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Risk analysis of subsea jumper in installation period based on fuzzy FMEA

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ABSTRACT

In order to identify the risks in the installation period of subsea jumper effectively, with a typical M shape jumper as an example, a FMEA (failure modes and effects analysis) method based on fuzzy theory was used to analyze the numerous risk factors in this period. Based on traditional FMEA, the fuzzy linguistic terms were determined by the expert experience and knowledge. The modified RPN (risk priority number) of risk factors would be obtained by fuzzy inference, and then be sorted to determine the key risks. The improved method eliminated the subjectivity and fuzziness of traditional FMEA and improved accuracy. The analysis result was consistent with the actual.
KEYWORDS: Subsea jumper; fuzzy theory; failure modes and effects analysis (FMEA); risk priority number

1. INTRODUCTION

Jumper is an important part to connect pipeline and Christmas tree, pipeline and PLEM, PLEM and Christmas tree, PLEM and riser in the development type of deep-water oil and gas field. With the development of deep-water offshore oil & gas industry, the task to ensure safety of continuous production of oil & gas is more and more important and difficult (Gui 2014). However, there are various kinds of risks in the installation process of subsea jumper. Therefore, it is very important to identify the key risks in this period.

Failure modes and effects analysis (FMEA) is a widely used engineering technique for defining, identifying, and eliminating known and/or potential failures, problems and so on from system ,design, process, and/or service before they reach the customers(Wang 2009). The main analysis steps include decomposing the system, investigating the subsystems sequentially and finding the potential failure modes of components. Then, we can present all of the accident forms and proposed measures to improve the reliability and safety of the systems, processes and productions (Chen

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2014). The information of traditional FMEA is usually obtained from historical database. However, there is no relative historical database about subsea jumper installation, especially for deep-water jumpers. What is more, direct assessment from specialists will bring fuzziness and subjectivity (Mandal 2014). This paper focuses on the installation of subsea jumpers, proposes a modified FMEA method based on fuzzy inference theory to improve accuracy and reliability of risk analysis.

2. PROPOSED MODIFIED FMEA BASED ON FUZZY INFERENCE

The traditional FMEA obtains the Risk Priority Number (RPN) which is the multiplication of the occurrence (O), severity (S) and detection (D) by assessing failure modes, causes, effects. That is

$$RPN = O \times S \times D \tag{1}$$

where O is the frequency of the failure occurrence, S is the seriousness of the failure and D is the probability of not detecting the failure. Then, a rank list will be finished to confirm the key risks in the whole process. However, the modified FMEA method treats the risk parameters O, S and D as fuzzy numbers, and obtains modified RPN (mRPN) by fuzzy inference.

Fuzzy inference system combines fuzzy set theory and inference method to analyze the uncertainty of problems. It consists of fuzzification, fuzzy rules, inference method and defuzzification. The procedure of risk analysis based on fuzzy inference FMEA is described as follows:

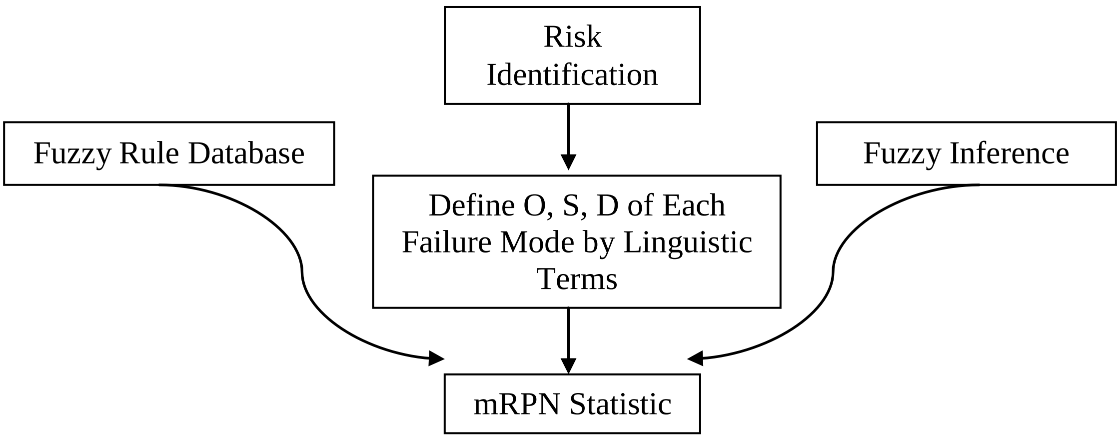


Fig. 1 Flow chart of proposed fuzzy FMEA method

2.1 Triangular fuzzy number (TFN)

A fuzzy set A in X is defined by a membership function $\mu_A(x)$. And X is called the universe which would be mapped into real numbers in the interval [0, 1]. The value of $\mu_A(x)$ indicates the degree of membership of x in A. A fuzzy number is thus a special case of a convex, normalized fuzzy set of the real line (Michael Hanss 2005). The most commonly used fuzzy number is triangular fuzzy number, because it can be easily handled arithmetically and interpreted intuitively. It's membership function is defined as follows:

$$\mu_A(x) = \begin{cases} (x - a)/(b - a), a \le x \le b \\ (c - x)/(c - b), b \le x \le c \\ 0, otherwise \end{cases} \quad (2)$$

This triangular fuzzy number is noted as: (a, b, c).

2.2 Fuzzy linguistic variable

Generally, human being prefers to use linguistic terms rather than numerical numbers to describe what they perceive. This paper treats 3 risk parameters (O, S, D) and risk as fuzzy linguistic variables. In every failure mode, each linguistic variable can be assessed by a linguistic term. Namely, U={very low (VL), low (L), moderate (M), high (H), very high (VH)} is used to assess the aforementioned 3 risk parameters and the risk. Besides, each of linguistic terms of U can be quantitatively described by a triangular fuzzy number. Specific illustration is shown in Table 1.

Table 1 Fuzzy linguistic terms

Linguistic terms	Fuzzy number	O	S	D	Risk
Very low	VL(0,0,2)	Almost impossible to happen for these failures, even once	Minimal influence to the whole process	Very possible to detect the potential failure reason	Almost can be ignored
Low	L(1,3,5)	Relatively impossible, but maybe occur once	Slightly influence to the system, but no damage	Likely to detect	Low priority to take measures
Moderate	M(3,5,7)	Occasionally happen	Make slightly damage to the system	Moderate chance to detect	Moderate priority to take measures
High	H(5,7,9)	Almost be sure to happen once	Make obvious damage to the system or minor injury	Relatively high chance to miss the potential failure causes	High priority to take measures
Very high	VH(8,10,10)	Almost be sure to happen more than once	Seriously reduce the ability to finish work, make serious injury or deaths	Very high chance to miss the potential failure causes	Very High priority to take measures

2.3 Fuzzy inference

2.3.1 Fuzzy rule base

The fuzzy inference approach uses the concept of fuzzy logic system wherein the fuzzy rule base which consists of a collection of fuzzy If-Then rules (Liu 2009). Fuzzy rule is the core of fuzzy inference system. This paper adopts so called “multiple fuzzy if-then rule multiple input model” as the inference engine. It is shown as follows:

Therefore, for FMEA used in this paper, we can define the rules as follows:

If there are m rules, then

Rule R_1	If x_1 is $A_{11} \wedge x_2$ is $A_{12} \ldots \wedge x_n$ is A_{1n}	Then y is C_1
Rule R_2	If x_1 is $A_{21} \wedge x_2$ is $A_{22} \ldots \wedge x_n$ is A_{2n}	Then y is C_2
……	……	……
Rule R_m	If x_1 is $A_{m1} \wedge x_2$ is $A_{m2} \ldots \wedge x_n$ is A_{mn}	Then y is C_m
New Input	If x_1 is $A_1 \wedge x_2$ is $A_2 \ldots \wedge x_n$ is A_n	
Output		Then y is C'

Rule i: If O is A_{i1}, S is A_{i2}, D is A_{i3}
Then Risk is C_i (i=1, 2, 3, … , m)

With the help of the knowledge and expertise of experts, the fuzzy rule base to the process we want to analyze will be established.

2.3.2 Fuzzy inference method

In fact, what is mentioned before could be explained by fuzzy mathematics. In this theory, the established rule base is expressed by a fuzzy relation R, therefore, fuzzy inference model is given as follows:

$$C = A \circ R \text{ ('}\circ\text{' represents a fuzzy operator)} \quad (3)$$

where A is the input, then we can get the output C' .

There are lots of fuzzy operators in fuzzy mathematics theory, for example, "$\vee - \wedge$", "$\vee - \bullet$", "$\oplus - \wedge$", "$\oplus - \bullet$". This paper adopts Mamdani max-min inference method (Mandani 1975) which is one of the most commonly used methods. The specific process is clearly described as follows:

In this paper, let the actual inputs of the O, S, D mentioned before be A_1' , A_2' , A_3' , then the mRPN of final C could be calculated by the following steps(Cheng 2013).

$$\mu_{C_i'}(y) = (a_{i1} \wedge a_{i2} \wedge a_{i3}) \wedge \mu_{C_i}(y) \quad (i=1, 2, 3,\ldots, m) \quad (4)$$

$$a_{ij} = \sup_x [\mu_{A_j'}(x) \wedge \mu_{A_{ij}}(x)] \quad (j=1, 2, 3) \quad (5)$$

Here, $\mu_{C_i'}(y)$ represents the output membership function of C_i' under the ith rule. $\mu_{A_{ij}}(x)$ represents the membership function of variables(O, S, D) in the ith fuzzy rule. Besides, $\mu_{A_j'}(x)$ represents the membership function of input variables. The next equation will aggregate the output value of each of rules used.

$$\mu_C(y) = \mu_{C_1'}(y) \vee \mu_{C_2'}(y) \vee \cdots \vee \mu_{C_m'}(y) \quad (6)$$

What we obtained from Eq. (6) is a fuzzy set, but in order to know the risk priority, we need to transfer it to a crisp number. This is the so called defuzzification. The equation of defuzzification is given as(Li 2012):

$$y^* = \frac{\int y \cdot \mu_C(y)dy}{\int \mu_C(y)dy} \quad (7)$$

where y* is the eventual value of mRPN.

By the steps mentioned above, the mRPN value of every failure mode will be calculated and then be ranked in a statistic to identify the key risk factors.

3. CASE STUDY

3.1 project introduction

Fig. 2 The installation of subsea jumper

Jumper is a very large subsea structure. Integral lifting is the most widely used method in the jumper installation(See Fig. 2). Due to the bulk mass of subsea jumper, especially for deep-water, and the uncertainty of sea conditions, the installation of subsea jumper demands high-level equipment and precise handing performance. The installation process of subsea jumper consists of 3 stages. They are respectively preliminary work, jumper lifting and lowering, subsea connector connecting to the hub. Technicians will face various kinds of complex technical problems and risk sources. This paper will make a risk analysis of subsea jumper in installation period based on the method mentioned before.

3.2 Risk identification

Based on the processes of 3 stages mentioned above, the team analyzes 21 potential failure modes in detail. They are gathered in a risk list shown in Table 2.

3.3 Risk assessment

As mentioned before, in order to finish fuzzy inference, a fuzzy rule base is required. Here, this paper adopts a rule base which is suitable for installation process. It is based on the knowledge and expertise from experts in many areas. The rule base including 36 rules is shown in Table 3.

Table 2 Risk list of jumper installation

Stage	No.	Failure mode	Stage	No.	Failure mode
Preliminary work	1	Rigging Connecting fail to meet the requirements	Jumper lifting and lowering	12	Failures of AHC
	2	The arrangement of lifting points of spreader bar is not enough proper		13	Connects' collision with subsea facility
	3	The running tool of subsea connector has not been fixed on the jumper properly		14	towing lines of ROV and riggings intertwines
	4	Unable to identify the subsea marks and obstacles properly		15	Sudden change of sea state
Jumper lifting and lowering	5	Installation vessel's collision with barge		16	Braking vastly
	6	Installation vessel's collision with jumper	Subsea connector connecting to the hub	17	The connectors are far away from the destination
	7	Failures of crane or winch		18	Collet segments locking failures
	8	Fatigue or wear of riggings or ropes		19	Seal gaskets failure
	9	Failures of welds		20	Hydraulic Cylinders failure
	10	Serious deformation of lifting eye		21	The unlocking of RTs failures
	11	Exceed max landing speed(0.8m/s)			

Table 3 Fuzzy rules base

Rule	O	S	D	Risk
R_1	L(1,3,5)	R(0,0,2)	L(1,3,5)	R(0,0,2)
R_2	R(0,0,2)	L(1,3,5)	R(0,0,2)	R(0,0,2)
R_3	L(1,3,5)	L(1,3,5)	R(0,0,2)	R(0,0,2)
R_4	L(1,3,5)	M(3,5,7)	L(1,3,5)	L(1,3,5)
R_5	M(3,5,7)	L(1,3,5)	L(1,3,5)	L(1,3,5)
…	…	…	…	…
R_{32}	VH(8,10,10)	H(5,7,9)	H(5,7,9)	VH(8,10,10)
R_{33}	H(5,7,9)	H(5,7,9)	M(3,5,7)	H(5,7,9)
R_{34}	H(5,7,9)	M(3,5,7)	H(5,7,9)	H(5,7,9)
R_{35}	H(5,7,9)	VH(8,10,10)	H(5,7,9)	VH(8,10,10)
R_{36}	H(5,7,9)	H(5,7,9)	VH(8,10,10)	VH(8,10,10)

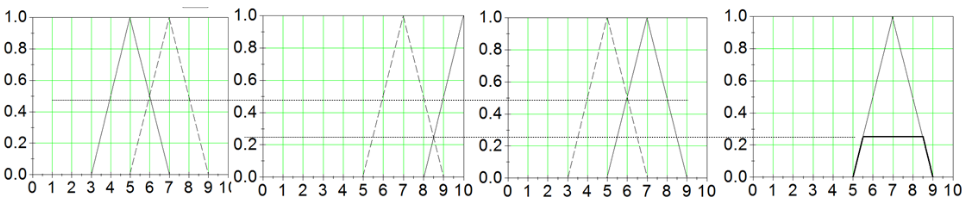
By means of investigation and detailed analysis of the jumper installation process, This paper assesses O, S, and D by the forementioned linguistic terms and corresponding fuzzy number. The statistic is shown in Table 4.

Then the mRPN could be calculated by using Eq. (3) - (7). Take the example of No.8 failure mode. Three rules (rule 33, 35, 36) can be aggregated to calculate the mRPN. Fig.3 explains the fuzzy inference process of No.8 failure mode.

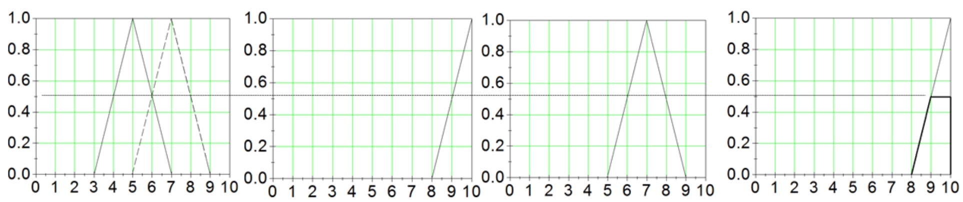
Table 4 Statistic of risk assessment of jumper installation

Stage	No.	O	S	D
preliminary work	1	L(1,3,5)	H(5,7,9)	L(1,3,5)
	2	M(3,5,7)	M(3,5,7)	L(1,3,5)
	3	L(1,3,5)	H(5,7,9)	M(1,3,5)
	4	M(3,5,7)	M(3,5,7)	M(3,5,7)
jumper lifting and lowering	5	H(5,7,9)	M(3,5,7)	M(3,5,7)
	6	VH(8,10,10)	H(5,7,9)	M(3,5,7)
	7	M(3,5,7)	L(1,3,5)	L(1,3,5)
	8	M(3,5,7)	VH(8,10,10)	H(5,7,9)
	9	L(1,3,5)	VH(8,10,10)	L(1,3,5)
	10	L(1,3,5)	VH(8,10,10)	L(1,3,5)
	11	M(3,5,7)	M(3,5,7)	M(3,5,7)
	12	L(1,3,5)	H(5,7,9)	M(3,5,7)
	13	L(1,3,5)	H(5,7,9)	R(0,0,2)
	14	H(5,7,9)	M(3,5,7)	M(3,5,7)
	15	H(5,7,9)	H(5,7,9)	H(5,7,9)
	16	H(5,7,9)	H(5,7,9)	M(3,5,7)
subsea connector connecting to the hub	17	L(1,3,5)	H(5,7,9)	L(1,3,5)
	18	M(3,5,7)	M(3,5,7)	L(1,3,5)
	19	H(5,7,9)	H(5,7,9)	M(3,5,7)
	20	M(3,5,7)	M(3,5,7)	M(3,5,7)
	21	L(1,3,5)	M(3,5,7)	M(3,5,7)

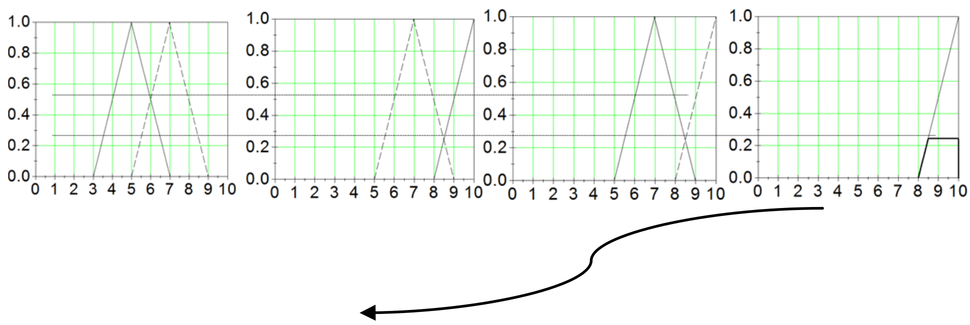
Rule 33:



Rule 35:



Rule 36:



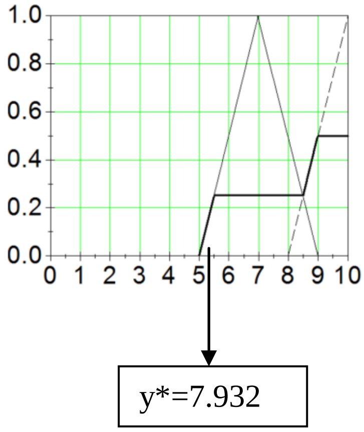


Fig. 3 Fuzzy inference process of No.8 failure mode

Where the dotted lines represent the fuzzy number of rules, the active lines represent the fuzzy number of failure No.8. By means of fuzzy inference, the mRPN is derived, y*=7.932. Therefore, other failure modes could also be calculated by the same method. The mRPN of each failure mode is shown in Table 5.

Table 5 The mRPN and rank of each failure mode

No.	1	2	3	4	5	6	7	8	9	10	11
mRPN	3.662	4.661	4.564	5.004	5.343	7.654	3.141	7.932	4.003	4.003	5.000
Rank	20	12	14	8	6	2	21	1	17	17	9
No.	12	13	14	15	16	17	18	19	20	21	
mRPN	4.562	4.451	5.343	7.001	6.853	3.664	4.663	6.853	5.000	4.661	
Rank	15	16	6	3	4	19	11	4	9	12	

Table 6 The list of top 3 high risk failure modes

High risk failure mode	Stage	Cause	Consequence	O	S	D	mRPN
fatigue or wear of riggings or ropes	Jumper lifting and lowering	Long-range and repeating accumulation	The drop of subsea jumpers, even make injury or deaths	M	VH	H	7.932
Installation vessel's collision with jumper	Installation vessel's collision with jumper	The influence of sea wave	Significant damage to the jumper or other equipment on the vessel	VH	H	M	7.654
Sudden change of sea state	Jumper lifting and lowering	Inaccuracy of weather forecast	Delay the installation of subsea jumpers	H	H	H	7.001

We can derive the high risk failure mode list from Table 5. The failure modes of top 3 are respectively fatigue or wear of riggings or ropes, installation vessel's collision with the jumper, sudden change of sea state. This corresponds with the actual condition. Table 6 illustrates it in detail.

4. CONCLUSIONS

1) The technique of installation of subsea jumper is quite complicated and risky. However, traditional FMEA risk analysis has inevitable subjectivity and fuzziness. This paper introduces a modified FMEA method based on fuzzy theory. It establishes the statistic of failure modes in the installation process of subsea jumper, and uses fuzzy number to describe linguistic terms. Besides, it builds a fuzzy rule base about installation process. To a large extent, this method improves the accuracy of risk analysis.

2) By means of risk analysis based on fuzzy FMEA, we derive a statistic about mRPN of each failure mode in the process of jumper installation. Then, the rank of priority of all the failure modes mentioned in Table 5 could be obtained. After identifying the high risk failure modes, we can take measures to reduce the occurrence rate and consequence of that. Meanwhile, this method is also used for risk analysis of other engineering construction.

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