

PAPER • OPEN ACCESS

The Application of FTA and FCE on Navigation Safety Assessment

To cite this article: Langtao Yan *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **790** 012022

View the [article online](#) for updates and enhancements.

You may also like

- [Reliability analysis of ballast cleaning device based on fuzzy FTA and FMEA](#)
J Wang, Z X Cui, S D Li et al.
- [Application Research of Fault Tree Analysis in Grid Communication System Corrective Maintenance](#)
Jian Wang, Zhenwei Yang and Mei Kang
- [Study on Fault Diagnosis of Optical Measurement Equipment Based on Fault Tree Analysis](#)
Changde Hu, Zhaohui Wang, Xiaotian Zheng et al.



ECS
The
Electrochemical
Society
Advancing solid state &
electrochemical science & technology

DISCOVER
how sustainability
intersects with
electrochemistry & solid
state science research

The Application of FTA and FCE on Navigation Safety Assessment

Langtao Yan*, Jiawan Tan, Jian Ai and Shuang Zhang

School of Shipping and Naval Architecture, Chongqing Jiaotong University

*Corresponding author

Abstract. In order to analysis the impact of ship state on the navigational safety, the fuzzy comprehensive evaluation method based on fault tree of ship safety state is to be present in this paper. The fault tree of ship navigation state to be established using the software named Easydraw, after analyzing systematically influence factors of ship safety navigation, and the structure important degree of the basic event is calculated based on the fault tree, which made the main factors influencing the ship navigation safety clear.. With the analyzing results of the navigation state fault tree, several important factors such as speed, channel and visibility, to be regard as the main correlation factor evaluating ship safety state, and the mathematical model of fuzzy comprehensive evaluation on ship safety state to be established. The experiment is conducted in the YouShui river, the relevant parameters is obtained, using the GPS navigation system on board, and the navigation state is to be analyzed and evaluated by the mathematical model. The evaluation results shows that the evaluation model applied to the ship safety state is reliable and effective.

Keywords: Ship safety; fault tree; fuzzy comprehensive evaluation.

1. Introduction

Ship status information includes all data reflecting the ship's real-time status. It includes ship's own equipment and structure information, and includes navigation environment information, such as the weather, channel condition, water flow speed, and so on.

One major shipwreck occurred in China in 2015, which is that one passenger ship named East Star sank within two minutes. The survey results showed that the factors such as weather and ship equipment status, affecting the safety of ship navigation, were ignored. So the ship status information is very important for safe navigation. But the factors such as the weather, channel condition, water flow speed and the signal strength of navigation satellite, affecting the safety of the ship navigation, is nondeterministic and difficult to quantify.

The combination of FCE (Fuzzy Comprehensive Evaluation) and FTA (Fault Tree Analysis) can solve the problem which is fuzzy and difficult to quantify, is suitable for solving nondeterministic problem. FCE is a comprehensive evaluation method based on fuzzy mathematics, which is used to transform the qualitative evaluation into quantitative evaluation using the membership degree theory, owning the character of clear result and strong systematicness. FTA (Fault Tree Analysis) is a method of exploring the fault cause, owning a high credibility. It is used to qualitative analysis and quantitative analysis. For qualitative analysis, the purpose is to clarify how many possibilities of a certain fault or the top event of one system or equipment, and analysis what factors will cause a failure of the system. For quantitative analysis, the aim is to get the quantitative indexes, such as the top event occurrence probability and the importance of the bottom events, under the condition that the bottom events are independent of each other and the occurrence probability is known.



2. The Fault Tree of Ship Safety States

2.1. The Analysis Process of Fault Tree

According to the reference^[1] know, the top event in the fault tree is the result of the bottom event, the bottom event is the reason that arouses the top event. The process of making use of fault tree to analyze a certain system is shown in figure 1.

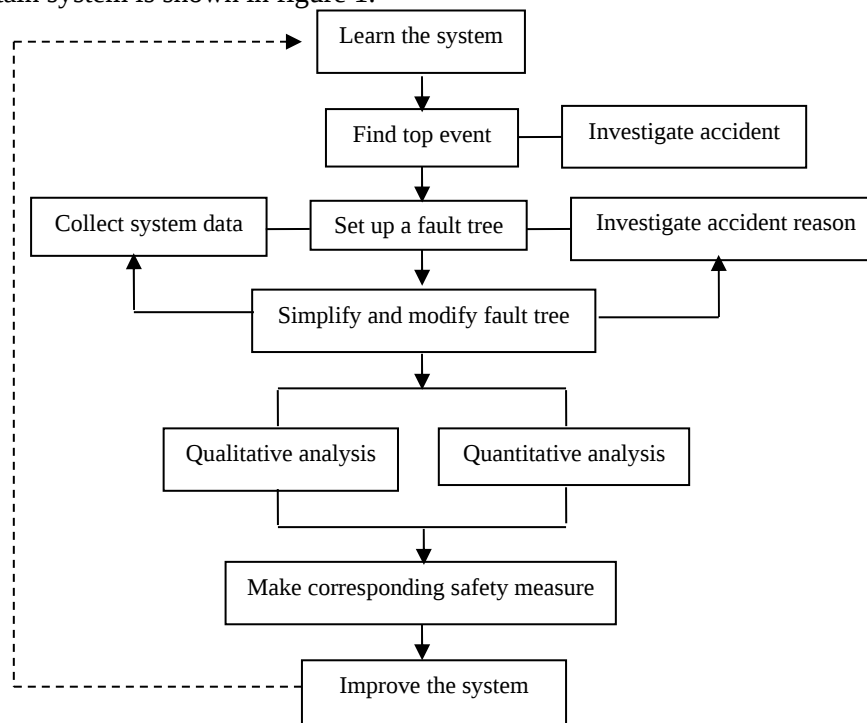


Figure 1. Fault tree analysis process.

The fault tree analysis process includes quantitative analysis and qualitative analysis, but because the statistics of system breakdown rate and personnel operation mistake rate in our country is inadequate enough now, this brought the quantitative analysis of system a bigger difficulty, today majority of the documents^[2] and the examples in the teaching material, all making use of the fault tree, does qualitative analysis to some system, and the analysis in the last few years proved that its qualitative analysis also has very good effect.

2.2. The Fault Tree of Ship Navigation Safety States

During the navigation, the safety states of ships will under the influence of various environment factors, artificial factors and other many factors. Indicating from numerous related documents^[3] and the statement of seamen questionnaire, the main factor influencing ships voyage safety can be included human factor, ship factor, environment factor and enterprise management factor. The key point that this text discusses is the ships status 'influence on its sailing safety during the voyage, and with 2011 national ships traffic accident statistics data^[4], basing on the analysis and induction, making software named Easydraw to construct ships safety states fault tree, as figure 2 shows.

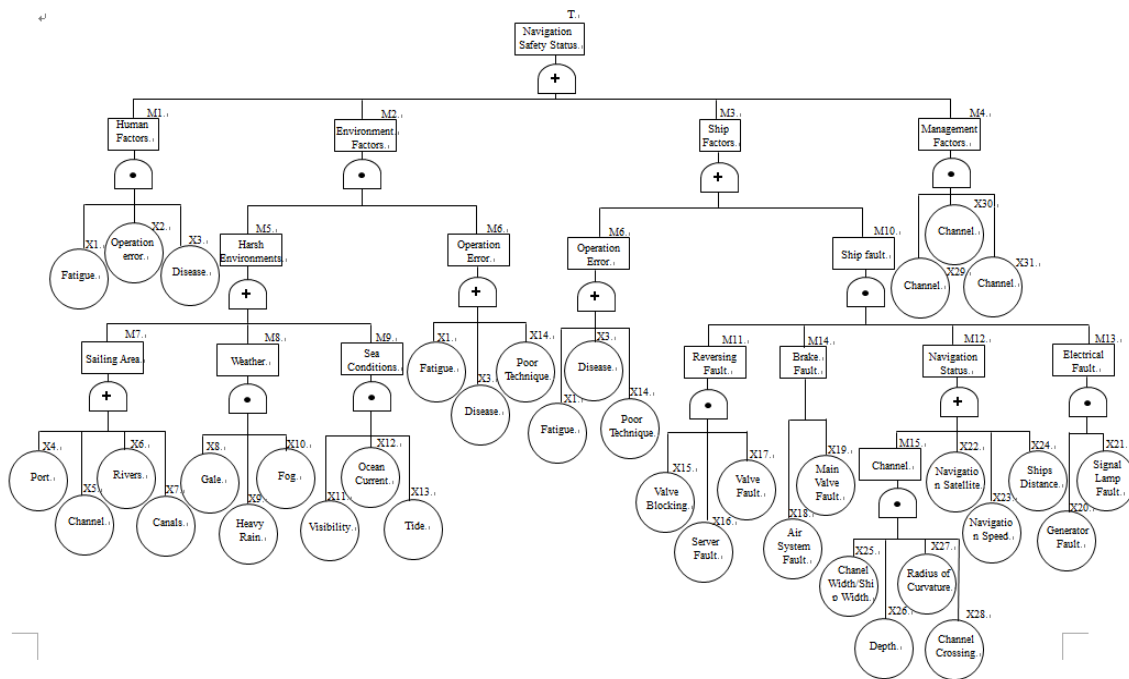


Figure 2. Fault tree of ship safety.

2.3. The Analysis of Safety States Factors

To carry on analyzing overall safety states impact factors, we have to correctly compute the basic event in fault tree of structure importance. The so-called structure importance is to take no account of the probability that the basic event takes place, just from the fault tree structure, analyzing influence degree of the occurrence of basic event to the occurrence of top event. The calculation method of structure importance of basic event mainly divides two kinds, namely making use of minimal cut set or minimum radius set to computing each basic event's structure importance. The method that this text receives is using minimal cut set to compute the structure importance of basic event.

2.3.1. The minimal cut set. According to figure 2, combining Boolean calculating principle, we can find the description of the minimal cut sets for ship sailing safety states' fault tree:

$$\begin{aligned}
 T &= M_1 + M_2 + M_3 + M_4 = X_1 X_2 X_3 + M_2 + M_3 + X_{29} X_{30} X_{31} \\
 &= X_1 X_2 X_3 + M_5 M_6 + (M_6 + M_{10}) + X_{29} X_{30} X_{31} \\
 &= X_1 X_2 X_3 + (M_7 + M_8 + M_9)(X_1 + X_3 + X_{14}) + \\
 &\quad (X_1 + X_3 + X_{14}) + (M_{11} + M_{12} + M_{13} + M_{14}) + X_{29} X_{30} X_{31} \\
 &= (X_4 + X_5 + X_6 + X_7 + X_8 X_9 X_{10} + X_{11} X_{12} X_{13})(X_1 + X_3 + X_{14}) \\
 &\quad + X_1 X_2 X_3 + X_1 + X_3 + X_{14} + X_{15} X_{16} X_{17} + X_{18} X_{19} + X_{25} X_{26} X_{27} X_{28} \\
 &\quad + X_{22} + X_{23} + X_{24} + X_{20} X_{21} + X_{29} X_{30} X_{31}
 \end{aligned} \tag{1}$$

We can get the minimal cut set $\{X_1, X_3, \dots, X_{25} X_{26} X_{27} X_{28}\}$ from the expression(1), totaled 11 sets.

2.3.2. The Structure Importance. Make use of the minimal cut/radius set to compute the structure importance coefficient of the basic event, it computes formula^[1] is as follows,

$$I_{\Phi(i)} = 1 - \prod_{X_i \in k_j} \left(1 - \frac{1}{2^{n_j-1}}\right) \tag{2}$$

$I_{\Phi(i)}$ is the structure importance degree coefficient of the event basic event i in the expression(2). Symbol n_j is the total number of the event i basic event in k_j 's basic events. We can get structure importance of each basic event by calculation as table 1.

Table 1. Structure importance of each basic event.

the serial number	the coefficient number of structure importance	degree
1	$X_{22}=X_{23}=X_{24}$ $I_{\Phi(22)} = I_{\Phi(23)} = I_{\Phi(24)} = 0.131$	
2	$X_{18}=X_{19}=X_{20}=X_{21}$ $I_{\Phi(18)} = I_{\Phi(19)} = I_{\Phi(20)} = I_{\Phi(21)} = 0.068$	
3	$X_{15}=IX_{16}=IX_{17}$ $I_{\Phi(15)} = I_{\Phi(16)} = I_{\Phi(17)} = 0.046$	
4	$X_{25}=IX_{26}=IX_{27}=X_{28}$ $I_{\Phi(25)} = I_{\Phi(26)} = I_{\Phi(27)} = I_{\Phi(28)} = 0.036$	

3. The Mathematical Model of Fuzzy Comprehensive Evaluation for Ship Safety States

3.1. The Process of Building Mathematical Model

Building the mathematical model of fuzzy comprehensive evaluation usually has few steps as follow^[5], The first step is determining the factor sets $U=\{u_1, u_2, \dots, u_n\}$ and the judgment sets $V=\{v_1, v_2, \dots, v_n\}$; then establishing the factors sets U 's weight set $\omega = \{\omega_1, \omega_2, \dots, \omega_m\}$ (ω_i is u_i 's weight coefficient, and the weight coefficient sums 1, $\sum_{i=1}^m \omega_i = 1$); the fuzzy evaluation sets V to be constructed corresponding some factor i in factor sets U ; Then we get fuzzy evaluation matrix^[6-7] $R = (r_{ij})_{m \times n}$; finally we can make comprehensive assessment according to fuzzy operators $B = \omega \times R$.

3.2. The Evaluation Mode

3.2.1. The determination of factor sets U . The ship named "You Shui 8" in this thesis to be used as experiment ship, Some factors including the navigation speed, distance approach, the GPS navigate satellite number, air distribute machine and reversing electronic valve, channel /ship breadth, under keel clearance, the channel curvature radius, channel cross, totaled 9 factors to be regard as adjudicate index of ships sailing safety states, named the factor sets $U=\{u_1, u_2, \dots, u_9\}$.

3.2.2. The determination of weight sets. According to table 2 evaluation scale and meaning, combining the analysis of fault tree of ship navigation safety states, and making a careful comparison and analysis for he above 9 indicators, we can get judge matrix A , its expression as formula^[8-10] (3).

Table 2 Evaluation scale and meaning.

The priority coefficient	Meaning
1	a_i and a_j are equally important
3	a_i slightly more important than a_j
5	a_i obviously important than a_j
7	a_i highly important than a_j
9	a_i absolutely important than a_j
2 4 6 8 the reciprocal of non-zero number above	intermediate value of the above two adjacent scale the judgment value of a_i and a_j is r_{ij} , then the judgment value of a_j and a_i is $1/r_{ij}$.

$$A = \begin{bmatrix} 1 & 5/4 & 7/4 & 3 & 9/2 & 5 & 6 & 7 & 8 \\ 4/5 & 1 & 8/5 & 3 & 4 & 5 & 5 & 6 & 7 \\ 4/7 & 5/8 & 1 & 5/2 & 3 & 7/2 & 4 & 5 & 6 \\ 1/3 & 1/3 & 2/5 & 1 & 2 & 3 & 7/2 & 9/2 & 5 \\ 2/9 & 1/4 & 1/3 & 1/2 & 1 & 5/2 & 3 & 4 & 9/2 \\ 1/5 & 1/5 & 2/7 & 1/3 & 2/5 & 1 & 8/5 & 2 & 3 \\ 1/6 & 1/5 & 1/4 & 2/7 & 1/3 & 5/8 & 1 & 6/4 & 2 \\ 1/7 & 1/6 & 1/5 & 2/9 & 1/4 & 1/2 & 4/6 & 1 & 4/3 \\ 1/8 & 1/7 & 1/6 & 1/5 & 2/9 & 1/3 & 1/2 & 3/4 & 1 \end{bmatrix} \quad (3)$$

Summing each line of matrix A and getting each-self arithmetician average, we can obtain ω by normalization processing.

$$\omega = \{0.239, 0.213, 0.167, 0.128, 0.104, 0.057, 0.041, 0.029, 0.022\} \quad (4)$$

Using the software named Matlab, we can get The Max-Eigen of matrix A, $\lambda_{\max} = 9.269$, then we can use the Max-Eigen to judge the consistency of matrix A.

$$CI = \frac{\lambda_{\max} - n}{n - 1} = \frac{9.269 - 9}{9 - 1} = \frac{0.269}{8} = 0.034 \quad (5)$$

According to CI in expression(4), and combine CR in expression(5), we can make judgment and modification.

$$CR = \frac{CI}{RI} \quad (6)$$

In the expression (5), RI is the mean random consistency index. If $CR < 0.1$, we can consider matrix A agree with random consistency scale; if $CR \geq 0.1$, matrix A don't agree with random consistency scale, we must make judgment and modification.

Further more the value of RI need to seek table to obtain, normally the RI value table of 1-9 order matrix calculated by Satty used in many documents, but they have no the process of realizing, this paper will use the RI value of 1-15 order comparison matrix repeatedly calculated 1000 times. As table 3 shows.

Table 3. RI value of 1-15 order comparison matrix.

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49	1.52	1.54	1.56	1.58	1.59

We can get $CR = \frac{CI}{RI} = \frac{0.034}{1.46} = 0.023 < 0.1$ according to expression (5) and table 3, so we judge matrix A agree with random consistency index, its inconsistency can be acceptable. Finally the weight vector of factor set as follows:

$$\omega = \{0.239, 0.213, 0.167, 0.128, 0.104, 0.057, 0.041, 0.029, 0.022\} \quad (7)$$

3.2.3. The determination of evaluation sets. Evaluation sets is a collection of elements which the evaluators make m choices to the evaluation objects. In this paper, the classical taxonomy level 5 to be used to construct the evaluation set of ships safety states, namely evaluation sets,

$V = \{v_1, v_2, v_3, v_4, v_5\} = \{\text{very safe, safe, basic safe, unsafe, definitely unsafe}\}$, Combining safe technique condition of ship movement, we can get the Evaluation index parameter as table 4 shows.

3.2.4. *The analysis of results.* According to table 4 and judgment sets $V = \{v_1, v_2, \dots, v_5\}$, constitute the corresponding evaluation matrix R , the expression of R as follows,

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{15} \\ r_{21} & r_{22} & \cdots & r_{25} \\ \vdots & \vdots & \ddots & \vdots \\ r_{91} & r_{92} & \cdots & r_{95} \end{bmatrix} \quad (8)$$

Table 4. Evaluation index and its value.

Factor	V_1	V_2	V_3	V_4	V_5	Remarks
$U_1(\text{kn})$	3-6	6-10	10-15	<3	>15	Normal distribution
$U_2(\text{m})$	>20	20-13	13-8	8-3	<3	Analogue
$U_3(\text{pc})$	>7	7-5	5-3	3-2	<2	Number of satellite star
U_4	0	0	0	0	1	Failure to take 1
U_5	0	0	0	0	1	Failure to take 1
U_6	>10	10-5	5-3	3-1.8	<1.8	Ratio
$U_7(\text{m})$	>3	3-2	2-0.6	0.6-0.4	<0.4	Analogue
$U_8(\text{m})$	>1500	1500-1000	1000-500	500-300	<300	Analogue
$U_9(\text{pc})$	0	0-1	1-2	2-3	>3	Junction mouth

Using weight vector ω and evaluation matrix R , we can obtain the corresponding fuzzy evaluation sets $B = [b_1, b_2, \dots, b_5] = \omega \bullet R$. Let the vector formed by each factor's order in the fuzzy evaluation sets B be $\{1, 2, 3, 4, 5\}$, then using the weighted average principle, we can work out B 's maximum membership degree b as follows:

$$b = \frac{\sum_{i=1}^5 b_i i}{\sum_{i=1}^5 b_i} = \frac{b_1 \times 1 + b_2 \times 2 + b_3 \times 3 + b_4 \times 4 + b_5 \times 5}{b_1 + b_2 + b_3 + b_4 + b_5} \quad (9)$$

Analysis and evaluation can be carried out according to the principle of the largest close degree and the maximum membership degree b .

4. Analysis of Navigation Trial

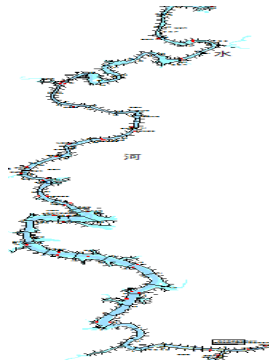


Figure 3. Navigation chart.

The relevant data of this navigation trial mainly depend on the GPS and Electronic Chart System. The trial channel is the channel segment of Youshui River between ShiTi town and YouChou power station, as Fig.3 shown, the channel starting point is intersection of two rivers and regarded as 0 kilometer. We obtain many important parameters in the ship voyage, as shown in Table 5.

Table 5. State parameters of ship voyage.

Mileage points	Speed(Kn)	Spacing (m)	Satellite Numbers	Air distributor	Reversing electronic valve	Channel /ship breadth	Under keel clearance (m)	Curvature radius(m)	Channel cross
3.0km	5.18	24.05	6	0	0	13.45	26.8	380.5	0
5.0km	8.20	26.00	4	0	0	14.38	38.1	785.6	0
6.0km	5.29	36.80	4	0	0	19.52	33.0	446.3	3
10.0km	5.67	35.05	7	0	0	157	29.6	1320	1
15.5km	8.00	42.05	5	0	0	19.15	31.3	854.8	0
18.3km	6.40	28.30	3	0	0	15.48	45.3	381.8	0
20.0km	6.16	177.50	6	0	0	43.21	34.2	325.4	1
24.0km	5.70	36.40	4	0	0	19.33	29.6	433.7	1
27.5km	7.55	17.00	3	0	0	10.10	26.3	542.4	0
32.5km	5.07	17.57	4	0	0	9.37	21.7	297.7	1

From table 5, we select the mileage point 32.5 km as one analysis points for fuzzy evaluation, because this mileage point owns narrow channel and small curvature radius. Combining evaluation indexes' set value in table 4, we obtain fuzzy judgment matrix R,

$$R = \begin{bmatrix} 0.31 & 0.69 & 0 & 0 & 0 \\ 0.35 & 0.65 & 0 & 0 & 0 \\ 0 & 0.25 & 0.5 & 0.25 & 0 \\ 0.13 & 0.87 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.01 & 0.99 \end{bmatrix} \quad (10)$$

Then the ship safety judgment sets B can be described as follows,

$$B = [b_1, b_2, b_3, b_4, b_5] = \omega \bullet R = [0.264, 0.530, 0.112, 0.056, 0.038] \quad (11)$$

Let's take $b_1, b_2, \dots, b_5$ in expression (11) into expression (9), we can obtain b as follows,

$$b = \frac{\sum_{i=1}^5 b_i i}{\sum_{i=1}^5 b_i} = \frac{b_1 \times 1 + b_2 \times 2 + b_3 \times 3 + b_4 \times 4 + b_5 \times 5}{b_1 + b_2 + b_3 + b_4 + b_5} = 2.073 \quad (12)$$

According to the principle of maximum close degree, we can judge the ship is in safety voyage states at the mileage point of 32.5 Km.

5. Conclusion

One new evaluation method of judging ships voyage status safety or not is put forward, and on the foundation of good fault tree, each impact factor of influencing the ships voyage safety is analyzed, and the important degree of each impact factor has been computed in the way of minimal cut sets, the mathematical model of evaluation is to be built up according to analysis result.

For verifying the useful and accuracy of the evaluation's model, navigation trial to be carried out in channel segment between Wang Jia wharf and YouChou power station, the results of the experiment proves rationality and science of the evaluation's model.

Acknowledgments

This paper is partly supported by the science and technology project of Chongqing Education Commission (Project number: KJQN201800721)

Reference

- [1] Tolentino, Joven A.; Gerardo, Bobby D.; Medina, Ruji P. Enhanced manhattan-based clustering using fuzzy C-means algorithm. *Advances in Intelligent Systems and Computing (IC2IT2018)*, V769, P126-134, 2019.
- [2] Saaty T L. *Fundamentals of Decision Making and Priority Theory* [M]. 2nd ed. Pittsburgh, PA: RWS Publications, 2000.
- [3] Íñiguez, Luis ; Galar, Mikel; Fernández, Alberto , *IEEE International Conference on Fuzzy System*, v2018-July, October 12, 2018.
- [4] JIAO Shufeng. The Algorithm of Mean Random Consistency Index in AHP and its Implementation. *Journal of Taiyuan Normal University*. 2006.12:45-47.
- [5] Yali Jin, Weihua Cao, Min Wu. Accurate fuzzy predictive models through complexity reduction based on decision of needed fuzzy rules. *Neurocomputing* 323(2019)175-187.
- [6] Gerami Seresht, Aminah Robinson Fayer. Computational method for fuzzy arithmetic operations on triangular fuzzy numbers by extension principle. *International Journal of Approximate Reasoning*. 106(2019):172-193.
- [7] WANG Chunlei, WU Yungang, KUI Jintao. Fuzzy comprehensive evaluation for risk assessment on debris flow[J]. *Safety and Environmental Engineering*, 2010,17(3):14-16.
- [8] Eustáquio, Fernanda ; Camargo, Heloisa; Rezende, Solange; Nogueira. On fuzzy cluster validity indexes for high dimensional feature space. *Advances in Intelligent Systems and Computing*, v642, p12-23, 2018.
- [9] Massanet, Sebastia; Mayor, Gaspar; Mesiar, Radko. On fuzzy implications: An axiomatic approach. *International Journal of Approximate Reasoning*, v 54, n 9, p 1471-1482, November 2013.
- [10] Yang, Miin-Shen (Department of Applied Mathematics, Chung Yuan Christian University, Chung-Li; 32023, Taiwan); Tian, Yi-Cheng. Bias-correction fuzzy clustering algorithms. *Information Sciences*, v 309, p 138-162, July 10, 2015.