416e-05
X2	Ship stranded	1	0.02439	1.3510263e-08
X3	Mooring loose	3	0.3	0.00088728496
X4	Lightning strikes the hull	4	0.5	0.00500034534
X5	No lightning rod installed	2	0.1508935	8.0772416e-05

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X6	Lightning rod damaged	5	0.694445	0.017777996
X7	Low hull wind resistance	2	0.1508935	8.0772416e-05
X8	Weak hull structure	3	0.3	0.00088728496
X9	Level gauge failure, overcharge	2	0.1508935	8.0772416e-05
X10	LNG evaporates too fast	2	0.1508935	8.0772416e-05
X11	Incorrect selection	3	0.3	0.00088728496
X12	Damaged safety valve	5	0.694445	0.017777996
X13	Incorrect oil selection	3	0.3	0.00088728496
X14	Too little mixed air	3	0.3	0.00088728496
X15	Blocked scrubber duct	4	0.5	0.00500034534
X16	Temperature control system failure	3	0.3	0.00088728496
X17	Defective dryer	4	0.5	0.00500034534
X18	No desiccant or desiccant failure	5	0.694445	0.017777996
X19	Broken thermometer	3	0.3	0.00088728496
X20	Evaporator damaged	3	0.3	0.00088728496
X21	Damaged reservoir	3	0.3	0.00088728496
X22	Compressor damaged	4	0.5	0.00500034534
X23	Defective separator	4	0.5	0.00500034534
X24	Damaged insulation	4	0.5	0.00500034534
X25	Insufficient selection of insulation material	5	0.694445	0.017777996
X26	Valve leak	6	0.8491	0.05085343985
X27	Flange seal failure	2	0.1508935	8.0772416e-05
X28	The service life of the pipeline is too long	6	0.8491	0.05085343985
X29	Substandard pipe material	3	0.3	0.00088728496
X30	Unloading arm extended too long	5	0.694445	0.017777996
X31	Water vapor generated during operation	4	0.5	0.00500034534
X32	Failure of nitrogen purge system	3	0.3	0.00088728496
X33	Valve leak	6	0.8491	0.05085343985
X34	Flange faces are not tight	5	0.694445	0.017777996

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X35	Electro-hydraulic control system is out of control	2	0.1508935	8.0772416e-05
X36	Damaged compression spring	4	0.5	0.00500034534

3.3 Discussion

The author invited ten senior experts in the field to give judgments on the basic events, and integrated the expert opinions through formulas (10)-(13), and calculated FPS and FFR. The probability of obtaining the top event "LNG ship leak" through the logic gate operation of fuzzy Bowtie model is 0.851%. The safety barrier success rate was obtained through surveys: the VTS success rate was 48.7%, and the boat intervention rate was 80.0%. Calculated OE1 = 0.414%, OE2 = 0.349%, OE3 = 0.083%.

4. Conclusion

Improved fuzzy Bowtie risk assessment method better solves the uncertainty problem in LNG ship leakage risk assessment, realizes the transition from qualitative to quantitative assessment, and introduces the BTS method instead of the traditional weighting method based on the original Greatly reduced the subjectivity of the model. The method in this paper is suitable for scenarios without sufficient data support. It is helpless to use expert judgment, and more scientific and objective risk assessment methods have yet to be proposed.

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