Development of Modified Evaluation and Prioritization of Risk Priority Number in FMEA

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Abstract

Failure Mode and Effects Analysis (FMEA) is a tool used for identifying, analyzing and prioritizing failure modes of a product and process. The traditional FMEA determines the risk priority of each failure mode using the risk priority number (RPN) by multiplying the ranks of the three risk factors namely the Severity (S), Occurrence (O) and Detection (D). FMEA is carried out by a team of members and the critical problem is that the team often demonstrates different opinions from one member to another. Then, there is a disagreement in ranking value for the three risk factors. In case average out of difference is considered, the different combination of three risk factors may produce an identical RPN value for different failure modes. In the present work, the modified RPN prioritization method is introduced into traditional FMEA to solve the above issue and this method is applied in the risk evaluation of water leakage in the building. Finally, the proposed method has been evaluated using statistical analysis techniques. The result indicates that the proposed method is useful for RPN evaluation and prioritization of failure modes.

Keywords: Failure Modes, Risk Factors, Risk Priority Number, Risk Prioritization, Statistical Analysis.

1. INTRODUCTION

Failure Mode and Effects Analysis (FMEA) is a method used for evaluating a product or a process for possible failures. It is used to quantify and record the risk level associated with each potential failure mode for the prioritization and review process. In 1963, FMEA was first used by NASA in the product design phase [1]. FMEA is carried out for each element of a system and sub-system. It determines the effect of failure mode on the system performance. Design and process FMEA were introduced in early period then variants of its kind like system, service, software and maintenance. FMEAs were developed for different applications [2]. FMEA is a popular tool that allows us to prevent a product or a process failure before they occur. It is used to reduce failure cost by identifying early in the product development cycle [3]. FMEA is a proactive tool which is commonly used in Engineering and Medical field. It is widely used in new product design, process and service to identify potential failure modes and determine its effect before they occur [4]. Design FMEA is applied in the design process to avoid design complications and in turn to reduce failure cost. It is further extended to manufacturing phase to improve product quality and reliability [5]. FMEA is a systematic approach to evaluate a product, process and service for improvement. It identifies possible potential failure modes and estimates its severity, occurrence and detection [6].

Sankar and Prabhu introduce a new technique for prioritization of risk using risk priority ranks (RPRs) in a system failure mode and effects analysis. The conventional RPN technique uses a numeric scale from 1 to 10. It attempts to quantify risk without adequately quantifying the factors that contribute to risk and in some cases the RPN can be misleading the prioritization of risk. It is eliminated by the RPR, the risk is represented using the integers 1 through 1, 000 [7]. Jafari et al. first used the Machinery Failure Mode and Effects Analysis (MFMEA) with risk matrix for the study on reliability of a tunnel boring machine in tunneling [8]. The traditional FMEA process is carried out by the cross functional team, generally the FMEA team has different opinions from one member to another. It is difficult to incorporate the different assessment information in the FMEA process by the RPN model. Piltan et al. present Multi Input Single Output (MISO) fuzzy expert system in the calculation of RPN [9]. Chang et al. present the linguistic ordered weighted geometric averaging (LOWGA) operator in process FMEA [10]. Joo et al. analyze wrinkling and bursting defects of a hydroformed automotive part during flange hydroforming process. In order to increase the reliability of the part, the FMEA approach was used to study the relationship between process parameters and defects [11].

FMEA is a widely used systematic process to identify the possible potential failure modes of a system and process. Many researchers proposed various modified FMEA process including failure cost, fuzzy logic, grey theory, utility priority number, life cost based FMEA and many more. It was found that these approaches do not solve the drawback of traditional FMEA process as mentioned in the problem statement. The main objective of this present study was to introduce a modified risk evaluation and prioritization methodology for design FMEA process. It is a unique and novel approach for prioritization of risk, when the FMEA team has different opinions in ranking scale.

2. FMEA STANDARDS

There are a number of FMEA standards developed and recommended for different applications. Some of important standards are MIL-P-1629, AIAG and SAE J-1739.The FMEA discipline was developed by the United States Military and introduced the military procedure, titled “Procedures for Performing a Failure Mode, Effects and Criticality Analysis MIL-P-1629”, in November 9, 1949.

The objective of the MIL standard is to identify failure modes of critical components of a system with its effect. The International Organization for Standardization (ISO) published the ISO 9000 series of business management standards in the year 1988. The requirements of 1SO-9000 forced organizations to develop formal Quality Management Systems (QMS) that are concentrated on the needs, and expectations of customers. A task force representing Chrysler Corporation, Ford Motor Company, and General Motors Corporation introduced QS-9000 to standardize automotive supplier quality systems. In accordance with QS-9000, automotive suppliers shall use Advanced Product Quality Planning (APQP), which includes design and process FMEAs. The Automotive Industry Action Group (AIAG) and the American Society for Quality Control (ASQC) copyrighted industry-wide FMEA standards in February, 1993. That was the technical equivalent of the Society of Automotive Engineers procedure SAE J-1739. The standards and guidelines are presented in the FMEA Manual are approved and supported by all three automakers [12].

A trial and error method was followed prior to the introduction of FMEA procedure to identify what could go wrong with a product (or) process. Later it was found that it is a time consuming process and steered to wastage of resources in some situation. Otherwise, FMEA is a structured systematic approach used to identify failure modes, its effects and causes. Application of FMEA helps organizations to improve customer satisfaction, safety and comfort.

3. PROCEDURE

Failure Mode and Effects Analysis (FMEA) is accomplished through step-by-step process in the conceptual design phase to identify potential design weaknesses. The objective of FMEA is to identify potential failure modes that may affect safety and product performance [13]. Normally FMEA is carried out by a team of members from design, production, assembly, testing and quality control departments. The team identifies the product failure modes and assigns ranking for severity, occurrence and detection indexes. The risk level is measured using the Risk Priority Number (RPN). The RPN is a product of the severity, occurrence and detection ranking value. Then, the failure modes are prioritized based on RPN value. The importance will be given to the failure mode which produces higher RPN value.

RPN = Severity ranking (S) x Occurrence ranking (O) x Detection ranking (D) (1)

Severity is ranked based on the effect of failure, Occurrence is the frequency of the failure and Detection is the ability to detect the failure [14]. Figure 1 shows the various steps involved in the FMEA process.

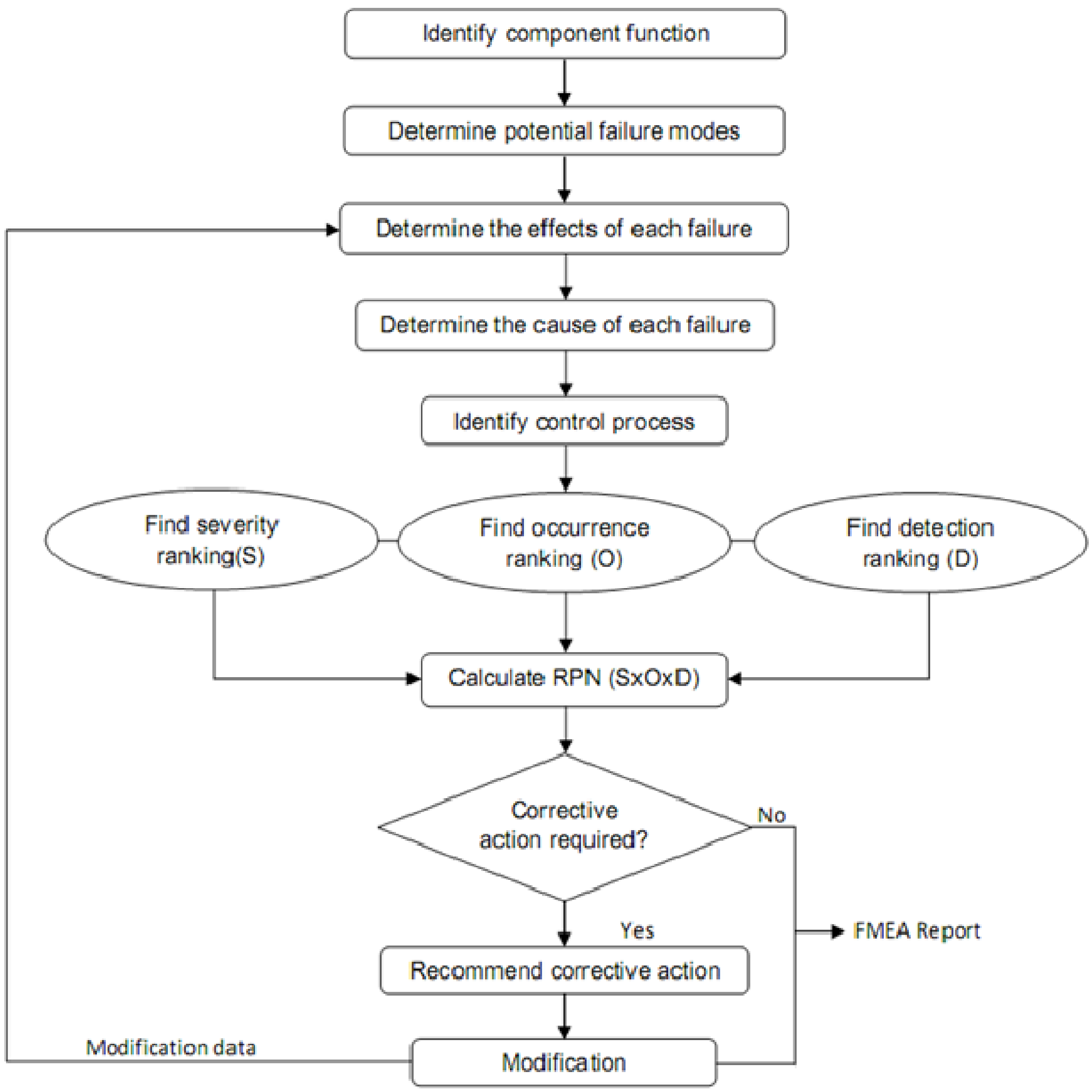

FIGURE 1: FMEA Process.

Table 1 shows the ranking scales (1 – 10) used to measure the severity, occurrence and detection. The calculation of the RPN helps the FMEA team to analyze all the possible failure modes and to identify the most critical failure mode which needs to be addressed immediately.

Accordingly, the FMEA team proposes corrective action to reduce the risk of failure modes. Then, it is re-evaluated after the implementation of corrective action.

Rank	Severity (S)	Occurrence (O)	Detection (D)
10	Hazardous without warning	Extremely high	Absolutely uncertainty
9	Hazardous with warning	Very high	Very remote
8	Very high	High	Remote
7	High	Frequent	Very low
6	Moderate	Moderate	Low
5	Low	Occasion	Moderate
4	Very low	Slight chance	Moderately high
3	Minor	Very slight chance	High
2	Very minor	Remote, very unlikely	Very high
1	None	Extremely remote	Almost certain

TABLE 1: Ranking Scale for Severity, Occurrence and Detection Indexes.

4. PROBLEM STATEMENT

The traditional FMEA approach proposed no threshold value for evaluation of RPNs. There is no value above which it is mandatory to take a recommended action or below which the team is automatically excused from an action. The most critically debated disadvantage of the traditional FMEA is that taking average or higher numerical value for the severity, occurrence and detection indexes, when the FMEA team has a disagreement in the ranking scale. For example, if one member says 6 and someone else says 7, the ranking in this case should be 7 (6+7=13, 13/2=6.5), however this may produce an identical value of RPN.

5. PROPOSED RPN PRIORITIZATION METHODOLOGY

The purpose of the present study is for the development of modified prioritization of risk priority number in design FMEA, when there is a disagreement in ranking scale for severity, occurrence and detection indexes. The modified design FMEA method is used for investigation of water leakage in a building design. The proposed risk prioritization method helps to analyze the possible failure modes and its effects of water leakage in a more systematic approach.

Table 2 shows five common possible failure modes identified for water leakage in buildings. It includes failure modes from rain water leakage, leakage from water installations and drainage leakage in the buildings. The water leakage will have different consequences depending on where it occurs. In rooms with drain system, the water can run out without making damage and the repair cost will be low. It will lead to more extensive damage, if the water leakage is found where there is no drain system like in living rooms, hall and hidden spaces. In this case, the repair cost also will be high, if it is not stopped immediately.

The RPNs for the possible five failure modes due to water leakage in a building are tabulated in Table 2. It is noticeable that all failure modes are produced an identical value of average RPN. One of the drawbacks in the traditional FMEA is that more than one failure modes will produce an identical value of RPN. Therefore it is suggested that, consider all proposed ranking indexes, if there is a disagreement in the ranking process. Then, calculate RPN range for each failure mode and the failure mode with the lowest RPN range will be evaluated first to establish the control plan to eliminate or to reduce the effect. The risk of each failure is prioritized based on the RPN range, when risk priority number (RPN) average is same for more than one failure modes.

This situation arises when there is a disagreement in the ranking score for the risk factors among the team members. Hence, a general statement is given as **"The higher the RPN mean is more severe. When the RPN means are same, the smaller the RPN range is more severe".**

6. METHODOLOGY

The data presented in the Table 2 was analyzed for the purpose of evaluating the proposed risk evaluation and prioritization method. The proposed method was evaluated using statistical analysis methods like Multiple Regression Analysis, Analysis of Variance (ANOVA), Multi-collinearity Analysis and Residual Analysis with help of SPSS (Statistical Package for the Social Sciences) program.

6.1 Multiple Regression Analysis

Multiple regression is a statistical technique is more suitable method to examine the relationship between a dependent variable and an independent or predictor variables. The independent variables may be quantitative or qualitative and this method helps us to study the effect of one or more variables with other variables [15].

In this research work, we are interested in predicting RPN values (y) using three predictors namely Severity (x1), Occurrence (x2) and Detection (x3).

A multiple regression equation for predicting y can be expressed as follows;

$$y = A + B1\ x1 + B2\ x2 + B3\ x3 \qquad (2)$$

Where;

y = Dependent variable RPN
x1, x2, and x3 = Three independent variables S, O and D
B1, B2, and B3 = Co-efficient of the three independent variables
A = Constant

Test hypothesis and null hypothesis are stated as;

$$H0: B1 = B2 = B3 = 0 \qquad (3)$$

$$Ha: \text{at least one } Bi \neq 0 \qquad (4)$$

(At least one of the coefficients is not zero)

For the regression model to be valid, there are three assumptions to be checked on the residues:

(i) No outliers.
(ii) Independency of data points.
(iii) Residuals are normally distributed with constant variance.

Failure mode	Effect of failure	Cause of failure	Current control	Severity (S)	Occurrence (O)	Detection (D)	RPN[1]	RPN Average	RPN Range	RPN Rank
Leakage in roofing material	Dripping or water flow in the building during and after rain	Aging of material	Use tested material for aging in a climate as on site	3 4	4 5	5	60, 75, 80, 100[1]	78.75	40	1
Leakage from roofing felt joint	Dripping or water flow in the building during and after rain	Poor workman-ship	Have control system for workmanship	5	2 5	3 6	30, 60, 75, 150	78.75	120	3
Leakage from joint to walls	Dripping or water flow in the building during and after rain	Montage error	Rain should not be able to come under the roof material at joint	4 5	3 7	3 4	36, 48, 84, 112, 45, 60, 105, 140	78.75	104	2
Leakage from drains and watertight floors	Dripping or water flows	Montage error, leakage through joints	Look for crack	3 4	5	4 7	60, 105, 80, 140	96.25	80	5
Leakage from pipe fittings	Wall damage	Leakage from joints between pipes	Areas around pipe fittings make watertight solutions	7	2 3	5 6	70, 84, 105, 126	96.25	56	4

TABLE 2: Potential Failure Modes and Prioritization of RPN for Water Leakage Problems in Buildings.

[1]RPN = Risk Priority Number. RPN values are produced by different combinations of S, O and D ranking scales.
For example 3x4x5=60, 3x5x5=75, 4x4x5=80, 4x5x5=100

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B		Correlations			Collinearity Statistics	
	B	Std. Error	Beta			Lower Bound	Upper Bound	Zero-order	Partial	Part	Tolerance[1]	VIF
1 (Constant)	-134.184	15.975		-8.399	.000	-167.508	-100.860					
Severity	14.039	1.926	.537	7.289	.000	10.021	18.057	.171	.852	.475	**.780**	**1.282**
Occurrence	18.184	1.486	.915	12.236	.000	15.084	21.284	.540	.939	.797	**.759**	**1.318**
Detection	16.575	1.722	.639	9.624	.000	12.983	20.168	.515	.907	.627	**.963**	**1.038**

TABLE 3: Multiple Regression Analysis for RPN.

[1]Tolerance = 1 / VIF (1/1.282 = 0.780, 1/1.318 = 0.759, 1/1.038 = 0.963)

6.2 Analysis of Variance (ANOVA)

The next part of the output contains an analysis of variance (ANOVA) that tests whether the model is significantly better at predicting the RPN. The ANOVA table 4 shows the “usefulness” of the multiple regression model.

Model	Sum of Squares	Degrees of freedom	Mean Square	F	Sig.
1 Regression	23316.590	3	7772.197	71.765	.000a
Residual	2161.243	20	108.062		
Total	25477.833	23			

TABLE 4: Analysis of Variance for RPN.

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					Durbin-Watson
					R Square Change	F Change	df1	df2	Sig. F Change	
1	.957a	.915	.902	10.395	.915	71.923	3	20	.000	1.807

TABLE 5: Regression Model Summary for RPN.

R Square = $$\frac{RR_{\mathrm{Re}\,gression}}{RR_{Total}} \quad (5)$$

R Square = $$\frac{23316.590}{25477.833} = 0.915 \quad (6)$$

Test statistic, F = $$\frac{R^2 / k}{(1-R^2)/(n-k-1)} \quad (7)$$

Where; $R^2 = 0.915$

k = number of independent variables = 3

n = number of date points = 24

(n-k-1) = degrees of freedom = 24-3-1 = 20

F = $$\frac{.915/3}{(1-.915)/20} = 71.765 \quad (8)$$

6.3 Multi-collinearity Analysis

Often, two or more of the independent variables used in a regression model contribute redundant information. That is, the independent variables are correlated with each other. Table 2 presents data on RPN values for five failure modes with corresponding values of S, O and D for a sample size of 24.

The model is fit to the 24 data points in Table 2 and a portion of the output is shown in Table 3. A formal method of detecting multicollinearity is by means of “Variation Inflation Factors (VIF)”. The variation inflation factors measure how much the variances of the estimated regression coefficients are inflated when compared to the predictor variables that are not linearly related.

The general rule of thumb is;

VIF≤1	-	There is no multicollinearity exists among the predictors.
1<VIF≤4	-	May be moderately correlated and can be ignored.
5≤VIF<10	-	Warrant further investigation.
10≤VIF	-	Serious multicollinearity requiring correction.

Multicollinearity exists when tolerance is below .1

$$\text{Tolerance} = 1 - R^2 \tag{9}$$

$$\text{Variation Inflation Factor (VIF)} = 1/\text{Tolerance} \tag{10}$$

7 RESULTS AND DISCUSSION

7.1 Statistical Analysis Results

The statistical analysis is performed using SPSS program. In multiple regression, the model takes the form of an equation that contains a coefficient (B) for each predictor. The first part of the table gives us estimation for these B values and these values indicate the individual contribution of each predictor to the model.

From the output given in Table 3, the regression equation can be written as;

$$y = -134.184 + 14.039*S + 18.184*O + 16.575*D \tag{11}$$

- The B value gives the relationship between RPN and each predictor. If the value is positive, then there is a positive relationship between the outcome and the predictors, whereas a negative coefficient represents a negative relationship.
- From the data shown in the Table 3, all the three predictors have positive B values indicating positive relationship.
- The data points are independent and predictors (severity, occurrence and detection) have positive relationship, hence, the model is valid.
- All of the VIF_k are less than 4 and tolerance is greater than .1 (highlighted in the Table 3), suggesting that there is no multicollinearity is present among the three predictors.

The Analysis of variance (ANOVA) for RPN is presented in Table 4, which shows the sum of squares, mean squares and significance.

- ✓ From Table 4, we see that F = 71.765 and p = 0.000. This is enough to tell us that the p-value or significance of the F is p<.001. Since this is the smallest value at which we can reject the hypothesis, we can reject at .05, .01 and .001.

- ✓ At the α = 0.05 level of significance, there exists enough evidence to conclude that at least one of the predictors is useful for predicting RPN; therefore the model is useful for RPN evaluation and prioritization.

The regression model summary for RPN is presented in Table 5 and the column labeled R is the values of the multiple correlation coefficients between the predictors (severity, occurrence and detection) and the outcome (RPN). The next column gives us a value of R^2, which is a measure of how much of the variability in the outcome is accounted by the predictors.

- The R Square value is 0.915; therefore about 91.5 % of the variation in the RPN is explained by severity, occurrence and detection and hence the model is valid at .95 confidence interval.

- The Durbin-Watson estimate ranges from zero to four. Values distributed around two showed that the data points are independent. Values near zero mean strong positive correlations and four indicates strong negative. In this model the value Durbin Watson is 1.807, which is so close to 2, hence, the independency of data point's assumption is met.

Figure 2 shows that most (95 percent) of the standard residuals are falls within two standard deviations of the mean, which is -2 to +2 and all of them are placed within ±3 standard deviation. More residuals are distributed around zero line and fewer residuals are away from zero.

Figure 3 shows a normal probability plot of the standardized residuals. It shows that the residuals are close to the diagonal line, which means the normality condition is met.

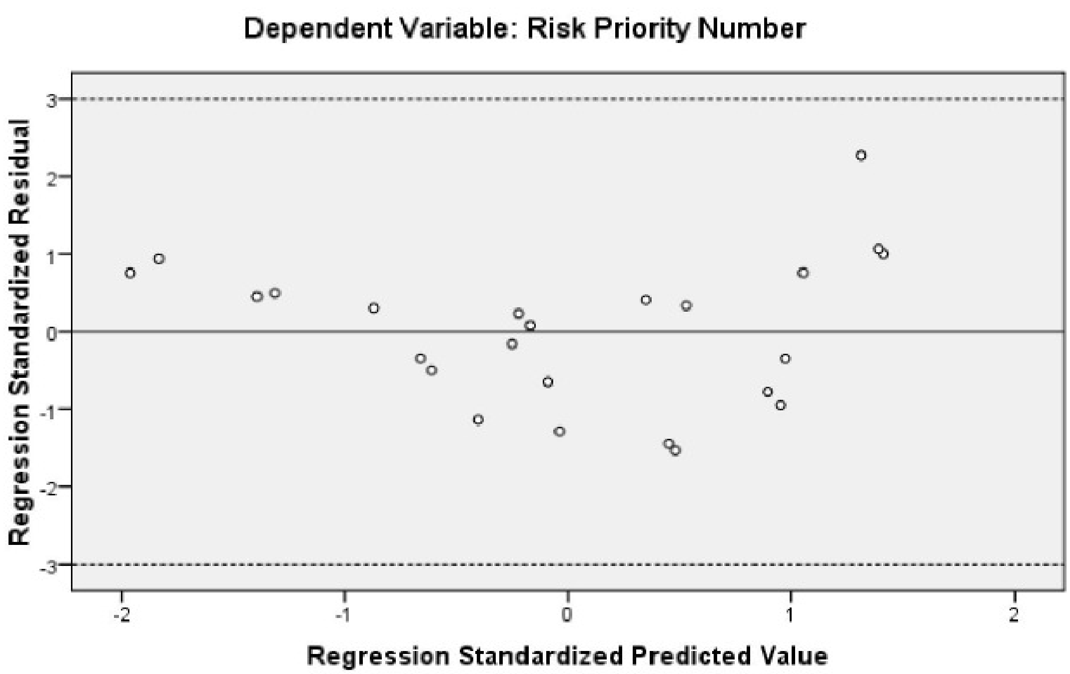

FIGURE 2: Scatter Plot of Standard Residuals.

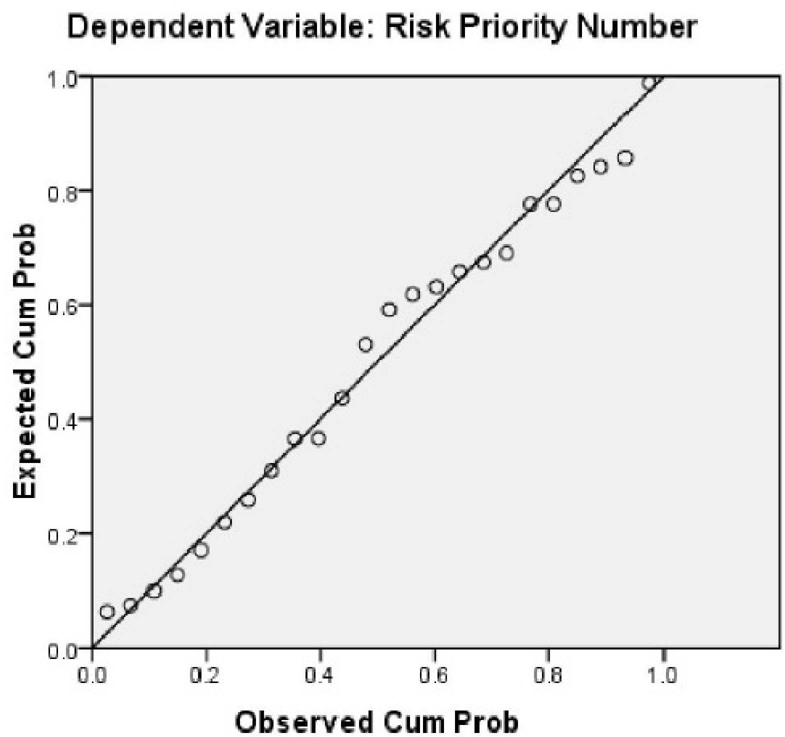

FIGURE 3: Normal Plot of Regression Standardized Residuals.

8. CONCLUSION

The aim of this present paper is to develop an effective modified RPN evaluation and failure mode prioritization method for FMEA to improve the traditional approach. The case study demonstrates that the proposed risk prioritization method is useful in risk evaluation, ranking and prioritization of failure modes;

- When there is a disagreement in ranking score for the three risk factors namely the severity, occurrence and detection.

Finally, the statistical analysis like multiple regression analysis and residual analysis provides a strong evidence for the usefulness of the overall model.

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