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Risk Assessment using Fuzzy FMEA (Case Study: Tehran Subway Tunneling Operations)

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Abstract

Background/Objective: FMEA is an appropriate tool for identification, evaluation and effective management of risks in a project. For this purpose, the proposed work tried to assess the risks by using a fuzzy FMEA. **Methods:** On the one hand, the parameter input of the method (frequency, occurrence, severity and detection of a failure mode) is determined by experts and can be found in difficult due to several uncertainties as well as qualitative and subjective judgments. **Results:** On the other hand, tunnel construction projects are found among the riskiest projects due to lack of sufficient knowledge of land characteristics, surrounding conditions, diversity of activities, expansion, equipment density, human factors and uncertainties related to their design and implementation. Failure in identification, evaluation, timely and effective management of these projects can increase the duration and cost of implementing these projects. In this study, fuzzy logic (using two computational approaches) is used as a complementary tool to perform a consistent and logical analysis. **Conclusion:** The results showed that Fuzzy FMEA is more flexible and realistic compared with the traditional FMEA method.

Keywords: Fuzzy Logic, FMEA, Risk Assessment, Tunneling

1. Introduction

FMEA (failure mode and effects analysis) is an important technique for identification and radical analysis of potential failure modes of a productor process, and perhaps no other risk analysis technique can be an alternative to FMEA[1]. This technique can also be used to improve processes and enhance product quality at each stage of production. In this technique, failure modes are analyzed by an expert team and three parameters of severity, occurrence and detection are considered for each failure mode. These three parameters usually have values between 1 and 10 and their multiplication gives a value between 1 and 1000, which is known as RPN (risk priority number). Different failure modes are prioritized in terms of severity score as well as RPN. This method is based on human thinking and feeling and so the works face a vague imprecise concept and an accurate quantitative value cannot be considered for the triple parameters. In other words, can assign a value between 1 to 10 to each of the factors influencing the risk is a difficult task for the relevant multi-disciplinary team and causes considerable discrepancy in calculations.

Given the need to make a final decision concerning the causes of non-compliance in analysis methods of failure modes and their consequences as well as exposure to inaccurate parameters, fuzzy theory seems to be capable of mathematical formulation of vague and inaccurate variables needed to calculate the risk priority number to enable prioritization of ultimate causes of nonconformities[2-4]. Since Fuzzy FMEA is a relatively new subject, few studies have been done in this field, the most important of which are listed in Table 1.

Tunnel construction projects are among the riskiest projects given the lack of sufficient awareness of land features, surrounding circumstances, diversity of activities, expansion, equipment density, human factors as well as uncertainties associated with their design and

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implementation. Failure to identify, access and manage the risks associated with these projects in a timely and effective manner can increase the period and cost of implementing these projects.

FMEA is a proper approach for identification, evaluation and effective management of risks in tunneling projects. As noted, the input parameters in this approach (occurrence, severity and detection of failure mode) are determined by experts, which may be difficult due to uncertainties of these projects as well as qualitative and subjective judgments.

In this study, fuzzy logic (by two computational approaches) was used as a complementary means to conduct a consistent and logical analysis and the conventional FMEA model was modified and modeled considering three parameters of severity, occurrence and detection probability of failure mode.

2. Fuzzy Numbers

Calculations involving fuzzy numbers are highly complex and time-consuming due to their specific structure. To facilitate the use of fuzzy numbers, specific fuzzy numbers (bell, triangular, trapezoidal, etc.) are used in calculations[14,15]. In this research, triangular fuzzy numbers have been used. Consider the triangular fuzzy number $\tilde{M} = (l, m, u)$ in which u and l are respective top and bottom ends and m is the vertex of triangle (median value). Membership function of the triangular fuzzy number is defined as follows[15]:

$$\mu_{\tilde{M}}(x) = \begin{cases} \dfrac{x-l}{m-l}, & l \le x \le m \\ \dfrac{u-x}{u-m}, & m \le x \le u \\ 0 & otherwise \end{cases} \quad (1)$$

3. Defuzzification of a Fuzzy Number

To convert a fuzzy number to a concrete value, there are several methods such as center of gravity, maximum membership function, left and right rating of fuzzy number[16,17]. In this study, the center of gravity method has been used in figure 1. Suppose a triangular fuzzy set

Table 1. Most important studies in the field of combining fuzzy logic with FMEA[5-13]

In [5]	To assess the risk of events and accidents in an emergency center, the fuzzy if-then rules have been used to estimate RPN in FMEA method [5].
In [6]	To predict the risk of ground subsidence due to digging underground space using Fuzzy Inference System (FIS) based on if-then rules and artificial neural network (ANN) to estimate RPN in FMEA method[6].
In [7]	To assess and minimize information security risks in a business center, if- then fuzzy rules were used in FMEA method to estimate the RPN value [7]
In [8]	To assess the risk in a system of coastal engineering, Fuzzy Evidential Reasoning (FER) approach based on if-then fuzzy rules was used to estimate the RPN value in FMEA method [8].
In [9]	To identify and assess risks in production of poultry feed, the if-then fuzzy rules based on expert opinion was used to estimate the RPN value in FMEA method [9].
In [10]	A new approach was used based on fuzzy if-then rules and possibility to estimate the RPN value in FMEA method and was eventually implemented in two case studies [10].
In [11]	To assess and manage the risks in a public hospital in order to improve the catering process, Fuzzy Inference System (FIS) based on if-then rules was used to estimate the RPN value in FMEA method [11].
In [12]	To assess the risks in a typical PWR auxiliary feed water system, Fuzzy Inference System (FIS) was used based on if-then rules to estimate RPN value in FMEA method [12].
In [13]	To assess the risk in an engine system based on expert opinion and definition of different membership functions, if-then fuzzy rules were used to estimate the RPN value in FMEA method [13].

as $A=(\alpha,m,\beta)$. Membership function of fuzzy number A is as follows:

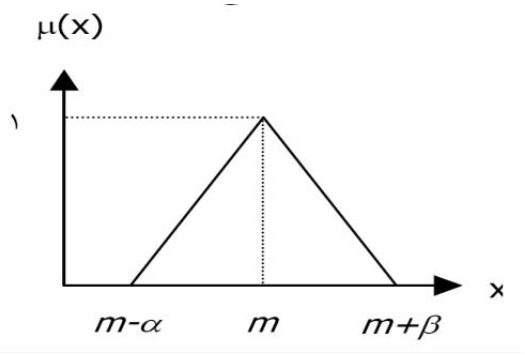

Figure 1. Triangular fuzzy number.

$$\mu_A(x)=\begin{cases}\dfrac{x-(m-\alpha)}{\alpha}; & m-\alpha\le x\le m\\ \dfrac{(m+\beta)-x}{\beta}; & m\le x\le m+\beta\end{cases} \quad (2)$$

Left rating $\mu_L(A)$, right rating $\mu_R(A)$ and $T(A)$ total score of *a* fuzzy number are calculated using the following equations [16]:

$$\mu_L(A)=1-\frac{m}{1+\alpha} \quad (3)$$

$$\mu_R(A)=\frac{m+\beta}{1+\beta} \quad (4)$$

$$T(A)=\frac{(\mu_R+1-\mu_L)}{2} \quad (5)$$

4. Development of Fuzzy FMEA Model

To calculate the degree of risk priority and prioritization of failures and their consequences, two main steps should be taken using fuzzy theory: 1) Choosing a fuzzy membership function and (2) Defuzzification of membership function.

4.1 Choosing a Fuzzy Membership Function

For all the factors affecting the degree of risk (severity, probability (occurrence), and detection probability of failure), three decuple ranges were used that are shown in Tables 2 to 4, respectively and their membership function can be seen in Figure 2.

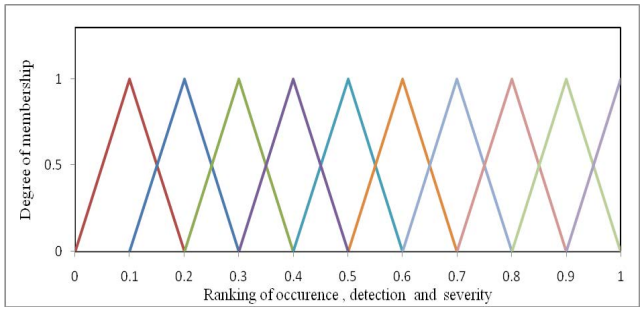

Figure 2. Failure mode fuzzy definition.

Table 2. FMEA occurrence evaluation criteria

Probability of failure		Likely failure rates overdesign life	Ranking	Fuzzy Number
Very High: persistent failures	Very High A (VHA)	≥100perthousanditems	10	(0.9 , 1 , 1)
	Very High B (VHB)	50perthousanditems	9	(0.8 , 0.9 , 1)
High: frequent failures	High A (HA)	20perthousanditems	8	(0.7 , 0.8 , 0.9)
	High B (HB)	10perthousanditems	7	(0.6 , 0.7 , 0.8)
Moderate: occasional failures	Moderate A (MA)	5perthousanditems	6	(0.5 , 0.6 , 0.7)
	Moderate B (MB)	2perthousanditems	5	(0.4 , 0.5 , 0.6)
	Moderate C (MC)	1perthousanditems	4	(0.3 , 0.4 , 0.5)
Low: relatively few failures	Low A (LA)	0.5perthousanditems	3	(0.2 , 0.3 , 0.4)
	Low B (LB)	0.1perthousandvehicles/item	2	(0.1 , 0.2 , 0.3)
Remote: failure is unlikely	Remote (R)	≤0.01perthousanditems	1	(0 , 0.1 , 0.2)

Table 3. FMEA severity evaluation criteria

Effect	Severity of effect	Ranking	Fuzzy Number
Hazardous Without Warning (HWoW)	Very high severity ranking when a potential failure mode affects safe vehicle operator and/ or involves noncompliance with government regulation without warning	10	(0.9 , 1 , 1)
Hazardous With Warning (HWW)	Very high severity ranking when a potential failure mode affects safe vehicle operator and/ or involves noncompliance with government regulation with warning	9	(0.8 , 0.9 , 1)
Very High (VH)	Vehicle/item inoperable (loss of primary function)	8	(0.7 , 0.8 , 0.9)
High (H)	Vehicle/item operable but at a reduced level of performance. Customer very dissatisfied	7	(0.6 , 0.7 , 0.8)
Moderate (M)	Vehicle/item operable but comfort/convenience item(s) operable at a reduced level of performance. Customer somewhat dissatisfied	6	(0.5 , 0.6 , 0.7)
Low (L)	Vehicle/ item operable but comfort/convenience item(s) operable at a reduced level of performance. Customer somewhat dissatisfied	5	(0.4 , 0.5 , 0.6)
Very Low (VL)	Fit and finish/squeak and rattle item does not conform. Defect noticed by most customers (greater than 75%)	4	(0.3 , 0.4 , 0.5)
Minor (Mi)	Fit and finish/squeak and rattle item does not conform. Defect noticed by 50 percent of customers	3	(0.2 , 0.3 , 0.4)
Very Minor (VM)	Fit and finish/squeak and rattle item does not conform. Defect noticed by discriminating customers (less than 25%)	2	(0.1 , 0.2 , 0.3)
None (N)	No discernible effect	1	(0 , 0.1 , 0.2)

Table 4. FMEA detection evaluation criteria

Detection	Likelihood of detection by design control	Ranking	Fuzzy Number
Absolute Uncertainty (AB)	Design control will not and/or cannot detect a potential cause/mechanism and subsequent failure modes; or there is no design control	10	(0.9 , 1 , 1)
Very Remote (VR)	Very remote chance the design control will detect a potential cause/mechanism and subsequent failure modes	9	(0.8 , 0.9 , 1)
Remote (R)	Remote chance the design control will detect a potential cause/mechanism and subsequent failure modes	8	(0.7 , 0.8 , 0.9)
Very Low (VL)	Very low chance the design control will detect a potential cause/mechanism and subsequent failure modes	7	(0.6 , 0.7 , 0.8)
Low (L)	Low chance the design control will detect a potential cause/ mechanism and subsequent failure modes	6	(0.5 , 0.6 , 0.7)
Moderate (M)	Moderate chance the design control will detect a potential cause/mechanism and subsequent failure modes	5	(0.4 , 0.5 , 0.6)
Moderately High (MH)	Moderately high chance the design control will detect a potential cause/mechanism and subsequent failure modes	4	(0.3 , 0.4 , 0.5)
High (H)	High chance the design control will detect a potential cause/ mechanism and subsequent failure modes	3	(0.2 , 0.3 , 0.4)
Very High (VH)	Very high chance the design control will detect a potential cause/mechanism and subsequent failure modes	2	(0.1 , 0.2 , 0.3)
Almost Certain (AC)	Design control will almost certainly detect a potential cause/mechanism and subsequent failure modes	1	(0 , 0.1 , 0.2)

4.2 Problem Solving by Defuzzification of Membership Function

To defuzzify the membership function, two approaches have been used: (1) Using the defuzzification method "left and right rating of the fuzzy number" and (2) Using the product of three triangular numbers[16,17].

5. Case Study

For risk assessment using Fuzzy FMEA technique, tunneling operations of Tehran subway projects have been selected. Modes, effects, causes of failures (risk) in accordance with conventional FMEA approach are shown in Table 5.

Afterwards, to use the two approaches presented for fuzzification of FMEA method, linguistic variables corresponding to the values obtained for each risk for assessment parameters (Severity, Occurrence and Detection) are substituted and Table 6 is thus formed. It should be noted that the mean values for each risk have been calculated for Severity and Occurrence parameters.

Table 5. Risk assessment of Tehran metro tunneling operations using FMEA

Description of conditions	Failure mode	Failure effects	Causes	Severity	Occurrence	Detection	Risk Number
designer	Wrong design	- Delay - Losses - Costs	-Upstream design -Downstream design	7 9 3	3 7	3	Risk 1
	Inappropriate location of work-place	- Urban traffic - Lack of space - Slow process	-Switching suppliers during work -Lack of proper design equipment - Lack of proper vision -Inadequate workshop equipment - Incorrect geotechnical design of workshop	7 2 5	9 6 1 5 1	6	Risk 2
	Lack of appro-priate standards for fire-fighting equipment and operations	- Dealing with disasters - Unexpected collisions - Jeopardized safety of workers and equipment	- Negligence of standards - Saving money - Unprofessional behavior	9 8 1	7 9 1	3	Risk 3
Responsible for safety and health	Failure to provide safety and health program	- Low level of safety - Low level of occupa-tional health - High level of acci-dents	- Lack of a clause on safety and health in the contract - Lack of legal obligation - Lack of monitoring by author-ities	5 4 8	9 2 1	3	Risk 4

Contractual problems	Successive changes in employer demands	- Spending time - Costs - Contractor complaints - Dissatisfaction of workers - Employer's failure to provide finance on time	- No penalty - Non-functional legal framework	6 9 2 3 8	9 5	2	Risk 5
Contractor	Basic Information	- Lack of visibility - Wrong process	Lack of information. - Errors in the information. - Tangled and complex information	6 7	5 2 1	3	Risk 6
	Operational capacity of contractors	- Delay - Not meeting the employer demands	- Disregarding the operational capacity of contractors - Wrong claims by contractors	8 3	1 1	1	Risk 7
	Engineering skills	- Implementation error - Accidents - Personal injury - Financial damage	- Low-grade engineering skills	7 8 9 9	4	5	Risk 8
	Relationship between labor and contractor	- Lack of information exchange - Contractor's failure to use potential advantages	- The absence of workers in risk management	4 2	9	1	Risk 9
	Lack of programs for risk assessment	- - Failure to identify risks - Breakdowns and accidents	- Lack of risk culture - Lack of attention to risk	9 10	10 10	9	Risk 10

Table 6. Evaluation of parameters using triangular fuzzy numbers according to linguistic variables

Risk Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Severity	VH	L	HWW	M	M	M	L	VH	Mi	HWW
Occurrence	MB	MC	MA	MC	HB	LA	R	MC	VHB	VHA
Detection	H	L	H	H	VH	H	AC	M	AC	VR

5.1 Using Defuzzification Method "Left and Right Rating of Fuzzy Number" (Method 1)

In this regard, first the fuzzy number is defuzzified using "left and right rating of fuzzy number" and a final score is assigned to each fuzzy number. Then, an FMEA problem with definitive parameters (crisp) is obtained, the failures and consequences of which can be prioritized using the method presented by conventional FMEA-i.e. the product of three parameters. Left, right and total points assigned to each of the linguistic variables using the mentioned method is presented in Table 7.

In the following, non-fuzzy values of failure severity parameter (S), probability of occurrence (O) failure detection (D) along with relevant RPN value, which is the product of three non-fuzzy parameters as well as priority number of each risk are shown in Table 8.

5.2 Using the Product of Three Triangular Fuzzy Numbers (Method 2)

In this method, using triangular fuzzy numbers multiplication operations, first the three parameters of severity (S), probability of occurrence (O), probability of detection (D) are multiplied as fuzzy numbers and RPN is calculated as a triangular fuzzy number. Then, the RPN fuzzy number is defuzzified and the risks are prioritized using the "left and right rating of fuzzy number" method.

In other words, the factors affecting the risk priority number are prioritized in the following steps:

- Allocation of a linguistic variable to each of the factors of risk number.
- Definition of each linguistic variable as a triangular fuzzy number as follows:

If M is a linguistic variable, the corresponding triangular fuzzy number is defined as follows:

$$M = (l, m, u) \tag{6}$$

in which m presents the value of a linguistic variable with membership number 1, l lower bound and u upper bound.

- Multiplying the risk factors as fuzzy numbers and RPN calculation using the following equation:

$$\text{RPN} = S * O * D = (l_1, m_1, u_1) * (l_2, m_2, u_2) * (l_3, m_3, u_3) = (l_1 l_2 l_3, m_1 m_2 m_3, u_1 u_2 u_3) \tag{7}$$

- Defuzzification of RPN values and prioritization of causes.

Fuzzy values assigned to each of the linguistic variables using triangular membership function as well as concrete (non-fuzzy) values assigned to RPN are given in Table 9.

Table 7. Absolute values (crisp) assigned to each fuzzy number

detection evaluation criteria	severity evaluation criteria	occurrence evaluation criteria	Fuzzy value	Right score	Left score	Total score
(AB)	(HWoW)	(VHA)	(0.9 , 1 , 1)	1.000	0.091	0.955
(VR)	(HWW)	(VHB)	(0.8 , 0.9 , 1)	0.909	0.182	0.864
(R)	(VH)	(HA)	(0.7 , 0.8 , 0.9)	0.818	0.273	0.773
(VL)	(H)	(HB)	(0.6 , 0.7 , 0.8)	0.727	0.364	0.682
(L)	(M)	(MA)	(0.5 , 0.6 , 0.7)	0.636	0.455	0.591
(M)	(L)	(MB)	(0.4 , 0.5 , 0.6)	0.545	0.545	0.500
(MH)	(VL)	(MC)	(0.3 , 0.4 , 0.5)	0.455	0.636	0.409
(H)	(Mi)	(LA)	(0.2 , 0.3 , 0.4)	0.364	0.727	0.318
(VH)	(VM)	(LB)	(0.1 , 0.2 , 0.3)	0.273	0.818	0.227
(AC)	(N)	(R)	(0 , 0.1 , 0.2)	0.182	0.909	0.136

Table 8. Defuzzified values of parameters along with respective RPN

Risk Number	1	2	3	4	5	6	7	8	9	10
Severity	0.773	0.500	0.864	0.591	0.591	0.591	0.500	0.773	0.318	0.864
Occurrence	0.500	0.409	0.591	0.409	0.682	0.318	0.136	0.409	0.864	0.955
Detection	0.318	0.591	0.318	0.318	0.227	0.318	0.136	0.500	0.136	0.864
RPN	0.1229	0.1209	0.1624	0.0769	0.0915	0.0598	0.0092	0.1581	0.0374	0.7129
Rank	4	5	2	7	6	8	10	3	9	1

Table 9. Fuzzy values assigned to parameters and Fuzzy RPN calculation

Risk Number	Severity	occurrence	Detection	Fuzzy RPN	DefuzzyRPN	Rank
1	(0.7 , 0.8 , 0.9)	(0.4 , 0.5 , 0.6)	(0.2 , 0.3 , 0.4)	(0.06 , 0.12 , 0.22)	0.1307	4
2	(0.4 , 0.5 , 0.6)	(0.3 , 0.4 , 0.5)	(0.5 , 0.6 , 0.7)	(0.06 , 0.12 , 0.21)	0.1300	5
3	(0.8 , 0.9 , 1.0)	(0.5 , 0.6 , 0.7)	(0.2 , 0.3 , 0.4)	(0.08 , 0.16 , 0.28)	0.1740	2
4	(0.5 , 0.6 , 0.7)	(0.3 , 0.4 , 0.5)	(0.2 , 0.3 , 0.4)	(0.03 , 0.07 , 0.14)	0.0807	7
5	(0.5 , 0.6 , 0.7)	(0.6 , 0.7 , 0.8)	(0.1 , 0.2 , 0.3)	(0.03 , 0.08 , 0.17)	0.0940	6
6	(0.5 , 0.6 , 0.7)	(0.2 , 0.3 , 0.4)	(0.2 , 0.3 , 0.4)	(0.02 , 0.05 , 0.11)	0.0620	8
7	(0.4 , 0.5 , 0.6)	(0.0 , 0.1 , 0.2)	(0.0 , 0.1 , 0.2)	(0.00 , 0.01 , 0.02)	0.0097	10
8	(0.7 , 0.8 , 0.9)	(0.3 , 0.4 , 0.5)	(0.4 , 0.5 , 0.6)	(0.08 , 0.16 , 0.27)	0.1713	3
9	(0.2 , 0.3 , 0.4)	(0.8 , 0.9 , 1.0)	(0.0 , 0.1 , 0.2)	(0.00 , 0.03 , 0.08)	0.0357	9
10	(0.8 , 0.9 , 1.0)	(0.9 , 1.0 , 1.0)	(0.8 , 0.9 , 1.0)	(0.58 , 0.81 , 1.00)	0.7953	1

RPN results from the two fuzzy approaches, namely "left and right rating of fuzzy number". The product of three triangular fuzzy numbers is better than conventional RPN and it is shown in Figure 3. Also, the ranks from three methods of RPN calculation have been presented in Figure 3. As can be seen, the results of the two fuzzy approaches are quite the same. However, in the first, second, fourth and fifth risks, fuzzy RPN results are different from conventional fuzzy ones. Therefore, regarding several preferences and superiorities of fuzzy logic and its ability is covered the uncertainties. The results of Fuzzy FMEA approach are more reliable and there is higher confidence in responding to risks in designs based on its priorities. It is shown in Table 10.

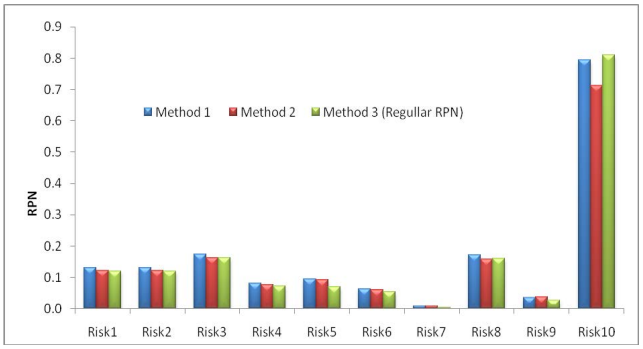

Figure 3. RPN values from two membership function defuzzification approaches.

6. Conclusion

Risk management of tunnel construction projects is given importance because of the involvement of huge sum of investment and grave consequences of failure or improper design. FMEA is an important technique for radical identification and analysis of potential failure modes in a process or project. Given that this method is based on human thinking and feeling, the project faces a vague imprecise concept and a quantitative value cannot be assigned to triple parameters; therefore, fuzzy theory is used as a valuable tool for calculations in uncertainty mode.

In this study, following identification of the most important risks in Tehran subway tunneling operations using FMEA approach, the risks were assessed using Fuzzy FMEA method. Triangular membership function was used for fuzzy evaluation of each parameter and two approaches were used for defuzzification of membership functions. Thus, some of the results are as follows: 1) In calculating the degree of risk using fuzzy model, due to frequent use of concepts and terminology of FMEA team, the problems associated with conventional methods mentioned were acceptably resolved, 2) Working with product of three triangular fuzzy numbers model is simple and easily understandable, 3) With regard to factors such as time and cost needed for corrective action,

Table 10. Ranks based on RPN related to different methods

	Risk1	Risk2	Risk3	Risk4	Risk5	Risk6	Risk7	Risk8	Risk9	Risk10
Method 1	5	4	2	6	7	8	10	3	9	1
Method 2	4	5	2	7	6	8	10	3	9	1
Method 3 (Regular RPN)	4	5	2	7	6	8	10	3	9	1

the production rate of the process can be investigated for development of FMEA process.

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