A New Approach for Prioritization of Failure Modes in Design FMEA using ANOVA

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Abstract**—**The traditional Failure Mode and Effects Analysis (FMEA) uses Risk Priority Number (RPN) to evaluate the risk level of a component or process. The RPN index is determined by calculating the product of severity, occurrence and detection indexes. The most critically debated disadvantage of this approach is that various sets of these three indexes may produce an identical value of RPN. This research paper seeks to address the drawbacks in traditional FMEA and to propose a new approach to overcome these shortcomings. The Risk Priority Code (RPC) is used to prioritize failure modes, when two or more failure modes have the same RPN. A new method is proposed to prioritize failure modes, when there is a disagreement in ranking scale for severity, occurrence and detection. An Analysis of Variance (ANOVA) is used to compare means of RPN values. SPSS (Statistical Package for the Social Sciences) statistical analysis package is used to analyze the data. The results presented are based on two case studies. It is found that the proposed new methodology/approach resolves the limitations of traditional FMEA approach.

Keywords**—**Failure mode and effects analysis, Risk priority code, Critical failure mode, Analysis of variance.

I. INTRODUCTION

FAILURE Mode and Effects Analysis (FMEA) is commonly defined as "a systematic process for identifying potential design and process failures before they occur, with the intent to eliminate them or minimize the risk associated with them". The FMEA technique was first reported in the 1920s but its use has only been significantly documented since the early 1960s. It was developed in the USA in the 1960s by National Aeronautics Space Agency (NASA) as a means of addressing a way to improve the reliability of military equipment. It has been used in the automotive industry since the early 1970s and its use has been accelerated in the 1990s to address the major quality and reliability challenges caused by the Far Eastern car manufacturers [1]. In addition, the recent changes in the law on corporate responsibility have led to companies reviewing their product design safety through the use of the FMEA methodology. In doing the analysis, the system behavior is evaluated for every potential failure mode of every system component. Where unacceptable failure effects occur, design changes are made to mitigate those effects. The criticality part of the analysis prioritizes the failures for corrective action based on the probability of the item's failure mode and the severity of its effects. It uses linguistic terms to rank the probability of the failure mode occurrence, the severity of its failure effect and the probability of the failure being detected on a numeric scale from 1 to 10. These rankings are then multiplied to give the Risk Priority Number. Failure modes having a high RPN are assumed to be more important and given a higher priority than those having a lower RPN [2].

II. RPN METHODOLOGY

In the RPN methodology the parameters used to determine the "criticality' of an item failure mode are, the severity of its failure effects, its frequency of occurrence, and the likelihood that subsequent testing of the design will detect that the potential failure mode actually occurs. Tables I, II and III show the qualitative scales commonly used for the severity, the occurrence and the detectability indexes [3].

Severity is ranked according to the seriousness of the failure mode effect on the next higher level assembly, the system or the user. Occurrence is ranked according to the failure probability, which represents the relative number of failures anticipated during the design life of the item. The effects of a failure mode are normally described by the effects on the user of the product or as they would be seen by the user. Detectability is an assessment of the ability of a proposed design verification program to identify a potential weakness before the part or assembly is released for production.

The RPN is a mathematical product of the severity, the occurrence and the detection. In equation form, RPN = S * O * D. The number is used to identify the most critical failure mode, leading to corrective action [4].

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TABLE I
SEVERITY GUIDELINES FOR DESIGN FMEA
(1-10 QUALITATIVE SCALE)

Effect	Rank	Criteria
No	1	No effect.
Very slight	2	Customer not annoyed.
Slight	3	Customer slightly annoyed.
Minor	4	Customer experiences minor nuisance.
Moderate	5	Customer experiences some dissatisfaction.
Significant	6	Customer experiences discomfort.
Major	7	Customer dissatisfied.
Extreme	8	Customer very dissatisfied.
Serious	9	Potential hazardous effect.
Hazardous	10	Hazardous effects.

TABLE II
OCCURRENCE GUIDELINES FOR DESIGN FMEA
(1-10 QUALITATIVE SCALE)

Effect	Rank	Criteria
Almost never	1	Failure unlikely. History shows no failure.
Remote	2	Rare number of failures likely.
Very slight	3	Very few failures likely.
Slight	4	Few failures likely.
Low	5	Occasional number of failures likely.
Medium	6	Medium number of failures likely.
Moderately high	7	Moderately high number of failures likely.
High	8	High number of failures likely.
Very high	9	Very high number of failures likely.
Almost certain	10	Failure almost certain.

TABLE III
DETECTABILITY GUIDELINES FOR DESIGN FMEA
(1-10 QUALITATIVE SCALE)

Effect	Rank	Criteria
Almost certain	1	Proven detection methods available in concept stage.
Very high	2	Proven computer analysis available in early design stage.
High	3	Simulation and/or modeling in early stage.
Moderately high	4	Tests on early prototype system elements.
Medium	5	Tests on preproduction system components.
Low	6	Tests on similar system components.
Slight	7	Tests on product with prototypes and system components installed.
Very slight	8	Proving durability tests on products with system components installed.
Remote	9	Only unproven or unreliable technique(s) available.
Almost impossible	10	No known techniques available.

III. DRAWBACKS OF TRADITIONAL FMEA APPROACH

The traditional FMEA has been a well-accepted safety analysis method; however, it suffers from several drawbacks. The first drawback is the method that the traditional FMEA employs to achieve a risk ranking. The purpose of ranking risk in order of importance is to assign the limited resources to the most critical risk items. Traditional FMEA approach uses a RPN to evaluate the risk level of a component or process. The RPN is obtained by finding the multiplication of three factors, which are the severity of the failure (S), the probability of occurrence (O) and the probability of detection (D).

The most critical disadvantage of the traditional FMEA is that various sets of S, O and D may produce an identical value of RPN; however, the risk implication may be totally different. For example, consider two different events having values of 2, 3, 2 and 4, 1, 3 for S, O and D respectively. Both these events will have a total RPN of 12 ($RPN_1 = 2x3x2 = 12$ and $RPN_2 = 4x1x3 = 12$), however, the risk implications of these two events may not necessarily be the same. This could entail a waste of resources and time or in some cases a high-risk event going unnoticed. The other prominent disadvantage of the traditional FMEA approach is taking average in ranking scale for the three failure indexes, when the team has a disagreement in ranking scale. For example, if one member says 2 and someone else says 6, the ranking in this case should be 4 (2 + 6 = 8, 8/2 = 4), however, this may produce an identical value of RPN.

These issues are stimulated the idea of developing an alternative method to the traditional one. At the end of discussion, an application example is presented to demonstrate the new approach.

IV. RESEARCH LITERATURE

A number of approaches have been suggested earlier to overcome some of the drawbacks mentioned above as seen in previous studies. Significant efforts for prioritization of failure modes for overcoming the short comings of the traditional RPN can also be seen in FMEA literature.

John B. Bowles and C Enrique Peláez (1995) presented a new technique based on fuzzy logic for prioritization of failures for corrective actions in a failure mode, effects and criticality analysis (FMECA). They have used fuzzy linguistic terms to describe O, S, D and the risks of failures. The relationships between the risks and O, S, D were characterized by fuzzy if-then rules extracted from expert knowledge and expertise. Crisp ratings for O, S, and D were then fuzzified to match the premise of each possible if-then rule. The fuzzy conclusion was finally defuzzified by the weighted mean of maximum method as the ranking value of risk priority.

Rudiger Wirth et al. (1996) analyzed the problem in a conventional way of carrying out a FMEA. The project WIFA (Knowledge-based FMEA) was presented to improve the current state of the art of FMEA by knowledge-based support of the user. It supported both process and design FMEAs. First, WIFA provided access to factual knowledge contained in existing FMEAs. Second, WIFA provided a semantic knowledge base containing typical recurring technical knowledge about types of systems, functions, failure modes, processes and actions.

Fiorenzo Franceschini and Maurizio Galetto (2001) introduced a new method to calculate the risk priority level for the failure mode in FMEA. It was able to deal with situations having different importance levels for the three failure mode component indexes (Occurrence, Severity and Detection).

Ravishankar and Prabhu (2001) presented a modified approach for prioritizing failures in a system FMEA to perform corrective actions, which used ranks 1 through 1000 called risk priority ranks (RPRs) to represent the increasing risk of the 1,000 possible severity-occurrence-detection combinations. These 1,000 possible combinations were tabulated by an expert in order of increasing risk and can be interpreted as 'if-then' rules. The failure having higher rank was given a higher priority.

Anand Pillay and Jin Wang (2003) proposed a new approach by using 'fuzzy rule base' and 'grey relation theory' to overcome some of the drawbacks of traditional FMEA approach. The first step of their approach was to set up the membership functions of the three risk factors O, S and D. Once these membership functions have been developed, FMEA was carried out in the traditional manner with the use of brainstorming techniques. Each failure mode was then assigned a linguistic term for each of the risk factors. The three linguistics terms were integrated using the fuzzy rule base generated to produce a linguistic term representing the priority for attention. This linguistic term represented the risk ranking of the failure mode. Once a ranking has been established, the process then followed the traditional method of determining the corrective actions and generating the FMEA report.

Seung J. Rhee and Kosuke Ishii (2003) addressed the shortcomings of traditional FMEA and introduced a new methodology called, Life Cost-Based FMEA, which measured failure/risk in terms of cost. A Monte Carlo simulation was applied to the Cost-Based FMEA to perform a sensitivity analysis on the variables associated to failure cost: occurrence, detection time, fixing time, and delay time.

Seyed-Hosseini et al. (2006) developed a method called Decision Making Trial and Evaluation Laboratory (DEMATEL) approach for reprioritization of failure modes in a system Failure Mode and Effects Analysis (FMEA) for actions, which prioritizes alternatives based on severity of effect or influence and direct and indirect relationships between them. Direct relations were a set of connections between alternatives with a set of connection weights representing severity of influence of one alternative on the other. An indirect relation was defined as a relation that could only move in an indirect path between two alternatives and meant that a failure mode could be the cause of other failure mode(s). Arunachalam and Jegadheesan (2006) proposed a modified FMEA with a reliability and cost-based approach to overcome the current drawbacks of the conventional FMEA.

Chensong Dong (2007) presented a cost effective failure mode and effects analysis tool to overcome the disadvantages of the traditional FMEA wherein the cost due to failure is not defined. It uses utility theory and fuzzy membership functions for the assessment of severity, occurrence and detection and to account relationship between the cost due to failure and the ordinal ranking. Jih Kuang Chen (2007) proposed an interpretive structural model (ISM) to evaluate the structure of hierarchy and interdependence of corrective action and the analytic network process (ANP) to calculate the weight of a corrective action and a utility priority number (UPN) to combine the utility of corrective actions and make a decision on improvement priority order of FMEA.

Ying-Ming Wang et al. (2008) introduced Fuzzy Risk Priority Numbers (FRPNs) for prioritization of failure modes. The FRPNs were defined as fuzzy weighted geometric means of the fuzzy ratings for occurrence (O), severity (S) and detection (D) and could be computed using alpha-level sets and linear programming models. For ranking purpose, the FRPNs are defuzzified using centroid defuzzification method, in which a new centroid defuzzification formula based on alpha-level sets was derived.

The new methods proposed for the prioritization of failures in the literature does not remove some of the drawbacks in the traditional FMEA approach as mentioned in the previous section. The main aim of this study is to introduce a new approach for prioritization of failures in design FMEA, when two or more failure modes have the same RPN value and if there is a disagreement in ranking value for failure mode indexes occurrence (O), severity (S) and detection (D). Finally, it verifies the feasibility and effectiveness of this method by applying it to a case study.

V. METHODOLOGY

This paper presents a new method to prioritize failure modes when two or more failure modes have the same RPN value and proposes a new approach when, the team has a disagreement in ranking value for the three failure indexes.

The proposed method is able to deal with the situation when;

- Two or more failure modes have the same RPN.
- The team has a disagreement in the ranking scale for severity, occurrence and detection.
- It is assumed that the three S, O, and D indexes are all equally important.

A general method with 'n' failure mode is discussed below with the same RPN.
Let 'L_{ij}' denote the ranks of 'S', 'O' and 'D' respectively corresponding to the failure mode 'a_i', where i = 1, 2, 3 … n and j = 1, 2, 3. Where, $1 \leq L_{ij} \leq 10$ for all i, j.

The L_{ij}'s precisely takes the ranks {1,2,3,4,5,6,7,8,9 and 10} in some order, where the ranks 1,2,3….10 are given by combing of Table I, Table II and Table III as follows:

TABLE IV
GENERAL FORM OF FAILURE MODE INDEXES AND RPN

Failure Mode	S	O	D	RPN
a_1	L_{11}	L_{12}	L_{13}	R_1
a_2	L_{21}	L_{22}	L_{23}	R_2
.	.	.	.	.
$\mathbf{a_i}$	$\mathbf{L_{i1}}$	$\mathbf{L_{i2}}$	$\mathbf{L_{i3}}$	$\mathbf{R_i}$
.	.	.	.	.
.	.	.	.	.
$\mathbf{a_k}$	$\mathbf{L_{k1}}$	$\mathbf{L_{k2}}$	$\mathbf{L_{k3}}$	$\mathbf{R_k}$
.	.	.	.	.
.	.	.	.	.
a_n	L_{n1}	L_{n2}	L_{n3}	R_n

The method suggests a three-step procedure;

(i) Critical Failure Mode (CFM) Index

$$\text{CFM index } I(a) = \min \{\max (L_{11}, L_{21} \ldots L_{n1}), \max (L_{12}, L_{22} \ldots L_{n2}), \max (L_{13}, L_{23} \ldots L_{n3})\} \quad (1)$$

(ii) Risk Priority Code (RPC)

$$\text{RPC } (a_i) = N (a_i) \quad (2)$$

Where, $N(a_i)$ be the number of places, in the row corresponding to 'a_i' for which $L_{ij} > I(a)$.

(iii) Critical Failure Mode (CFM)

$$\text{CFM } (a) = \text{failure mode corresponding to } \max \{N (a_i)\} \quad (3)$$

If there is a tie situation, consider the set of all a_i's for which $N (a_i)$ are equal, for such a_i's we define;

$$T (a_i) = \max \{ \left|L_{i1} - L_{k1}\right|, \left|L_{i2} - L_{k2}\right|, \left|L_{i3} - L_{k3}\right|\} \quad (4)$$

$$\text{CFM } (a) = \text{failure mode corresponding to } \max \{T (a_i)\} \quad (5)$$

VI. RESEARCH STUDY

Case Study 1

- Two or more failure modes have the same RPN.
- The assumption is that the three S, O, and D indexes are all equally important.

Let us consider an example of fan motor design and analyse four different failure modes with the same RPN 120 (see Table V).

TABLE V
APPLICATION OF DESIGN FMEA TO FAN MOTOR DESIGN

Part name	**Function**	**Failure mode**	**Effect of failure**	**Cause of failure**	**Current control**	**S**	**O**	**D**	**Risk Priority Number (RPN)**
Motor	Provide mechanical power to fan	Fan vibration from imbalance	Audible noise, vibration, increased motor wear	Fan center of gravity off axis of rotation	Design light weight fan	3	8	5	120 (4)
		Motor burn out, bearing and bush failure	Loss of cooling and A/C function	Overheating, lack of air circulation	Vent holes in motor case	4	6	5	120 (3)
		Misassemble to shroud, off-center or crooked	Loss of cooling function	Noise or motor burnout	Design for easy assembly	8	5	3	120 (2)
		Fan retainer compression too high	Lost cooling function	"e" clip too close to shaft and slot	Maintain dimensional capability within limits of tolerance	10	6	2	120 (1)

(a) All characteristic indexes have the same level of importance. Calling a_1, a_2, a_3 and a_4 the four failure modes;

a_1 = Fan vibration from imbalance

a_2 = Motor burnout, bearing and bush failure

a_3 = Misassemble to shroud, off-center or crooked

a_4 = Fan retainer compression too high

(i) Critical Failure Mode (CFM) Index by using (1),

$$I(a) = \min\{\max(3, 4, 8, 10), \max(8, 6, 5, 6), \max(5, 5, 3, 2)\}$$

$$= \min\{10, 8, 5\} = 5$$

(ii) Calculate RPC (a_i) from each failure mode by using (2),

$$N(a_1) = 1;\quad N(a_2) = 1;\quad N(a_3) = 1;\quad N(a_4) = 2$$

In this case, by using (3), the most Critical Failure Mode (CFM) is a_4.

Then, there is a tie between failure modes a_1, a_2 and a_3. Using (4), we can discriminate this tie situation.

(iii) Critical Failure Mode (CFM)

$$T(a_1) = \max\{\,|3-4|,\ |8-6|,\ |5-5|\,\}$$

$$= \max\{1, 2, 0\} = 2$$

$$T(a_2) = \max\{\,|4-8|,\ |6-5|,\ |5-3|\,\}$$

$$= \max\{4, 1, 2\} = 4$$

$$T(a_3) = \max\{\,|8-3|,\ |5-8|,\ |3-5|\,\}$$

$$= \max\{5, 3, 2\} = 5$$

Using (5), the next level failure modes are a_3, a_2 and a_1.

Table VI contains some more application examples, the critical failure modes are identified as explained above.

TABLE VI
WHEN TWO FAILURE MODES HAVE THE SAME RPN, THE SYMBOL (*) HIGHLIGHTS THE MOST CRITICAL FAILURE MODE

Potential Failure mode	S	O	D	RPN	I (a)	N (a_i)	CFM (a_i)
a_1	4	8	2	64^*	4	1	a_1
a_2	4	4	4	64		0	
a_3	8	3	2	48^*	2	2	a_3
a_4	6	4	2	48		2	
a_5	6	4	8	192^*	8	0	a_5
a_6	8	8	3	192		0	

Case Study 2

- The team disagreed on the ranking scale for severity, occurrence and detection.
- The assumption is that the three failure mode indexes are all equally important.

In some particular contexts, there may be disagreement in the ranking value. Table VII shows an example for evaluating RPN when there is disagreement in the ranking scale.

TABLE VII
NEW APPROACH FOR EVALUATION OF RPN

Failure Mode	S	O	D	RPNs	RPN Mean	RPN Range
1	5 6	2 3	7 6	70, 60 105, 90 84, 72 126, 108	89.375	66 (5)
2	8 7	6 5	5 4	240, 192 200, 160 210, 168 175, 140	185.625	100 (1)
3	4 5	7 8	4 7	112, 196 128, 224 140, 245 160, 280	185.625	168 (2)
4	3 4	8 7	5 4	120, 96 105, 84 160, 128 140, 112	118.125	76 (3)
5	6 9	3 6	4 3	72, 54 144, 108 108, 81 216, 162	118.125	162 (4)

The failure modes 2 and 3 have the same RPN 185.625 (mean) and failure modes 4 and 5 have the same RPN 118.125 (mean) with different ranking value for occurrence, severity and detection. For determining the most significant failure mode with different ranking scale, calculate RPN mean and range as shown in Table VII. According to RPN mean failure modes 2 and 3 have the highest value and failure modes 4 and 5 have the next highest value. According to RPN range, the critical failure mode is 2 then the next level failure modes are 3, 4, 5 and 1.

The general rule for the above case is stated as follows; "The higher the RPN mean is more severe. When the RPN means are same, the smaller the RPN range is more severe".

VII. ANALYSIS OF VARIANCE (ANOVA)

Analysis of variance (ANOVA) is a statistical technique used to compare the means of two or more samples. The different types of ANOVA reflect the different experimental designs and situations for which they have been developed.

In this study, we used SPSS statistical analysis software to compare the mean RPNs associated with five failure modes.

TABLE VIII
RPNS FOR FAILURE MODES

Count	FM1	FM2	FM3	FM4	FM5
1	70	240	112	120	72
2	60	192	196	96	54
3	105	200	128	105	144
4	90	160	224	84	108
5	84	210	140	160	108
6	72	168	245	128	81
7	126	175	160	140	216
8	108	140	280	112	162

a) We want to test whether the data in Table VIII provide sufficient evidence to conclude that the failure modes RPN mean differ. Thus, we want to test the null hypothesis:

H0: $\mu_{fm1} = \mu_{fm2} = \mu_{fm3} = \mu_{fm4} = \mu_{fm5}$

Ha: The mean RPN differ for at least two of the failure modes

The test statistic compares the variation among the five failure modes RPN means to the sampling variability within each of the failure modes.

Test statistic: F = MST/MSE

Rejection region: $F > F\alpha = F.05$, with $v1 = (k - 1) = 4$ numerator degrees of freedom and $v2 = (n - k - b + 1) = 28$ denominator degrees of freedom. From the percentage points of the F-distribution ($\alpha = .05$), we find F.05 = 2.71. Thus, we reject H0 if F > 2.71. The assumptions necessary to ensure the validity of the test are as follows: (1) the probability distributions of the RPN for each failure mode are normal, (2) the variances of the RPN for each failure mode are normal.

The results of an analysis of variance (ANOVA) can be summarized in a simple tabular format. The general form of the table is shown in Table IX, where symbols df, SS and MS stand for degrees of freedom, Sum of Squares and Mean Square respectively.

TABLE IX
GENERAL ANOVA SUMMARY TABLE

Source	df	SS	MS	F
Treament	k-1	SST	MST	MST/MSE
Block	b-1	SSB	MSB	
Error	n-k-b+1	SSE	MSE	
Total	n-1	SS (Total)		

b) SPSS is used to analyze the data in Table VIII, and the result is shown in Table X. The F-ratio for failure modes (highlighted in the Table X) is F = 8.356, which exceeds the tabulated value 2.71. We therefore reject the null hypothesis at $\alpha = .05$ level of significance, concluding that at least two of the brands differ with respect to mean RPN for failure modes.

TABLE X
SPSS PRINTOUT FOR ANOVA OF DATA IN TABLE VIII

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	70116.975[a]	11	6374.270	3.219	.000
Intercept	777015.625	1	777015.625	392.429	.000
FAILURE MODES	61450.000	4	15362.500	8.356	.000
RPN	8666.975	7	1238.139		
Error	51480.400	28	1980.015		
Total	898613.000	40			
Corrected Total	121597.375	39			

Tests of Between-Subjects Effects
Dependent Variable: RPN
[a] R Squared = .505 (Adjusted R Squared = .449)

The results of ANOVA are summarized in Table XI. The randomized block design is characterized by three sources of variance – Treatments, Blocks and Error, which sum to the Total Sum of Squares.

TABLE XI
ANOVA RESULTS FOR DATA IN TABLE VIII

Source	df	SS	MS	F	P
Treament	4	61,450.0	15,362.5	8.356	0.000
Block	7	8,666.9	1,238.1		
Error	28	51,480.4	1,980.0		
Total	39	1,21,597.3			

A graph of the relationship between RPN count and RPN value for the five failure modes (data in Table VIII) considered in this study are displayed in the following figures.

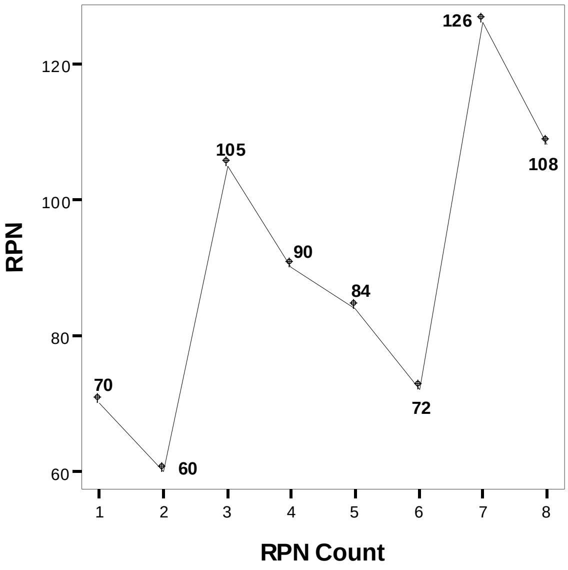

Fig. 1 SPSS printout for failure mode 1

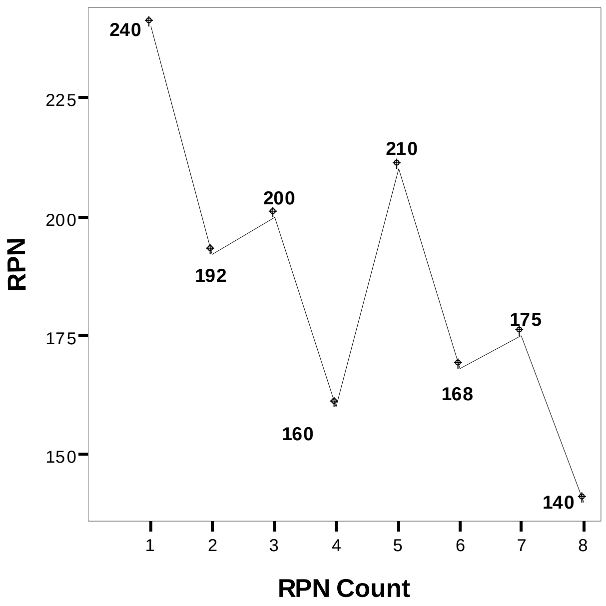

Fig. 2 SPSS printout for failure mode 2

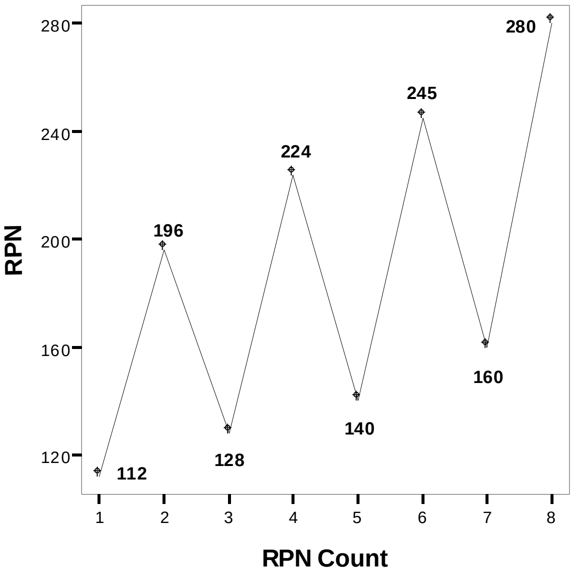

Fig. 3 SPSS printout for failure mode 3

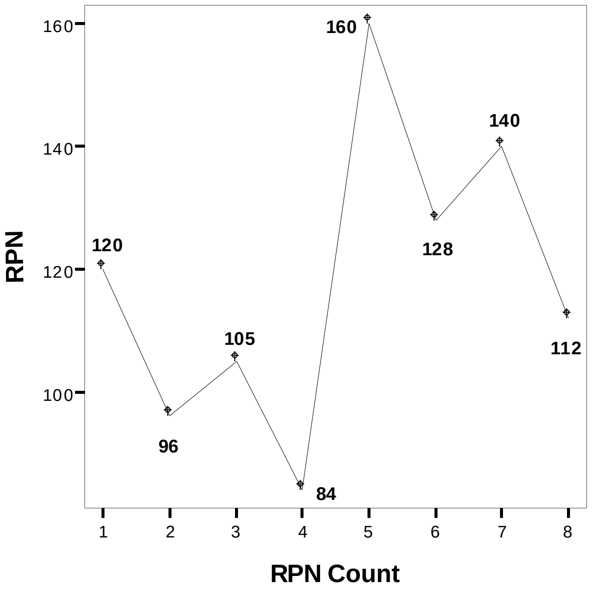

Fig. 4 SPSS printout for failure mode 4

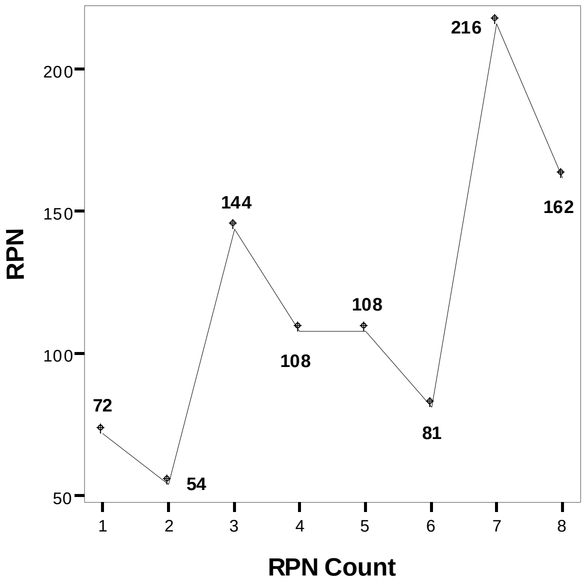

Fig. 5 SPSS printout for failure mode 5

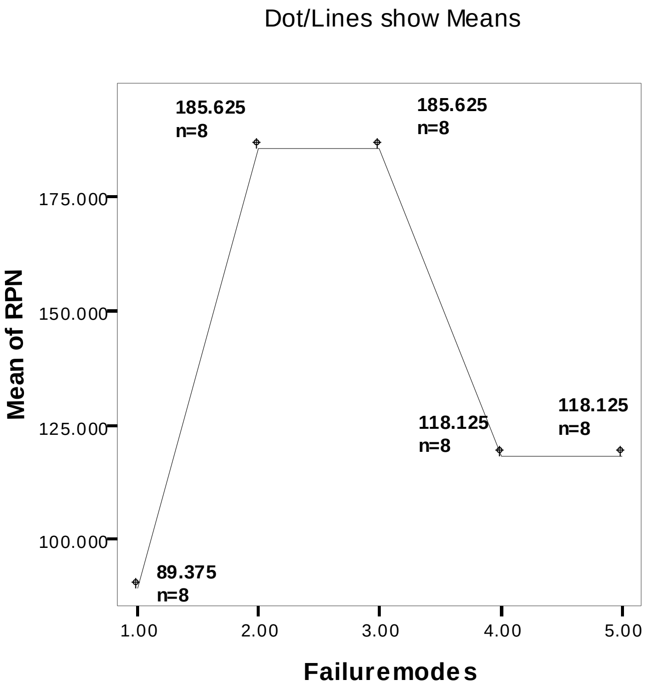

Fig. 6 SPSS printout for means plot of data in Table VIII

A graph showing the mean RPN values for the five failure modes are displayed in Fig. 6.

VIII. CONCLUSION

This paper demonstrates the new approach to prioritize failure modes and how it can improve the evaluation of risk priority number. The case study presented in this paper resolves the limitations of traditional FMEA technique. If two or more failure modes have the same RPN, it is possible to prioritize the failure modes with the help of Risk Priority Code (RPC). If there is a tie situation in RPC, a more detailed selection can be done with the T(a_i) index. When the team has a disagreement in the ranking value, RPN range helps to prioritize the failure modes. Thus, the proposed method of evaluation of RPN in design FMEA has benefits when;

- Two or more failure modes have the same RPN.
- The team has a disagreement in the ranking scale for severity, occurrence and detection.

In our study, one way ANOVA is used to compare the mean RPN values of failure modes. The statistical analysis supports our proposed methodology and approach, which could be implemented in the real time problem to overcome the shortcomings of traditional FMEA approach.

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