Application of Fault Tree Analysis in the Reliability Analysis of Oil-Gas Long Pipeline

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ABSTRACT

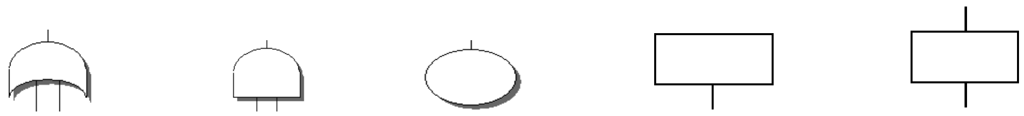
Fault tree analysis method is used to carry on the safety and reliability analysis to the oil-gas pipelines in this paper. Firstly, establish the fault tree which top event is pipeline failure. Next, carry on the qualitative analysis to the fault tree. By the qualitative analysis, we can discover the major factors which induce the pipeline to failure and then establish the main risk fault tree. Finally, carry on the quantitative evaluation to the fault tree with main risk factors. Expert estimation and fuzzy mathematics analysis methods are used in the quantitative evaluation. In this way, the weak points of the pipeline system are distinguished, and we can also point out the basic event which improves easily if the pipeline system breaks down.

KEYWORDS

Fault Tree Analysis; Oil-gas Pipeline; Reliability; Qualitative Analysis; Quantitative Evaluation

FAULT TREE ANALYSIS METHOD

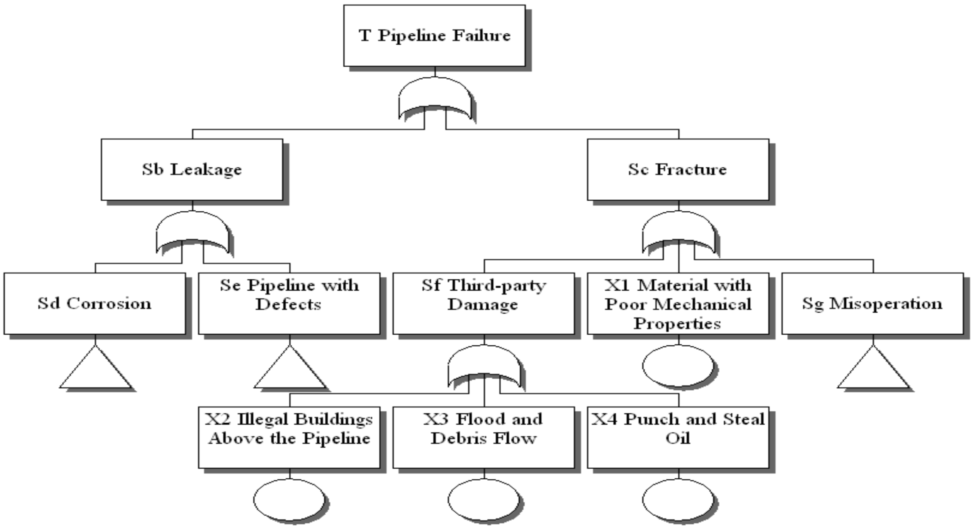
Fault Tree Analysis (FTA) is an effective tool which is applicable to complex system's safety and reliability analysis. It can improve both the reliability and the safety of the system. It regards incidents which the system does not want to have as the top event. We can find the basic reasons, bottom events of the fault tree, by analyzing various factors (hardware, software, environment, human factor) which lead the system to failure. The analysis steps are as follows: with the help of prescribed logical symbols, according to the dendritic structure, analyze all the possible direct factors and the logical relationship between each other further and further, until find out the basic causes of accidents. Thus, we can determine the different combination reasons and probabilities leading to system's failure, and take corresponding measures to improve the reliability of the system.
The notations and terminologies used in this paper are as follows:

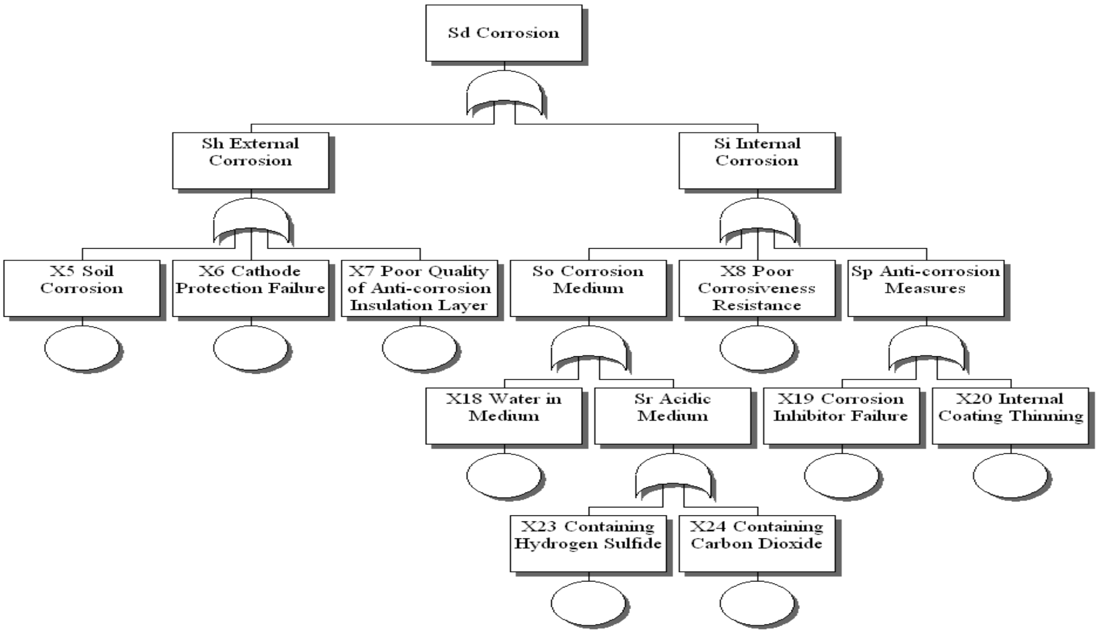


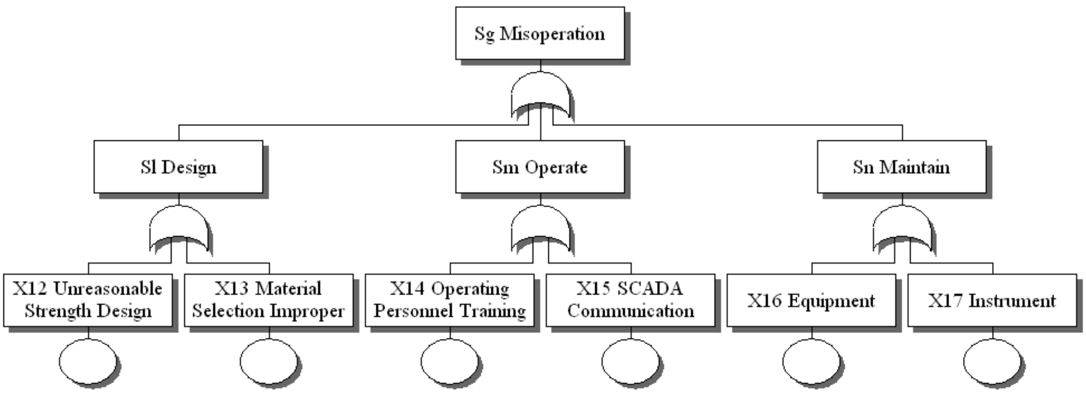
Or gate And gate Bottom (basic) event Top event Middle event

FAULT TREE QUALITATIVE ANALYSIS

Establish fault tree for oil-gas long distance pipeline.
According to the determination principle, for oil and gas long distance pipeline, select "pipeline failure" as the top event of the fault tree. It is known that either leakage or rupture can lead pipeline to failure (Dong et al., 2002). And then we take the two reasons leakage and rupture as the second top events, using similar methods to analyze deeply, until find the basic events representing various faults. Fig 1 is the oil and gas pipeline fault tree used in the study of this paper, which considering 24 basic events.


T Pipeline Failure
Sb Leakage
Sc Fracture
Sd Corrosion
Se Pipeline with Defects
Sf Third-party Damage
X1 Material with Poor Mechanical Properties
Sg Misoperation
X2 Illegal Buildings Above the Pipeline
X3 Flood and Debris Flow
X4 Punch and Steal Oil


Sd Corrosion
Sh External Corrosion
Si Internal Corrosion
X5 Soil Corrosion
X6 Cathode Protection Failure
X7 Poor Quality of Anti-corrosion Insulation Layer
So Corrosion Medium
X8 Poor Corrosiveness Resistance
Sp Anti-corrosion Measures
X18 Water in Medium
Sr Acidic Medium
X19 Corrosion Inhibitor Failure
X20 Internal Coating Thinning
X23 Containing Hydrogen Sulfide
X24 Containing Carbon Dioxide


Sg Misoperation
Sl Design
Sm Operate
Sn Maintain
X12 Unreasonable Strength Design
X13 Material Selection Improper
X14 Operating Personnel Training
X15 SCADA Communication
X16 Equipment
X17 Instrument

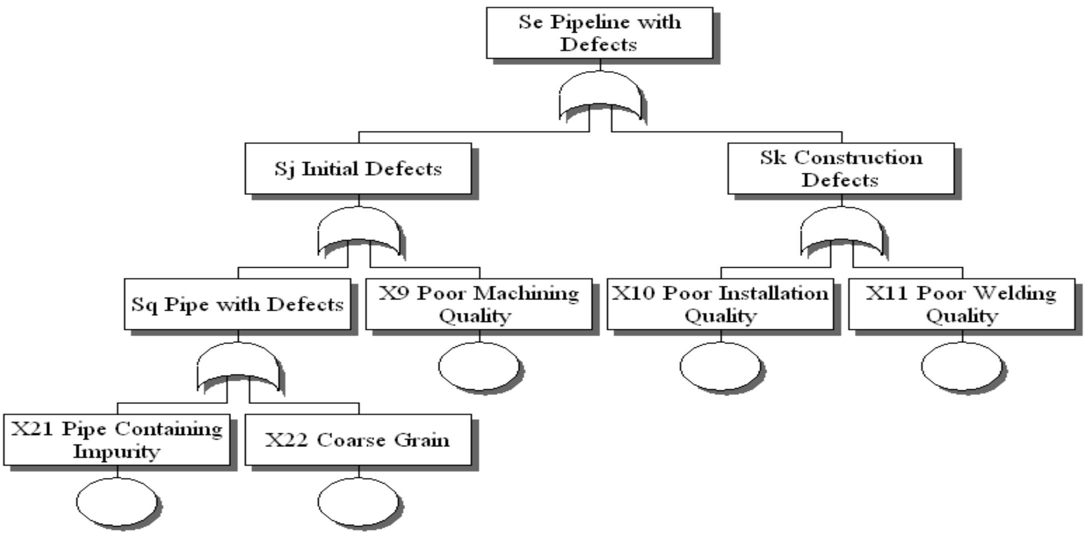


Figure1. Oil and gas pipeline fault tree

Solve minimum cut sets. In this paper, descending method is used to solve minimal cut sets, and the calculation results are shown in Table 1.

Table1. Minimum Cut Sets of Oil and Gas Long Distance Pipeline Fault Tree

				The Analysis Steps			Minimum Cut Set
1	2	3	4	5	6	7	
T	Sb	Sd	Sh	X5X6X7	X5X6X7	X5X6X7	X5X6X7
	Sc	Se	Si	SoX8Sp	X18SrX8X19	X18X23X8X19	X18X23X8X19
		Sf	Sj	Sq	X18SrX8X20	X18X24X8X19	X18X24X8X19
		Sg	Sk	X9	X21	X18X23X8X20	X18X23X8X20
		X1	X2	X10	X22	X18X24X8X20	X18X24X8X20
			X3	X11	X9	X21	X21
			X4	X2	X10	X22	X22
			Sl	X3	X11	X9	X9
			Sm	X4	X2	X10	X10
			Sn	X12	X3	X11	X11
			X1	X13	X4	X2	X2
				X14	X12	X3	X3
				X15	X13	X4	X4
				X16	X14	X12	X12
				X17	X15	X13	X13
				X1	X16	X14	X14
					X17	X15	X15

	X1	X16 X17 X1	X16 X17 X1

From Table 1, we can see that the fault tree consists of 15 first-order minimal cut sets, 1 three-order minimum cut set and 4 four-order minimal cut sets. Generally, the smaller the cut set's order, the bigger its occurrence possibility. Therefore, in order to improve the pipeline's safety and reliability, we should first consider the first-order minimal cut sets which are of the largest occurrence probability, such as the 21 first-order minimal cut sets and the basic events X8, X18 etc.

The main influence factors to pipeline failure. By fault tree qualitative analysis, the main factors causing pipeline failure are third-party damage, corrosion, misoperation and pipe defects.

FAULT TREE QUANTITATIVE ANALYSIS

The aim of fault tree quantitative analysis is to calculate the occurrence probability of the top event and to analyze the important degree for the basic events.

Establish fault tree with main risk factors. Because of the different pipe size, region, operation cycle and conveying medium, so, do complex fuzzy quantitative analysis to the whole fault tree is not of strong practical significance. The main purpose of this paper is to introduce the application of fault tree analysis method in oil and gas pipeline's safety and reliability analysis. Therefore, we can simplify the qualitative analysis results, find the main causes to the pipeline failure, then establish fault tree with the main risk factors as shown in Figure 2, and carry on the detailed quantitative analysis to it.

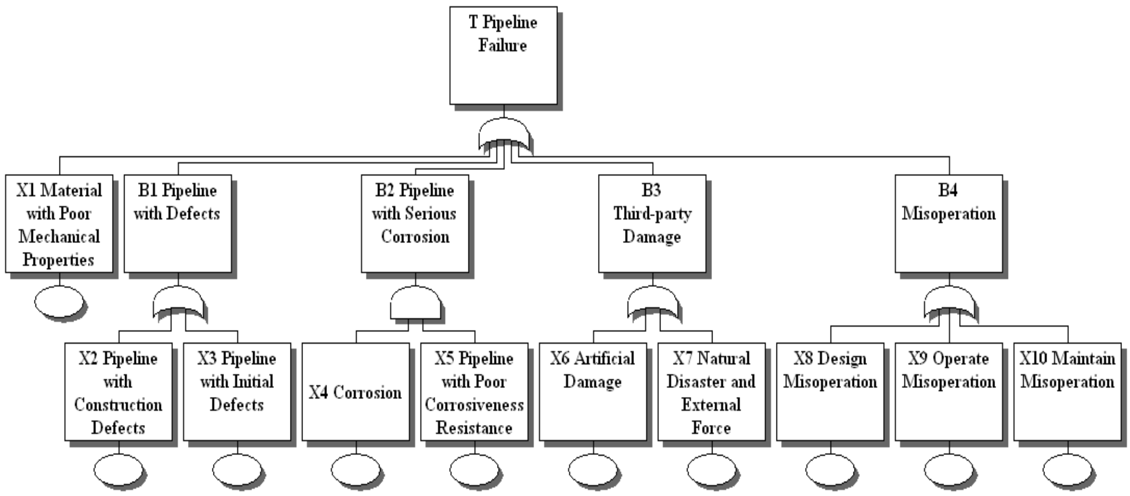


Figure2. Fault tree of the main risk factors

The fault tree consists of a top event, four intermediate events, ten basic events, four or gates and one and gate. According to the principle of descending method, the minimal cut sets of the fault tree are: {X1}, {X2}, {X3}, {X4, X5}, {X6}, {X7}, {X8}, {X9}, {X10}.

Probability determined for the basic (bottom) events. In order to calculate the occurrence probability of the system's top event and to analyze the importance of basic events, we must know the occurrence probability of the basic events. Expert judgment method combined with the fuzzy algorithm is used to estimate the occurrence probability of the basic events in this paper (Wang, 1983; Lin & Wang, 1997).

Expert judgment is the most commonly method used to determine the probability of event's occurrence (Li & Lu, 2000). Firstly, select experts from different fields to form an assessment team. Secondly, assessment consultation table including assessment contents is designed by analysis members. Thirdly, according to their own experience, experts make judgments of probability of the events. Because the expert may not accurately estimate the probability of the events, and when the description of the event is not clear, experts tend to use the natural language, such as" low"," high" to describe the probability of events. As natural languages have ambiguity, conventional methods are not adapt to treat them, so here fuzzy set theory is used to deal with the uncertain information. Triangular fuzzy number and trapezoid fuzzy number are used to replace the natural language. In the process of experts making judgments, such natural language "VL", "L", "FL", "M", "FH", "H" and "VH" is used. VL，L, FL, M, FH, H, VH represents relatively very low, low, rather low, medium, rather high, high, very high. Fuzzy numbers of the natural language are expressed in Figure 3(Hua et al., 1983).

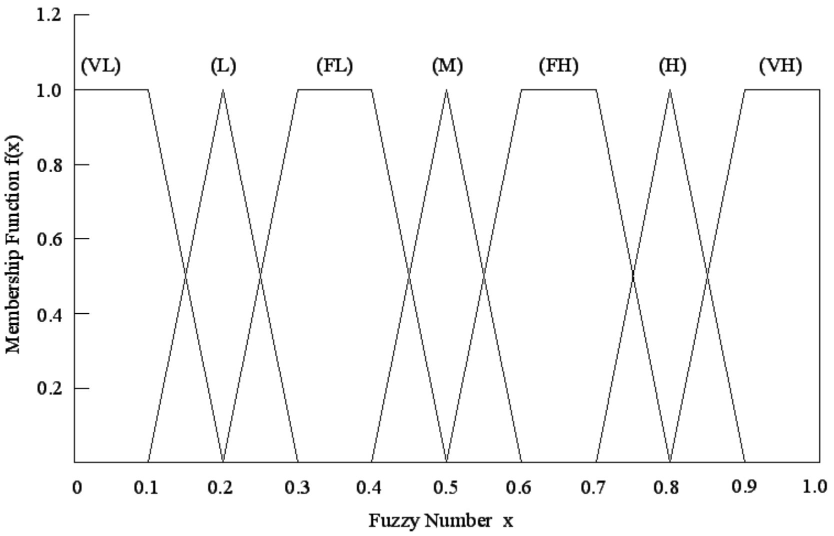


Figure3. Fuzzy number representing natural language

Fuzzy numbers of the natural language in Figure 3 are transformed into the following membership functions.

$$f_{VL}(x)=\begin{cases}1 & (0<x\le 0.1)\\ \dfrac{0.2-x}{0.1} & (0.1<x\le 0.2)\\ 0 & (others)\end{cases}\qquad f_{L}(x)=\begin{cases}\dfrac{x-0.1}{0.1} & (0.1<x\le 0.2)\\ \dfrac{0.3-x}{0.1} & (0.2<x\le 0.3)\\ 0 & (others)\end{cases}$$

$$f_{FL}(x)=\begin{cases}\dfrac{x-0.2}{0.1} & (0.2<x\le 0.3)\\ 1 & (0.3<x\le 0.4)\\ \dfrac{x-0.5}{0.1} & (0.4<x\le 0.5)\\ 0 & (others)\end{cases}\qquad f_{M}(x)=\begin{cases}\dfrac{x-0.4}{0.1} & (0.4<x\le 0.5)\\ \dfrac{0.6-x}{0.1} & (0.5<x\le 0.6)\\ 0 & (others)\end{cases}$$

$$f_{FH}(x)=\begin{cases}\dfrac{x-0.5}{0.1} & (0.5<x\le 0.6)\\ 1 & (0.6<x\le 0.7)\\ \dfrac{0.8-x}{0.1} & (0.7<x\le 0.8)\\ 0 & (others)\end{cases}\qquad f_{H}(x)=\begin{cases}\dfrac{x-0.7}{0.1} & (0.7<x\le 0.8)\\ \dfrac{0.9-x}{0.1} & (0.8<x\le 0.9)\\ 0 & (others)\end{cases}$$

$$f_{VH}(x)=\begin{cases}\dfrac{x-0.8}{0.1} & (0.8<x\le 0.9)\\ 1 & (0.9<x\le 1.0)\\ 0 & (others)\end{cases}$$

Take "pipeline construction defects" as example, we can take the following steps to estimate the probability of this bottom event.

(1) Select five experts from fields of pipeline design, construction, installation, maintain and management to form the evaluation group. Then make judgements of the occurrence probability for the bottom event "pipeline construction defects". The final assessment is VL, L, FL, L and M.

(2) Transform the natural language into fuzzy numbers and membership functions corresponding to Figure 3.

Average algorithm and α-cut of fuzzy set are used to combine different expert's opinion. Supposing α-cuts are $VL_\alpha=[v_1,v_2]$, $L_\alpha=[l_1,l_2]$, $FL_\alpha=[f_1,f_2]$, $M_\alpha=[m_1,m_2]$, $v_1,v_2,l_1,l_2,f_1,f_2,m_1,m_2$ relatively represents the upper/lower limit of the α-cut.

For VL_α, let α=（0.2-x）/0.1，while v_2=0.2-0.1α，v_1=0; in the same way, l_1=0.1α+0.1，l_2=0.3-0.1α，f_1=0.1α+0.2，f_2=0.5-0.1α，m_1=0.1α+0.4，m_2=0.6-0.1α。

Under α-cut, general fuzzy number of 5 experts' opinions is

$$f_{VL\oplus L\oplus FL\oplus L\oplus M}(z)=\max\left[f_{VL}(x)\wedge f_L(x)\wedge f_{FL}(x)\wedge f_L(x)\wedge f_M(x)\right]$$
$$=\left[(0.4\alpha+0.8),(1.9-0.5\alpha)\right]$$

The average fuzzy number of the above equation is

$$W=\frac{1}{5}\otimes\left[(0.4\alpha+0.8),(1.9-0.5\alpha)\right]=\left[(0.08\alpha+0.16),(0.38-0.1\alpha)\right]$$

From fuzzy set expansion theory, it is known that W is also fuzzy set.

$$W_\alpha=[z_1,z_2]=[(0.08\alpha+0.16),(0.38-0.1\alpha)],\ \text{well}\ \ \alpha=\frac{z_1-0.16}{0.08}\,or\,\alpha=\frac{038-z_2}{0.1}$$

Therefore, the relation function of the average fuzzy number W is

$$f_W(z)=\begin{cases}\dfrac{z-0.16}{0.08} & (0.16<z\le 0.24)\\ 1 & (0.24<x\le 0.28)\\ \dfrac{0.38-z}{0.1} & (0.28<x\le 0.38)\\ 0 & others\end{cases}$$

(3) Transform the fuzzy numbers into fuzzy possibility value（FPS）. The maximum fuzzy set and minimum fuzzy set are

$$f_{\max}(x)=\begin{cases}x & (0<x<1)\\ 0 & (others)\end{cases}\qquad\qquad f_{\min}(x)=\begin{cases}1-x & (0<x<1)\\ 0 & (other)\end{cases}.$$

The left and right FSP of fuzzy number W is

$$FPS_R(w) = \sup_x [f_w(x) \wedge f_{\max}(x)] = 0.3455$$

$$FPS_L(w) = \sup_x [f_w(x) \wedge f_{\min}(x)] = 0.7778$$

$$FPS_T(w) = {[FPS_R(w) + 1 - FPS_L(w)]}/{2} = 0.2839$$

(4) Convert FPS into fuzzy failure rate (FFR).

$$FFR = \begin{cases} \frac{1}{10^k} & (FPS \neq 0) \\ 0 & (FPS = 0) \end{cases} \qquad k = \left[{(1 - FPS)}/{FPS} \right]^{\frac{1}{3}} \times 2.301$$

The FFR of fuzzy number W is calculated 7.3699×10^{-4}, thus the probability of pipeline construction defect is 7.3699×10^{-4}.

In the same way, the probability of the ten bottom events is calculated in table 2.

Table 2.Probability of Occurrence of Ten Basic Events

Bottom Event	Expert Opinion	Bottom Events Probability
X1Material with Poor Mechanical	VL ,L,L,FL,L	0.00035474
Properties	VL, L, FL, L,M	0.00073699
X2Pipeline with Construction Defects	VL, FL, L, FL, M	0.00100383
X3 Pipeline with Initial Defects	FL, M, M,FH,M	0.00500035
X4Corrosion	VL, L, FL, FL, M	0.00100383
X5 Pipeline with Poor Corrosiveness	L, FL, M, FH, H	0.00500035
Resistance	L, M, M, FL, FL	0.00214987
X6 Artificial Damage	VL ,VL, L, L, FL	0.00023202
X7 Natural Disaster and External Force	L, L, FL, L, M	0.00098043
X8 Design	FL, L, FL, M, FL	0.00168707
X9 Operate		
X10 Maintain		

Probability calculated for the top event. The probability calculation formula (Nie & Duan, 2003; M.Dziubinski et al., 2006) for the top event is

$$P(T) = P\left[\coprod_{j=1}^{n} Kj\right] = \sum_{i=1}^{n} P(K_i) - \sum_{i<j-2}^{n} P(K_i K_j) + \sum_{i<j<k-3}^{n} P(K_i K_j K_k) + \Lambda + (-1)^{n-1} P(K_1 K_2 \Lambda\ K_n)$$

$$P(K_j) = \prod_{i \in K_j} q_i$$

Combined with the actual situation of engineering, the probability of top event" pipeline failure "for the main risk factors fault tree is simply calculated as follows:

$$P(T)=\sum_{i=1}^{9}P(K_i)=P(K_1)+P(K_2)+\Lambda\ +P(K_9)=q_1+q_2+q_3+q_4q_5+q_6+q_7+q_8+q_9+q_{10}$$

$$=1.215\times10^{-2}$$

Probability importance degree analyzed for ten bottom events. Probability importance degree represents contributions the bottom event made to the occurrence of the top event. The probability importance degree of the ten basic events is calculated in Table 3.

Table3. Probability Importance Degree of Ten Basic Events

Basic Event	The Corresponding Probability Importance Degree
X1Material with Poor Mechanical Properties	0.98820443
X2Pipeline with Construction Defects	0.98858667
X3 Pipeline with Initial Defects	0.98885351
X4Corrosion	0.00099164
X5 Pipeline with Poor Corrosiveness Resistance	0.00493961
X6 Artificial Damage	0.99285003
X7 Natural Disaster and External Force	0.98999955
X8 Design	0.98808171
X9 Operate	0.98883012
X10 Maintain	0.98953675

The bigger the bottom events' probability importance degree is, the weaker the pipeline's safety will be. We should pay attention to the bottom events which probability importance is big.

Critical importance degree analyzed for the basic events. The critical importance degree reflected the improvement difficulty of the basic events. The critical importance degree of the ten basic events calculated in table 4.

Table4. Critical Importance Degree of Ten Basic Events

Basic Event	The Corresponding Critical Importance Degree
X1Material with Poor Mechanical Properties	0.02885264
X2Pipeline with Construction Defects	0.05996520
X3 Pipeline with Initial Defects	0.08169851

X4Corrosion	0.00004081
X5 Pipeline with Poor Corrosiveness Resistance	0.00040811
X6 Artificial Damage	0.40860845
X7 Natural Disaster and External Force	0.17517435
X8 Design	0.01886908
X9 Operate	0.07979283
X10 Maintain	0.13740025

We can know how difficult it is to improve the basic events when they have fault by analyzing their critical importance degree. In this paper, as for the ten basic events of the main risk factors fault tree, their improved difficulty level from high to low is :" artificial damage"" natural disaster and external force "," maintain"," pipeline with initial defects "," operate "," pipeline construction defects"," poor mechanical properties of materials"," design"," pipeline with poor corrosiveness "and" corrosion". Therefore, it should be prepared to improve the more difficult events in advance, meanwhile, to do a good job in the safety work.

SUMMARY

In this paper, CAFTA software is used to draw the fault tree, which made the graph more concise and beautiful. In quantitative analysis, expert judgment method and fuzzy theory are used to calculate the failure probability of basic events. Then we get the occurrence probability of the top event “pipeline failure”. Besides, for each basic event, probability importance degree and critical importance degree are analyzed. From the results, we can find out weak links of the pipeline system, and points out whether the basic event is easy or hard to improve.

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