

Modified Prioritization Methodology for Risk Priority Number in Failure Mode and Effects Analysis

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Abstract

Failure Mode and Effects Analysis (FMEA) is a proactive process aimed to evaluate a system, design, process and service for possible ways in which failures can occur. The FMEA procedure assigns a numerical value to each risk associated with causing a failure using severity, occurrence and detection indexes and Risk Priority Number (RPN) is obtained by multiplying these numerical values. The traditional FMEA prioritization method has two main deficiencies as: various sets of severity, occurrence and detection indexes may produce an identical value of RPN and taking average or higher numerical value, when the team has a disagreement in the ranking index. In this paper an attempt is made to develop a new RPN prioritization method to address these two deficiencies. The proposed method has been evaluated by case studies and statistical analysis techniques.

Keywords: FMEA, RPN, Failure Mode, Prioritization, Statistical Analysis.

1. Introduction

FMEA is a reliability tool, which requires identifying failure modes of a specific product or system, their frequency and potential causes. According to Fiorenzo Franceschini and Maurizio Galetto (2001), the life cycle of a product is analyzed by an inter-functional work team [1]. Daimler Chrysler, Ford and General Motors are jointly developed an international standard named SAE J1739-2006 documentation for FMEA. This document provides general guidance in the application of different types of FMEA [2]. First, the potential failure modes and potential causes are identified along with its effects and then the current controls are determined [3]. FMEA method is used to calculate RPN for each failure mode and then proposed recommended actions to reduce the RPN [4]. The basic steps are to identify the root causes and potential problems that could occur, and then derive RPN which can direct improvement effort to the areas of greatest concern. Actions are then undertaken to reduce the risk presented by the failure mode [5]. FMEA was developed at Grumman Aircraft Corporation in the 1950 and 1960s and it was first applied to the naval aircraft flight control systems at Grumman. Since, then, it has been extensively used as a powerful technique for system safety and reliability analysis of products and processes in wide range of industries [6]. Xiuxu Zhao presented a new approach for enterprises which combined Statistical Process Control (SPC) with FMEA knowledge library [7].

2. Traditional FMEA Approach

FMEA is carried out by a cross-functional team of experts from various departments. Normally, a team is formed at the planning stage of a new product based on a concurrent engineering approach. The team analyzes each component and subsystem of the product for the failure modes. Then, the potential causes and effects are determined.

The risk of each failure is prioritized based on the risk priority number (RPN). RPN is a decision factor based on three ratings: Severity (S), Occurrence (O) and Detection (D). These ratings are scaled with numbers between 1 and 10 [8]. The analysis starts from the basic structure of the system and particularly from those system elements for which accurate information about failure mode and its causes are available. By analyzing the functional relationships among these elements, it is possible to identify the possibility of propagation of each type of failure to predict its effects on the production performance of the entire system. This is an inductive method to analyze failure modes using down-top methodology [9]. The FMEA is a formalized but subjective analysis for the systematic identification of possible root causes and failure modes and the estimation of their relative risks. The main goal is to identify and then limit or avoid risk within a design. Hence, the FMEA drives towards higher reliability, higher quality and enhance safety [10]. FMEA concentrates in identifying the severity and criticality of failures. FMEA is a fully bottom-up approach [11]. Risk Priority Number, which is the product of the severity, occurrence and detection ratings is calculated as $RPN = S \times O \times D$. The RPN must be calculated for each cause of failure. RPN shows the relative likelihood of a failure mode, in that the higher number, the higher the failure mode. From RPN, a critical summary can be drawn up to highlight the areas where action is mostly needed [12]. The RPN is re-calculated after the failure has been addressed. The revised RPN confirms the effectiveness of the corrective active undertaken [13].

Table 1. Qualitative Scale for Severity, Occurrence and Detection (Stamatis, 2003)

| Rank | Severity | Occurrence | Detection | Resolution |
|------|------------|-----------------|-------------------|--|
| 1 | None | Almost Never | Almost Certain | If the numerical value falls between two numbers always select the higher number. If the team has a disagreement in the ranking value the following may help. 1. If the disagreement is an adjacent category, average out the difference. For example, if one member says 5 and someone else says 6, the ranking in this case should be 6 (5 and 6 are adjacent categories. Therefore $5 + 6 = 11$, $11/2 = 5.5$) 2. If the disagreement jumps one category, then consensus must be reached. Even with one person holding out, total consensus must be reached. No average, no majority. Everyone in that team must have ownership of the ranking. They may not agree 100 percent, but they can live with it. |
| 2 | Very Minor | Remote | Very High | |
| 3 | Minor | Very Slight | High | |
| 4 | Very Low | Slight | Moderately High | |
| 5 | Low | Low | Moderate | |
| 6 | Moderate | Medium | Low | |
| 7 | High | Moderately High | Very Low | |
| 8 | Very High | High | Remote | |
| 9 | Serious | Very High | Very Remote | |
| 10 | Hazardous | Almost Certain | Almost Impossible | |

3. Problem Statement

The most critical disadvantages of the traditional FMEA are;

- The various sets of S, O and D may produce an identical value of RPN. For example consider the failure modes 1 and 2 in Table 3 having values of 6, 7, 3 and 9, 2, 7 for S, O and D respectively. Both these failure modes have a RPN value of 126. However, the risk implication may be totally different.
- Taking average and higher numerical value for the three failure indexes, when the team has a disagreement in ranking scale.

For example, if one member says 3 and someone else says 4, the ranking in this case should be 4 ($3 + 4 = 7$, $7/2 = 3.5$), however, this may produce an identical value of RPN. Consider the failure modes 3, 4 and 5 in Table 3.

A lot of research has been carried out to enhance the performance of FMEA in the past decade. Significant efforts have been made in FMEA for overcoming the shortcomings of RPN and it does not remove drawback of prioritization of RPN in the traditional FMEA approach as mentioned above. There is a clear need to develop a new methodology for prioritization of RPN in FMEA. This is main motivation of this paper.

This paper is organized as follows: The proposed modified risk prioritization methodology presented in section 4 with an application example of Design FMEA. Then, section 5 will provide statistical evidence for the usefulness of the proposed method. Finally, a conclusion is drawn in section 6.

4. An Application Example

Let us consider the example of a motor design (see Table 3). Let us analyze the RPNs for the following situations;

- Two or more failure modes have the same RPN.
- The team disagreed on the ranking scale for severity, occurrence and detection indexes.
- The assumption is that the three failure mode indexes are all equally important.

4.1. Methodology

The proposed failure mode prioritization method provides possibility of considering different failure modes with identical value of RPN, so avoiding a further work burden for designers. The assumption is that the three failure mode 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. 1 ≤ L_{ij} ≤ 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 from Tables 1. The general form of failure mode indexes and its corresponding RPN are presented in Table 2.

Table 2. 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 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| a _i | L _{i1} | L _{i2} | L _{i3} | R _i |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| a _k | L _{k1} | L _{k2} | L _{k3} | R _k |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| a _n | L _{n1} | L _{n2} | L _{n3} | R _n |

The prioritization method suggests a three-step procedure;

(i) Critical Failure Mode (CFM) Index

$$I(a) = \min \{ \max (S_{11}, S_{21} \dots S_{n1}), \max (O_{12}, O_{22} \dots O_{n2}), \max (D_{13}, D_{23} \dots D_{n3}) \} \tag{1}$$

(ii) Risk Priority Code (RPC) RPC (a_i) = N (a_i) (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)

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

All the possible functional failures in a motor design are listed in the design FMEA Table 3 as the potential failure modes. The ranking of the occurrence, the severity and the detection method are based on a 1 to 10 scale. The RPN number for each failure mode is computed by multiplying the ranking scale of severity, occurrence and detection indexes.

The failure mode with the highest RPN will be evaluated first to establish the control plan to eliminate or reduce the effect of this failure mode. The main aim of defining failure mode priorities is to draw the designer’s attention towards the most dangerous failure mode for the product.

Table 3. Potential Failure Modes of a Motor – Design FMEA

| Part Name | Failure Mode | Potential Effect of Failure | Potential Cause of Failure | Severity (S) | Occurrence (O) | Detection (D) | RPNs | RPN | |
|-----------|------------------------------------|-----------------------------|----------------------------|--------------|----------------|---------------|--|---------------|----------------|
| | | | | | | | | Mean | Range |
| Motor | (1) Stator insulation failure | Motor will not run | Insulation contaminate | 6 | 7 | 3 | 126 (2) | -- | -- |
| | (2) Rotor excessive vibration | Motor turns at wrong speed | Mechanical imbalance | 9 | 2 | 7 | 126 (1) | -- | -- |
| | (3) Bearing seized | Motor will not run | Improper lubrication | 2 3 | 7 6 | 4 3 | 56, 42 48, 36 72, 54 84, 63 | 56.875 | 48 (3) |
| | (4) Controller contactor failed | Motor will not run | Control circuit failure | 1 6 | 3 2 | 6 7 | 18, 21 12, 14 108, 126 72, 84 | 56.875 | 114 (5) |
| | (5) Loss of power supply | Motor will not run | Poor connection | 5 8 | 2 5 | 3 2 | 30, 20 75, 50 48, 32 120, 80 | 56.875 | 100 (4) |

From the Table 3, it is observed that the failure modes 1 and 2 produce same RPN value with different ranking scale for S, O and D indexes. There is a disagreement in ranking scale for the failure modes 3, 4 and 5.

Case I: Failure modes 1 and 2 in Table 3 show an identical RPN value of 126.

Assume that all three characteristic indexes have the same level of importance. Calling a_1 and a_2 are the two failure modes;

a_1 = Stator insulation failure

a_2 = Rotor excessive vibration

The aggregated CFM index calculation is performed as indicated by equation (1).

According to equation (1);

Critical Failure Mode (CFM) Index $I(a) = \min \{ \max (6, 9), \max (7, 2), \max (3, 7) \} = \min \{ 9, 7, 7 \} = 7$

Calculate RPC (a_i) from each failure mode.

According to equation (2); $N(a_1) = 0$; $N(a_2) = 1$

In this case, according to equation (3); the most Critical Failure Mode (CFM) is a_2 and next level failure mode is a_1 .

Case 2: The team disagreed on the ranking scale for severity, occurrence and detection indexes.

For the failure modes 3, 4 and 5 in Table 3, the team disagreed on the ranking scale for severity, occurrence and detection. According to RPN mean, the failure modes 3, 4 and 5 have the same mean RPN value 56.875 with different ranking value for occurrence, severity and detection. According to RPN range, the most critical failure mode is 3 then the next level failure modes are 5 and 4 respectively.

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”.

5. Statistical Analysis

The use of statistical methods in manufacturing, development of food products, computer software, pharmaceutical and many other areas involves the gathering of information or scientific data. Statistical methods help us to analyze the data and to make decisions. Furthermore, it is used to determine whether the conclusions drawn from a study are to be trusted and to provide evidence that the model is statistically useful for the purpose [14]. In order to analyze the data, we used MINITAB software package.

5.1. Multiple Regression Analysis

This application involves an investigation of the factors that affect the RPN. This study introduces a multiple regression model as a means of relating a dependent variable RPN to three independent variables S, O and D. Most practical applications of regression analysis utilize straight-line model. The dependent variable y is now written as a function of three independent variables x_1 , x_2 and x_3 . The random error term is added to make the model probabilistic rather than deterministic.

The form of multiple regression models is as shown in equation (4).

$$y = \beta_0 + \beta_1x_1 + \beta_2x_2 + \beta_3x_3 + \varepsilon \quad (4)$$

Where;

y is the dependent variable RPN.

x_1 , x_2 and x_3 are the three independent variables S, O and D.

β_0 , β_1 , β_2 , and β_3 are unknown model parameters.

ε is the random error.

To fit the model, we have selected a sample of $n = 24$ RPN values from three failure modes 3, 4 and 5. The data are given in Table 4.

Table 4. RPN Values for Three Failure Modes

| FAILURE MODES | S | O | D | RPN |
|---------------------------------|---|---|---|-----|
| (3) Bearing seized | 2 | 7 | 4 | 56 |
| | 2 | 7 | 3 | 42 |
| | 2 | 6 | 4 | 48 |
| | 2 | 6 | 3 | 36 |
| | 3 | 6 | 4 | 72 |
| | 3 | 6 | 3 | 54 |
| | 3 | 7 | 4 | 84 |
| | 3 | 7 | 3 | 63 |
| (4) Controller contactor failed | 1 | 3 | 6 | 18 |
| | 1 | 3 | 7 | 21 |
| | 1 | 2 | 6 | 12 |
| | 1 | 2 | 7 | 14 |
| | 6 | 3 | 6 | 108 |
| | 6 | 3 | 7 | 126 |
| | 6 | 2 | 6 | 72 |
| | 6 | 2 | 7 | 84 |
| (5) Loss of power supply | 5 | 2 | 3 | 30 |
| | 5 | 2 | 2 | 20 |
| | 5 | 5 | 3 | 75 |
| | 5 | 5 | 2 | 50 |
| | 8 | 2 | 3 | 48 |
| | 8 | 2 | 2 | 32 |
| | 8 | 5 | 3 | 120 |
| | 8 | 5 | 2 | 80 |

Table 5. Multiple Regression Analysis

| | | | | | |
|--|----------------|---------------------|--------------|--------------------------|--------------|
| Regression Analysis: RPN versus S, O, D | | | | | |
| The regression equation is | | | | | |
| RPN = - 132 + 14.9 S + 15.3 O + 15.1 D | | | | | |
| Predictor | Coef | SE Coef | T | P | |
| Constant | -131.70 | 15.40 | -8.55 | 0.000 | |
| S | 14.853 | 1.176 | 12.63 | 0.000 | |
| O | 15.273 | 1.504 | 10.15 | 0.000 | |
| D | 15.131 | 1.675 | 9.03 | 0.000 | |
| S = 11.1150 | | R-Sq = 89.9% | | R-Sq(adj) = 88.4% | |
| Analysis of Variance | | | | | |
| Source | DF | SS | MS | F | P |
| Regression | 3 | 21957.8 | 7319.3 | 59.24 | 0.000 |
| Residual Error | 20 | 2470.9 | 123.5 | | |
| Total | 23 | 24428.6 | | | |

Multiple regression analysis was carried out using MINTAB software package. A portion of the print out is reproduced in Table 5. The least square estimates of the parameters (highlighted) are $\beta_0 = -132$, $\beta_1 = 14.9$, $\beta_2 = 15.3$, and $\beta_3 = 15.1$. Therefore, the equation that minimizes SSE for this data set (i.e., the least square prediction equation) is;

$$y = -132 + 14.9x_1 + 15.3x_2 + 15.1x_3 \tag{5}$$

The minimum value of the sum of squared errors, highlighted in Table 5 is $SSE = 2470.9$

The estimator of σ^2 for the straight-line model is $S^2 = SSE / (n-2)$ and $n =$ number of estimated β parameters in the straight-line model. Since, we must estimate four parameters β_0 , β_1 , β_2 , and β_3 for the first-order model, the estimator of σ^2 is;

$$S^2 = SSE / (n-4) = SSE / (24-4) = 2470.9 / 20 = 123.545$$

This value often called the mean square for error (MSE) is also highlighted at the bottom of the MINITAB printout in Table 5.

The estimate of σ is, $S = \sqrt{123.545} = 11.1150$

This is highlighted in the middle of the print out in Table 5. One useful interpretation of the estimated standard deviation S is that the interval $\pm 2S$ will provide a rough approximation to the accuracy with which the model will predict future values of y for given values of x .

5.2. Assessing the Overall Adequacy of the Model

We want to test whether the data in Table 4 provides sufficient evidence to conclude that the model is statistically useful for prioritizing RPN values.

$H_0: \beta_0 = \beta_1 = \beta_2 = \beta_3 = 0$ [Note: $k = 3$]

H_a : At least one of the three model coefficients is non-zero.

$$\begin{aligned} \text{Test Statistic: } F &= \frac{(SS_{yy} - SSE) / k}{SSE / [n - (k + 1)]} = \frac{(R^2) / k}{(1 - R^2) / [n - (k + 1)]} & (6) \\ &= \text{Mean square (Model) / Mean square (Error)} = 7319.3 / 123.5 = 59.2655 \end{aligned}$$

Rejection region: $F > F_{\alpha}$ with k numerator degrees of freedom and $[n - (k + 1)]$ denominator degrees of freedom.

P-value: less than .0001

The test is to compare this computed value of F with the tabulated value based on $k = 3$ and $n = 24$. If we choose $\alpha = .05$, then $F_{.05} = 3.01$ and the rejection region is $F > 3.01$

In a multiple regression analysis, use the value of R^2 as a measure of how useful a linear model will be for prioritizing RPN.

The multiple coefficient of determination R^2 , is defined as;

$$\begin{aligned} R^2 &= 1 - \frac{SSE}{SS_{YY}} = \frac{SS_{YY} - SSE}{SS_{YY}} & (7) \\ &= \frac{24428.6 - 2470.9}{24428.6} \\ &= \text{Explained variability / Total variability} = 0.8988 \end{aligned}$$

According to equation (7); $R^2 = 89.9 \%$

As an alternative to using R^2 as a measure of adequacy, the adjusted multiple coefficient of determination, denoted, is often reported.

The adjusted coefficient of determination is given by;

$$R_a^2 = 1 - \left[\frac{(n-1)}{n-(k+1)} \right] \left(\frac{SSE}{SS_{yy}} \right) = 1 - \left[\frac{(n-1)}{n-(k+1)} \right] (1 - R^2) \tag{8}$$

According to equation (8);

$$R_a^2 = 1 - \left[\frac{(24-1)}{24-(3+1)} \right] (1 - 0.899) = 0.88385 = 88.4 \%$$

The R_a^2 value (highlighted in Table 5) is 88.4 % which is smaller than R^2 value. This implies that the least squares model has explained about 88.4 % of the total sample variation in y values (RPN) after adjusting for sample size and number of independent variables in the model.

Since, $\alpha = .05$ exceeds the observed significance level, $p < .0001$, the data provide strong evidence that at least one of the model coefficients is non-zero. The overall model appears to be statistically useful for prioritizing RPN values.

5.3. Analyzing Residuals

Residual analyses are useful for detecting one or more observations that deviate significantly from the regression model. We expect approximately 95% of the residuals to fall within 2 standard deviations of the 0 line and all or all most all of them to lie within 3 standard deviations of their mean of 0. Residuals that are extremely far from the 0 line are disconnected from the bulk of the other residuals.

The residual for straight-line model for the data is shown in Table 6. The residuals are highlighted in the MINITAB printout.

Table 6. Residual for Straight-Line Model

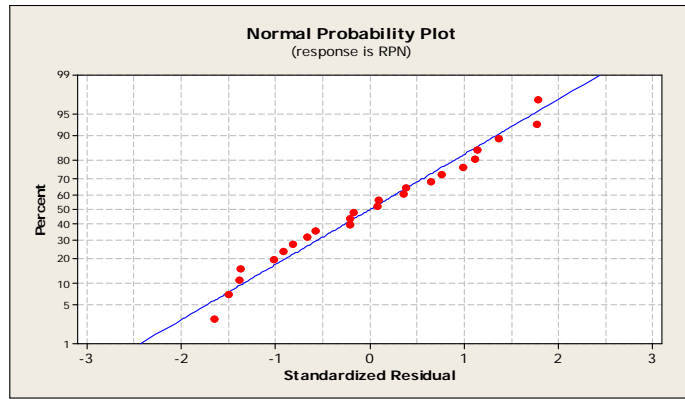
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The regression equation is
RPN = - 132 + 14.9 S + 15.3 O + 15.1 D
Predictor      Coef  SE Coef  T      P
Constant      -131.70  15.40   -8.55  0.000
S              14.853  1.176   12.63  0.000
O              15.273  1.504   10.15  0.000
D              15.131  1.675    9.03  0.000
S = 11.1150    R-Sq = 89.9%    R-Sq(adj) = 88.4%
Analysis of Variance

Source      DF      SS      MS      F      P
Regression  3      21957.8  7319.3  59.24  0.000
Residual Error  20    2470.9  123.5
Total      23    24428.6

Obs   S      RPN      Fit  SE Fit  Residual  St Resid
1    2.00  56.00  65.45  4.23    -9.45    -0.92
2    2.00  42.00  50.31  4.23    -8.31    -0.81
3    2.00  48.00  50.17  3.44    -2.17    -0.21
4    2.00  36.00  35.04  3.84     0.96     0.09
5    3.00  84.00  80.30  4.26     3.70     0.36
6    3.00  63.00  65.17  4.01    -2.17    -0.21
7    3.00  72.00  65.03  3.20     6.97     0.66
8    3.00  54.00  49.89  3.33     4.11     0.39
9    1.00  18.00  19.76  4.44    -1.76    -0.17
10   1.00  21.00  34.89  4.76   -13.89    -1.38
11   1.00  12.00   4.49  5.27     7.51     0.77
12   1.00  14.00  19.62  5.27    -5.62    -0.57
13   6.00 108.00  94.03  4.38    13.97     1.37
14   6.00 126.00 109.16  5.72    16.84     1.77
15   6.00  72.00  78.75  4.24    -6.75    -0.66
16   6.00  84.00  93.88  5.35    -9.88    -1.01
17   5.00  30.00  18.51  4.75    11.49     1.14
18   5.00  20.00   3.38  6.04    16.62     1.78
19   5.00  75.00  64.33  2.80    10.67     0.99
20   5.00  50.00  49.20  3.60     0.80     0.08
21   8.00  48.00  63.07  4.73   -15.07    -1.50
22   8.00  32.00  47.94  5.47   -15.94    -1.65
23   8.00 120.00 108.89  4.94    11.11     1.12
24   8.00  80.00  93.75  4.81   -13.75    -1.37
    
```


Fig. 1. Normal Probability Plot



A normal probability and residual plot for the residuals are shown in Figure 1 and 2.

Fig. 2. Residual Plots for RPN

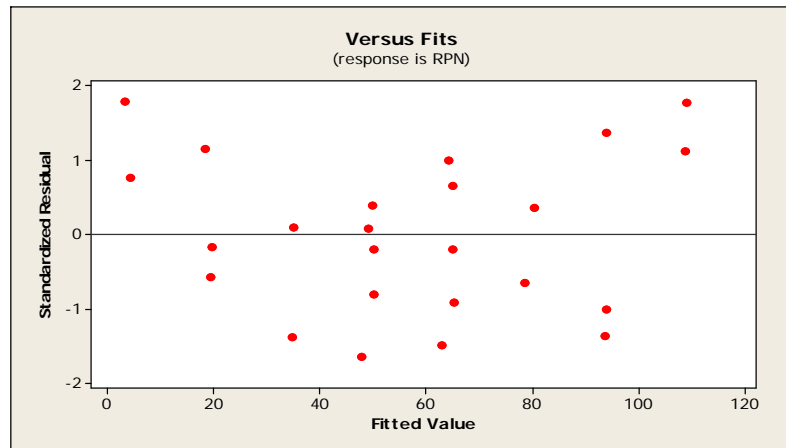


Figure 1 shows, how well the residuals match a normal distribution. The residuals fall in a straight line, that means the normality condition is met. Figure 2 shows, all (100 percent) of the standard residuals fall within two standard deviations of the mean, which is -2 to +2 and none of them lies beyond 3 standard deviations. More residuals hovering around zero and fewer of the residuals go away from zero. The implication is that the proposed model is more reliable and useful for prioritization of RPN in Design FMEA.

Conclusion

The aim of this paper is to develop an effective risk prioritization method to improve the traditional FMEA process. This paper has focused on the design FMEA to improve current design process and to ensure high quality and reliability of the products. Based on the data presented, two failure modes were found to give identical RPN values and there was a disagreement in ranking scale for three failure modes. The data were analyzed and proposed a modified risk prioritization methodology to deal with subjective and qualitative nature of information in design FMEA. The result obtained demonstrates the inherent potential of the modified prioritization of failure modes, when the team has a disagreement in the ranking scale. The statistical analysis package like MINITAB program was used for the data analysis and validation. The case studies presented in this paper resolves the following limitations of traditional FMEA technique;

- If two or more failure modes have the same RPN value, it is possible to prioritize the failure modes with the help of Risk Priority Code (RPC).
- RPN range helps to prioritize the failure modes, when the team has a disagreement in the ranking value for severity, occurrence and detection indexes.

The statistical analysis provides strong evidence that the proposed methodology is statistically useful for prioritizing RPN values and failure modes.

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