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A Novel Approach for Prioritization of Failure modes in FMEA using MCDM

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Abstract

Failure Mode Effect Analysis (FMEA) is one of user friendly and handy tool available in the hands of the process industries to identifying and eliminating the potential failures in systems, processes and designing. In this FMEA method prioritization of the failure modes are based on Risk Priority Number (RPN). This RPN can be calculated by multiplying the scores of various risk factors and categorized as Severity(S), Occurrence (O) and Detection (D). This RPN method has been criticized for its several limitations. So this paper aims to eliminate the limitations present in the RPN based prioritization by integrating with the Techniques of Multi Criteria Decision Making(MCDM) Model by fusing Analytical Hierarchy Process (AHP) with Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE).This hybridization of MCDM methods will enhance the precision of prioritizing failure modes by eliminating the limitations of traditional FMEA. The technique AHP is used to determine the weights for each risk factor and PROMETHEE is used to prioritize the failure mode based on the weights of risk factors.

Keywords: AHP, FMEA, MCDM, PROMETHEE, RPN, S, O, D and Risk Assessment

I. INTRODUCTION

It is quite common that accidents occur in industries due to the presence of hazardous nature of materials from low degree to high degree of occurrence. This undesirable event increased the importance of risk assessment techniques employed throughout the industries. There are several techniques developed to perform the risk assessment to mitigate the suffering. Failure Mode Effect Analysis (FMEA) is one of the most widely used risk assessment tool. This FMEA was first proposed by National Aeronautics and Space Administration (NASA, U.S.A.) in 1960. Then, it was adopted and promoted by Ford Motor in 1977.

Today, FMEA has been adopted in wide spectrum of fields such as the Chemical, Aerospace, Military, Automobile, Electrical, Mechanical and Semiconductor industries. The FMEA provides reliability and safety of a system and helps toidentify the potential products and process failures existing in the system.

This traditional FMEA method is purely based on Risk Priority Number (RPN).In order to prioritize the identified potential failure modes the RPN may be calculated by multiplying the scores of risk factors. There are three risk factors used for evaluating the RPN. This comprises Severity (S), Occurrence (O) and Detection (D). RPN can be represented mathematically as RPN = S*O*D. In these Severity(S) is the effect of failure on the system, Occurrence (O) is the frequency of failure and Detection (D) is the probability of detecting the failure. In this method experts will give their preference level based on the scale of importance to each failure modes. This scale of importance contains a numerical scale from 1 to 10. This RPN method has been criticized due to its limitations. So that, many authors proposed alternative methods to replace the traditional RPN method. To make the meaningful evaluation of RPN, few authors proposed FMEA with Multi Criteria Decision Making (MCDM) techniques. In 2001Chang et al.,[1] was computed FMEA in Grey theory to enhance the product and process stability.

In 2005, Stephen Heller [2] clearly appraised the advantages of MCDM in risk assessment. Multi Criteria Decision Analysis (MCDA) with risk assessment provides better-supported techniques for the comparison of alternatives based on decision matrices, and it also provides structured methods for the ranking of alternatives. Risk assessment alone can't reduce the risk effectively; Risk assessment along with decision making gives effective risk management.

Due to these advantages of MCDM few authors proposed FMEA with MCDM techniques for the risk assessment. In 2012, AhmetCan Kutlu et al.,[3]used the tool Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for providing solution for RPN based traditional method of FMEA.

In 2012, Hu-Chen Liu et al., [4] used extended VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje) method under the fuzzy environment for providing Risk prioritization in FMEA method.

Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) method was developed by the Brans and Vincke [5] in the year of 1985. It is the best outranking tool used in Multi criteria decision analysis (MCDA). This method mainly used for ranking the alternatives while considering several criteria. Due to its advantages Arunkumar et al., [6] used PROMETHEE method to minimize the overall demand for the blood in the region by prioritizing the collection centre's.

However, only limited publications were available for the risk assessment by using Multi Criteria Decision Making with FMEA. There is no evidence in the literature that any one of them were applied for risk assessment using FMEA with PROMETHEE. So this integrated method of FMEA with PROMETHEE and AHP will enhance the precision of FMEA by means of eliminating limitations in the traditional FMEA method.

Traditional Failure Mode Effect Analysis (FMEA) has been extensively criticized due its several limitations with Risk Priority Number (RPN) based prioritization. The following are the problems encountered with FMEA method by Chang et al.[1] (2001) and Hu-Chen Liu et al.,[7] (2011):

- Different combination of risk factors may produce same value of Risk priority number (RPN). For example two different failure modes with values of 6,2,1 and 3,2,2 for Severity, Occurrence and Detection will have same RPN as 12. It is difficult to prioritize the failure modes.
- The RPN numbers are duplicated. Only 120 out of 1000 numbers generated are unique.
- The relative importance among S, O and D is not taken into consideration. The three factors are assumed to have the same importance.
- The mathematical formula for calculating RPN is questionable and debatable. There is no rationale as to why S, O and D should be multiplied to produce the RPN.
- RPN value has high sensitivity to small change in the risk factor values due to multiplication of risk factors.

II. PROPOSED MODEL

The FMEA with hybrid Multi Criteria Decision Making (MCDM) tools will enhance the precision of prioritizing the failure modes by eliminating the limitations of using RPN method. Figure 1 shows the methodology flow chart. This proposed methodology consists of four stages for evaluating the risk assessment. In the first stage emphasizes the identification of probable failure modes by interviewing the experts through What – If analysis and failure records. In second stage, determine the Risk Factors with respect to failure modes. In third stage, determine the weights for each risk factor.

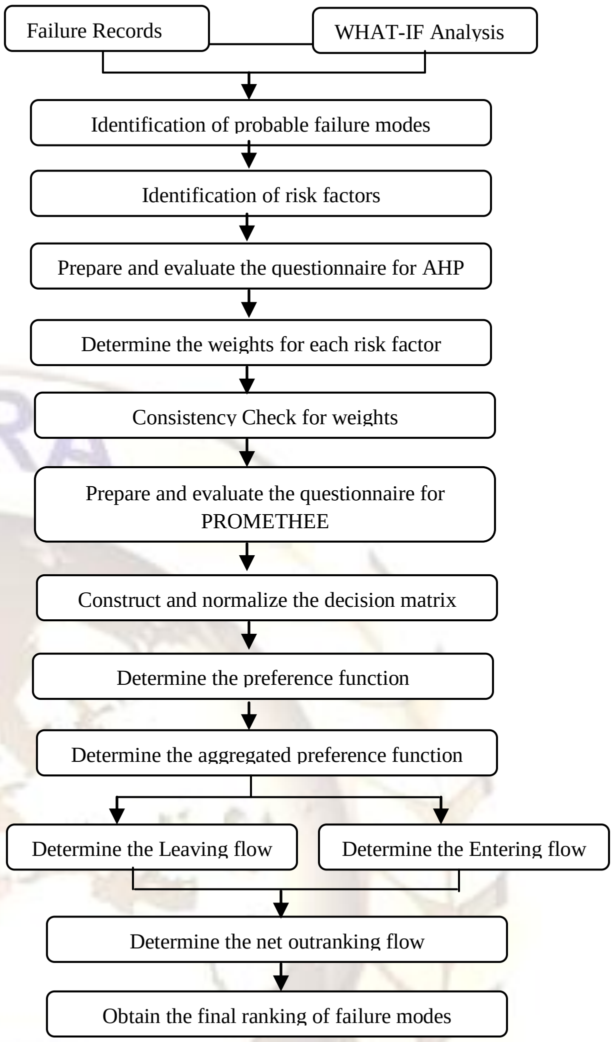

Fig. 1 Methodology Flow Chart

In fourth stage, ranking of each failure mode is determined for the selection of highest potential risk. In this new FMEA method, Analytical Hierarchy Process (AHP) is used to assign the weights for each risk factor and Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) is used to prioritize the failure modes.

A. Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) was developed by Saaty [8] in the year of 1980. It is a decision making approach for evaluating complex multiple criteria alternatives involving subjective judgment. This method is an effective and practical approach for solving complex and unstructured decision making problems. AHP method involves computation of weights and consistency check.

1). Computation of Weights:

The following are the steps involved in computation of weights by Analytical Hierarchy Process:

- ✓ Prepare the questionnaire for Analytical Hierarchy Process (AHP)
- ✓ Evaluate the questionnaire from various decision makers.
- ✓ Construct the decision matrix from the questionnaire by using Saaty scale.
- ✓ Calculate the weights for each criterion.

In this evaluation, decision matrix is formed from preference level given by the decision maker in the questionnaire. This preference level can be converted into numerical value based on the SAATY scale of importance. SAATY scale is given in the table 1.

Table 1 SAATY scale for AHP evaluation

Scale of importance	Crisp score
Equal importance	1
Moderate	3
Strong importance	5
Very Strong importance	7
Extremely preferred	9
Intermediate values	2,4,6,8

2). Consistency Check

The consistency of the subjective input in the pair-wise comparison matrix can be determined by calculating a Consistency Ratio (CR). In general, a CR having the value less than 0.1 is good (Saaty 1980). The CR for each square matrix is obtained from dividing CI values by Random Consistency Index (RCI) values.

$$CR = CI/RCI$$

Consistency index (CI) can be calculated by using the following formula:

$$CI = (\lambda max - n)/(n - 1)$$

In this 'n' is a number of criteria and λ_{max} is a mean of Eigen value. Random consistency index is given by Saaty. It is based on the matrix size.

B. PROMETHEE

Preference function based outranking method is a special type of MCDM tool that can provide a ranking of the decision options. The PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation) method was developed by Brans and Vincke [5] in 1985.

The procedural steps involved in PROMETHEE II method are enlisted as below:

Step 1: First of all, a committee of decision makers is formed and Scale of Importance for all criteria (Risk Factors) is defined.

Step 2: Then the Questionnaire for evaluating alternatives (Failure Modes) are prepared.

Step 3: Through this questionnaire, Suitable crisp score values (Scale of importance) are assigned for alternatives (Failure Modes) by each decision maker.

Step 4: Then the decision matrix is formed based on the preference level of Decision Makers from the Questionnaire.

Step 5: Normalize the decision matrix using the following equation:
For beneficial criteria:

$$R_{ij} = [X_{ij} - minX_{ij}]/[maxX_{ij} - minX_{ij}] \begin{pmatrix} i = 1,2 \ldots.., n: \\ j = 1,2 \ldots.., m \end{pmatrix}$$

Where X_{ij} is the performance measure of i^{th} alternative with respect to j^{th} criterion.

For non-beneficial criteria, above equation can be rewritten as follows:

$$R_{ij} = [maxX_{ij} - X_{ij}]/[maxX_{ij} - minX_{ij}]$$

Step 6: Calculate the preference function, $P_j(i,i')$.

It is very difficult to select the suitable preference function for each criterion by Brans and Vincke's proposal. So, the simplified preference function model by Vijay and Shankar (2010) is implemented here.

$$P_j(i,i') = 0 \; if R_{ij} \leq R_{i'j}$$

$$P_j(i,i') = R_{ij} - R_{i'j} \; if R_{ij} > R_{i'j}$$

Step 7: Calculate the aggregated preference function taking into account the criteria weights.
Aggregated preference function,

$$\pi(i,i') = \left[\sum_{j=1}^{m} [w_j \times P_j(i,i')] \Big/ \sum_{j=1}^{m} [w_j]\right]$$

where, w_j is the relative importance (weight) of j^{th} criterion.

Step 8: Determine the leaving and entering outranking flows as follows:
Leaving (or positive) flow for i^{th} alternative,

$$\phi^+(i) = \frac{1}{n-1} \sum_{i'=1}^{n} \pi(i,i') (i \neq i')$$

Entering (or negative) flow for i^{th} alternative,

$$\phi^-(i) = \frac{1}{n-1} \sum_{i'=1}^{n} \pi(i',i) \quad (i \neq i')$$

Where, n is the number of alternatives.

Step 9: Calculate the net outranking flow for each alternative.

$$\phi(i) = \phi^{+}(i) - \phi^{-}(i)$$

Step 10: Determine the ranking of all the considered alternatives depending on the values of $\phi(i)$.

III. ILLUSTRATIVE EXAMPLE

The Proposed methodology is applied to the boiler of a tyre manufacturing industry which can generate a steam of 5 tons per hour with operating pressure of 17.5 kg/cm2. In this method, Analytical Hierarchy Process (AHP) is to assign the weights for risk factors of boiler and Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) is to prioritize the failure modes of the boiler.

A. Determination of Failure Modes

By interviewing the boiler staffs and managers through What-If analysis some of the probable failure modes were analyzed. Evidently, the failure report reveals the probability of failures in the boiler. On analysis by using What–If analysis and failure records it is found that 27 types of failures were identified. Out of these only 10 failure modes were taken for evaluation. The following are the failure modes taken for evaluation:

FM1: Induced Draft fan gets tripped
FM2: Feed water pump gets failed
FM3: Safety valve fails to act
FM4: Nozzle failure at the fuel supply system
FM5: Low temperature of the furnace oil
FM6: Safety door fails to act
FM7: Electrode rod failure at the ignition system
FM8: Failure of Water Level Controller
FM9: Feed water pipe gets ruptured
FM10: Failure occurs in the steam separator

B. Determination of Risk Factors

By interviewing the experts in the industry, four risk factors such as Severity, Occurrence, Detection and Protection were identified.

Severity (S): Effect of failure on the system.
Occurrence (O): Frequency of the failure.
Detection (D): Probability of detecting the failure.
Protection (P): Protection measures against the failure.

C. Weights of Risk Factors

The weights of the risk factors to be used in the evaluation process are calculated by using Analytical Hierarchy Process (AHP). Table 2 shows the calculated weights of risk factors.

Table 2 Weights of risk factors

Risk factor	**Weights**	
Severity(S)	0.4996	C.I= 0.0656 C.R=0.0728
Occurrence(O)	0.2884	
Detection(D)	0.0655	
Protection(P)	0.1465	

D. Prioritization of Failure Modes

To obtain the prioritization of failure modes PROMETHEE is used. In this, questionnaire is framed for the ten failure modes. From this questionnaire, preference levels of the various experts are obtained. Experts can give their feedback based on the scale rating of failures. These scale ratings for all risk factors are given below:

Table 3 Scale Rating for Occurrence

Grade of Occurrence	**Number of times**	**Scores**
Extreme	More than one per day / every 1 to 2 days	10, 9
Very high	One per every 2-4 days / per one week	8,7
High	One per every 1-2 weeks/2-4 weeks/ per month	6,5,4
Moderate	One per every 1to 3 months / 3 to 6 months	3,2
Low	One occurrence per more than a year	1

Table 4 Scale rating for Severity

Grade of Severity	**Effects of Severity**	**Scores**
Extreme	Extreme harmful to environment and causes fatalities.	9
Very high	High harmful to environment and serious injury to human beings	7
High	Moderately harmful to environment, and moderate injury to human beings	5
Moderate	Little harm to environment and less chances for injury to human beings	3
Low	Very low effect, no harm to environment, no injury sustained by human beings.	1

Table 5 Scale Rating for Detection

Grade of Detection	Likelihood of Detection	Scores
Extreme	Extreme chance for the system to detect the failure	9
Very high	Very high chance for the system to detect the failure	7
High	High chance for the system to detect the failure	5
Moderate	Moderate chance for the system to detect the failure	3
Low	Low chance for the system to detect the failure	1

Table 6 Scale Rating for Protection

Grade of Protection	Likelihood of Protection	Scores
Extreme	**Extreme chance for the system to protect the failure**	**9**
Very high	**Very high chance for the system to protect the failure**	**7**
High	**High chance for the system to protect the failure**	**5**
Moderate	**Moderate chance for the system to protect the failure**	**3**
Low	**Low chance for the system to protect the failure**	**1**

Preference level of each decision maker has been obtained through this questionnaire and averages of the decision matrix were calculated. Table 7 shows the average of decision matrix.

Table 7 Decision Matrix

Failure Modes	S	O	D	P
FM 1	7.0	7.4	4.2	3.4
FM 2	5.8	4.4	7.4	7.8
FM 3	8.2	1.8	1.4	3.8
FM 4	6.2	5.4	2.2	3.4
FM 5	7.8	5.8	4.6	3
FM 6	7.0	1.8	1.4	1.8
FM 7	6.2	6.6	2.2	1.8
FM 8	6.6	3.6	3.4	5.8
FM 9	6.2	1.6	7.8	2.6
FM 10	6.6	2.0	1.8	1.8

Then, the decision matrix has been normalized using the appropriate formula. In this beneficial criteria are Detection, Protection and non beneficial criteria are Severity, Occurrence. This normalized decision matrix is shown in Table 8.

Table 8 Normalized Decision Matrix

Failure Modes	S	O	D	P
FM 1	0.500	0.000	0.437	0.266
FM 2	1.000	0.517	0.937	1.000
FM 3	0.000	0.965	0.000	0.333
FM 4	0.833	0.345	0.125	0.266
FM 5	0.166	0.276	0.500	0.200
FM 6	0.500	0.965	0.000	0.000
FM 7	0.833	0.138	0.125	0.000
FM 8	0.666	0.655	0.312	0.666
FM 9	0.833	1.000	1.000	0.133
FM 10	0.666	0.931	0.062	0.000

From the normalized decision matrix, preference function has been calculated by using Vijay and Shankar model. Then the aggregated preference function was calculated by using weights for each risk factor. This calculation of aggregated preference function satisfies the limitation of not considering the relative importance between the risk factors. From the aggregated preference function leaving flow and entering flow values have been calculated. Table 9 shows the leaving and entering flow values.

Table 9 Leaving and Entering flow values

Failure Modes	Leaving Flow	Entering Flow
FM 1	0.0768	0.3149
FM 2	0.4235	0.0622
FM 3	0.1484	0.3758
FM 4	0.1770	0.1424
FM 5	0.0512	0.3920
FM 6	0.1709	0.1748
FM 7	0.1452	0.2202
FM 8	0.2234	0.1031
FM 9	0.3273	0.0405
FM 10	0.2011	0.1190

Net outranking flow values are calculated from the table values by using appropriate formula. Failure modes are prioritized based on the net outranking flow values. Table 10 shows the final ranking of failure modes based on their net outranking flow.

Table 10 Net Outranking Flow

Failure Modes	Net Outranking Flow	Rank
FM 1	-0.2381	9
FM 2	0.3613	1
FM 3	-0.2274	8
FM 4	0.0346	5
FM 5	-0.3408	10
FM 6	-0.0039	6
FM 7	-0.0750	7
FM 8	0.1203	3
FM 9	0.2868	2
FM 10	0.0821	4

E. Determination of RPN for Failure Mode

Risk Priority Number (RPN) for Failure Modes have been calculated from the same expert's feedback. Based on this RPN values only failure modes are prioritized in the Traditional FMEA method. Highest RPN value will be considered as higher priority and lower RPN value will be considered as lower priority. Calculated RPN values are given in the table 11.

Table 11 Calculation RPN for Failure Modes

Failure Modes	Risk Factors (or) Criteria			RPN
	S	O	D	
FM 1	7	7	5	245
FM 2	5	5	7	175
FM 3	7	2	1	14
FM 4	7	5	3	105
FM 5	9	5	7	315
FM 6	7	2	1	14
FM 7	5	7	3	105
FM 8	5	4	5	100
FM 9	7	2	7	98
FM 10	7	3	1	21

F. Comparison of PROMETHEE & RPN Results

Table 12 shows the results of both RPN and PROMETHEE method. In this FM 3, FM 6 gets same RPN value as 14 and also FM 4, FM 7 gets same RPN value as 105. Because of this same RPN value it is very difficult to prioritize the failure modes. Also this RPN value is very sensitive due to multiplication and the relative importance between the Risk Factors also not considered.

While comparing these RPN results with PROMETHEE results, there is no such difficulty in the prioritization. Also it considers the relative importance between the Risk Factors.

Table 12 Comparison of PROMETHEE & RPN

Failure Mode	PROMETHEE		RPN	
	Net Flow	Rank	RPN	Rank
FM 1	-0.2381	9	245	2
FM 2	0.3613	1	175	3
FM 3	-0.2274	8	14	
FM 4	0.0346	5	105	
FM 5	-0.3408	10	315	1
FM 6	-0.0039	6	14	
FM 7	-0.0750	7	105	
FM 8	0.1203	3	100	6
FM 9	0.2868	2	98	7
FM 10	0.0821	4	21	8

IV. CONCLUSION

This hybridization of AHP-PROMETHEE method will enhance the prioritization of failure modes in the Failure Mode Effect Analysis (FMEA). In this new FMEA with MCDM approach will eliminate the problems with Risk Priority Number and relative importance between the risk factors. So this novel approach will enhance the precision of FMEA results in the field of risk assessment. In future software can be developed for this FMEA-MCDM method in order to minimize the calculation procedure.

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