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Prioritization of Failure Modes in Process FMEA using Fuzzy Logic

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Abstract: Failure mode and effect analysis (FMEA) is a widely used reliability analysis and risk assessment tool in various industries. It is one of the most established project management techniques to identify and eliminate failures before actual manufacturing starts. In traditional FMEA, Risk Priority Number (RPN) ranking system is used to evaluate; the risk level of failures, to rank failures, and to prioritize actions. Even through this approach is simple but there are some shortcomings in obtaining a good estimate of the failure ratings. Thus, a new risk assessment system based on the fuzzy set theory and fuzzy rule base theory is proposed to deal with these drawbacks. Furthermore, an analysis of a forging industry is presented to demonstrate the traditional FMEA and the proposed FMEA.

Keywords: Failure modes and effects analysis, Reliability management, Fuzzy logic

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1. Introduction

In present era of automation and modernization, setting up of production plants involves huge capital investment especially for the process industry. High productivity and high pay back ratios have become essential for the survival of these systems. So it is expected that a production system should remain operative for maximum possible duration to achieve the desired goal of production. The deterioration and failure of these systems might incur high costs due to production losses and delays, unplanned intervention on the system and safety hazards (A.Grall 2002). Overtime, however, a given system suffers failures and has to bring back to the serviceable state through appropriate maintenance and repairs. The causes of failure may be human error, poor maintenance, inadequate testing, inspection or improper use and the resulting effects vary from minor in convenience to lost service time and sometimes to loss of material, equipment‘s and even life (Charles E.Ebleing1999).

Several techniques have been used is to determine the causes for the failure modes and what could be done to eliminate or reduce the chance of failure. The most notable methodology dealing with this issue is the failure mode and effect analysis (FMEA) (Wang 1996). A failure mode and effects analysis can be described as a systematic way of identifying failure modes of a system, item or function, and evaluating the effects before they occur.

1.1. FMEA Method

Failure mode and effect analysis (FMEA) is a structured, bottom-up approach that starts with known potential failure modes at one level and investigates the effect on the next subsystem level (Wang et al., 1996). FMEA as a formal design methodology was developed at Grumman Aircraft Corporation in the 1950 and 60s (Coutinho, 1964) and was applied to naval aircraft flight control systems. Since then, it has been extensively used as a powerful tool for safety and reliability analysis of products and processes in a wide range of industries particularly, aerospace, nuclear and automotive industries (Gilchrist 1993, Connor 2001, Eblieng 2000). In 1977, it was adopted and promoted by Ford Motor Company. The Ford procedure extended FMEA methodology in automotive sector to assess and prioritize potential process and design- related failures. FMEA is a widely-used quality improvement and risk assessment tool in manufacturing industry. This method combines the human knowledge and experience to identify known or potential failure modes of a product or process. By evaluating the failures of a product or process and their effects, FMEA team could initiate corrective actions or preventive measures as soon as possible to eliminate or reduce the chance of the failures occurring. Shortly speaking, FMEA is a useful technique to identify: (1) the potential failure modes of a product or process, (2) the effects of these failures, and (3) the criticality of these failure effects in the performance of a product or process.

Failure mode and effects analysis (FMEA) is a widely used engineering technique for defining, identifying and eliminating potential failures and so on from system, design, process before they reach the customer (Stamatis, 1995). FMEA seeks for answer for questions like: what could go wrong with the system or process involved in creating the system; how badly might it go wrong; and what needs to be done to prevent failures?, The purposes of FMEA are as follows:

- Identify potential design and process related failure modes. Ideally, the design or process can changed to remove potential problems in the early stages of development (Pries, 1998).
- Find the effects of the failure modes. FMEA allows a team to analyse the effect of each failure.

- Find the root causes of the failure. An FMEA is designed to find the sources of the failures of a system.
- Prioritise recommended actions using the risk priority number. The risk priority number is computed using the probability of occurrence of the failure mode, the severity of the effect of the failure mode, and the probability of detection of the failure mode through manufacturing.
- Identify, implement, and document the recommended actions.

The first step in performing FMEA to analytical analysis is identification of potential failure modes. These failure modes are listed and then scored based on three aspects of the failure modes: occurrence (O), detection (D) and severity (S). Traditionally, this FMEA scoring is done by assigning discrete values to each of the items on a predefined scale, for example from 1 to 5 or 1 to 10 (Ying Ming Wang 2009). Risk priority number (RPN) is the product of the severity, occurrence, and detection ratings. And, the criticality of each failure mode can be generated by the calculation of RPN. The failure having a higher RPN will have a higher priority for corrective action or preventive measure.
Risk priority number (RPN) = S. O. D

1.2. Drawbacks of Traditional FMEA Approach

The main objective of FMEA is to discover and prioritize the potential failure modes by computing respective RPN. Even today RPN evaluation with FMEA is probably the most popular reliability and failure analysis technique for products and processes (Rajiv Kumar Sharma 2005). One of the major reasons for this success is due to its visibility and easiness. Unfortunately, several problems are associated with its practical implementation in real industrial situations.

The critical disadvantages include:

- In RPN analysis, various sets of S, O and D may produce an identical value; however, the risk implication may be totally different (Anish Sachdeva 2012).
- The relative importance among the three parameter ratings.
- The difference of risk representations between the failure modes having the same RPN (Rajiv Kumar Sharma 2005).

Consider two different examples having values of S= 2, O= 5, D= 5 and S=1, O=10, D=5. Both these events will have a total RPN=50; however, the risk factor of these two events may not necessarily be the same, which may result in high-risk events going unnoticed. The other drawback of the RPN ranking method is that it neglects the relative importance among S, O and D. The three factors are assumed to have the same importance but in real practical applications the relative importance among the factors exists. In another example say S=2, O=10, and D=5 may have a lower RPN=100 than one with all parameters moderate say S=6, O=6, and D=6 with RPN=216. There is high difference in RPN of both the events, though it should require a higher priority for corrective action in first event.

There are significant efforts have been made in FMEA to overcome the shortcomings of the traditional RPN (Wang, 2009). Most notably fuzzy theory with fuzzy If-then rule base, have been suggested in the literature to overcome the drawbacks. The studies about FMEA considering fuzzy approach use the experts who describe the risk factors O, S, and D by using the fuzzy linguistic terms (Bowles & Pelaez, 1995; Chin, 2008; Guimaraes & Lapa, 2004, 2007; Pillay & Wang, 2003; Sharma, 2005; Tay & Lim, 2006).

2. Fuzzy Methodology

Zadeh (1965) proposed the fuzzy set theory which is an important concept to deal with uncertainty-based information. . The parameters i.e. Severity (S), Occurrence (O) and Detection (D) which are used in FMEA are fuzzified using appropriate membership functions (Chang 1996). Fuzzy system is a knowledge-based system which is constructed from expertise and experience in the form of fuzzy IF-THEN rules (Tay & Lim, 2006). Through building knowledge-based model, expert knowledge and judgment can be utilized to make the FMEA assessment method more reasonable and convenient. The fuzzy conclusion is then defuzzified to get risk priority number. The main components associated with fuzzy are:

- Fuzzification
- Fuzzy rule base
- Defuzzification.

2.1. Fuzzification

Fuzzification refers to transformation of crisp inputs into a membership degree which expresses how well the input belongs to the linguistically defined terms (Rajiv Kumar Sharma 2005). Experts judgement and experience can be used for define degree of membership function for a particular variable. During Fuzzification, a fuzzy logic controller receives input data, also known as the fuzzy variable, and analyzes it according to user-defined charts called membership functions (Klir and Yuan, 1995).

2.2. Fuzzy rule base

The rule base describes the criticality level of the system for each combination of input variables. Often expressed in ‘If-Then', they are formulated in linguistic terms using two approaches (i) Expert knowledge and expertise (ii) Fuzzy model of the process (Zimmermann, 1996). Experts judgement and experience can be used for define degree of membership function for a particular variable.

2.3. Defuzzification

The defuzzification process examines all of the rule outcomes after they have been logically added and then computes a value that will be the final output of the fuzzy controller. During defuzzification, the controller converts the fuzzy output into a real-life data value (Rajiv Kumar Sharma 2005).

3. Fuzzy FMEA for Forging Shop

A case study was carried in one of the forging plant where automotive parts were forged and heat treated. Expert's judgment and knowledge is taken in making the model using three input parameters Severity of failure (S), Frequency of Occurrence of failure (O) and Non-detection of failure (D). An If-Then rule base is generated using fuzzy inference engine (FIS), which after defuzzification generates the fuzzy risk output number (FRPN). The Fuzzy Linguistic assessment model was developed using toolbox platform of MATLAB 7.0. Forging shop has various operations for which various failure modes and effects were collected by using expert's judgment and knowledge database.
Table 1 shows the combined list of:

1. Functions being performed in the shop
2. Failure that may happen
3. Potential effects of failures
4. Potential causes of failures

To find out all these failure causes, help is being taken from expertises, which includes; Product and process engineer, quality engineer, operation and maintenance department. Failure effect and its causes are produced by several years' experiences of concerned department. Total nine functions have been performed in a shop and with deep analysis 36 failure causes have been detected which may happen at manufacturing stage and cause failure of component. As shown in Table 1, these failures are expressed as 'F'.

TABLE 1. COMPONENT FUNCTIONS AND THEIR FALIURES IN FORGING SHOP

S. No.	FUNCTION	FAILURE	POTENTIAL EFFECTS OF FAILURE	POTENTIAL CAUSES OF FAILURE
1	Shearing	Weight less than specified	Unfilling	Initial Wrong Setting by operator (F1)
				Shifting of stopper during operation (F2)
		Weight more than specified	Component Over Size	Initial Wrong Setting by operator (F3)
				Shifting of stopper during operator (F4)
2	Heating	Temp. More than required	Less Thickness of Comp	More Soaking time (F5)
				Operator Missed to reduce air/fuel input (F6)
			Unfilled forging	More Soaking time (F7)
				Operator Missed to reduce air/fuel input (F8)
			Surface Crack Generation	More Soaking time (F9)
				Operator Missed to reduce air/fuel input (F10)
		Temp. Less than required	More thickness	Less Soaking Time (F11)
			Unfilled Forging	Less Soaking Time (F12)
			Surface Crack Generation	Less Soaking Time (F13)

3	Swaging	More Length	Surface Crack Generation	More Strokes Per Pc. (F14)
			Die unfilled	More Strokes Per Pc. (F15)
		less Length	Die unfilled	Less Strokes Per Pc. (F16)
		Uneven Surface	Surface Crack	Uneven strokes (F17)
		Surface Overlapping	Development of cracks at Normalizing	Play in Slides (F22)
				Die mismatch (F23)
		Unfilling Minor	Difficult Machining	Less Strokes during swaging (F24)
		Surface Dents	Difficult Polishing	Hot Pcs. Striking with another pcs. (F25)
4	Forging	Major Mismatch	uneven trimming	Initial Die Setting Problem (F18)
				Die Shift During Production (F19)
		Minor Mismatch	Difficult Machining	Initial Die Setting problem (F20)
				Die Shift During Production (F21)
		Surface Overlapping	Development of cracks at Normalizing	Play in Slides (F22)
				Die mismatch (F23)
		Unfilling Minor	Difficult Machining	Less Strokes during swaging (F24)
		Surface Dents	Difficult Polishing	Hot Pcs. Striking with another pcs. (F25)
5	Trimming	Dimensions of workpiece i more as per drawing	Difficult fitting during assembly	Die Wear (F26)
				Less no of strokes (F27)
		Dimensions of workpieces less as per drawing	Loose fitting during assembly	Die Wear (F28)
6	Coining	Height more than required	Rejection on subsequent operation	Initial Die Setting problem (F29)
7	Normalising	Hardness more than require	Difficult Machining	Less Soaking Time (F30)
				Less Normalising Temperature (F31)
		Hardness less than required	Functional failure	More soaking time (F32)
				More Normalising Temperature (F33)
8	Grinding	Excessive Grinding	Rejection on subsequent operation	Excessive pressure applied by operator (F34)
		Grinding Less than require	Rejection on subsequent operation	Less pressure applied by operator (F35)
9	Barrelling	Scale Not removed	Poor appearance	Less Barrelling time (F36)

Table 2 shows the basic data from which fuzzy rules have been made. Three factors have been considered, that includes; severity of failure (S), frequency of occurrence (O) and chance of non-detection of failure (D). According to the degree of the seriousness, all factors are rated on a 0 -to 10 scale. This data has been evaluated in fuzzy inference engine (FIS) and “If-Then” rules prepared accordingly. In Table 2, traditional method of FMEA has been used by multiplying all the three input variables and RPN number is generated.

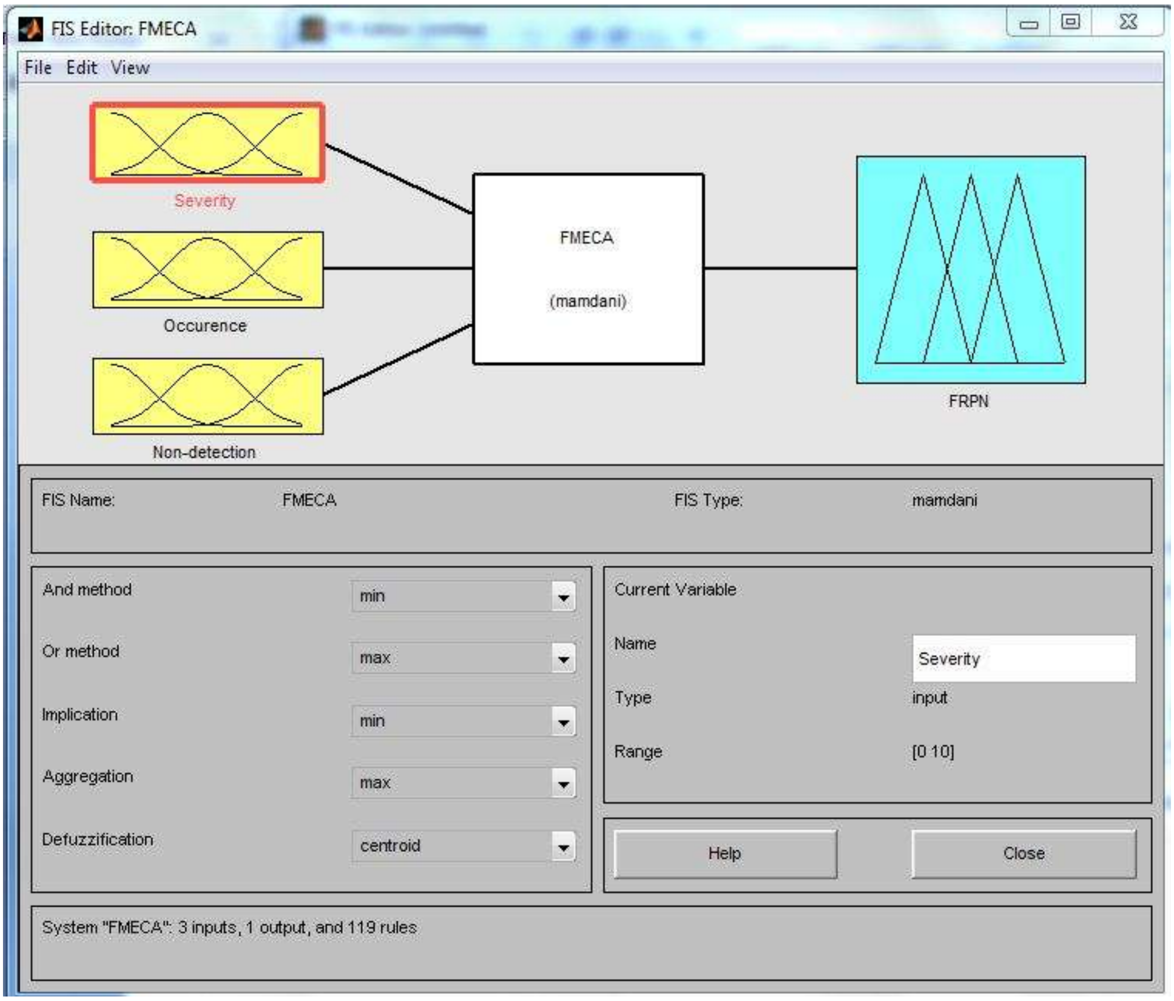
TABLE 2. COMPARISION BETWEEN TRADITIONAL RPN AND FUZZY RPN RANKING

FUNCTION	Failures	Severity	Occurrence	Non-Detection	RPN
Shearing	F1	6	4	4	96
	F2	6	4	10	240
	F3	4	4	5	80
	F4	4	4	10	160
Heating	F5	8	4	8	256
	F6	8	4	8	256
	F7	8	4	8	256
	F8	8	4	8	256
	F9	10	4	8	320
	F10	10	4	8	320
	F11	4	2	8	64
	F12	4	2	8	64
	F13	10	2	8	160
Swaging	F14	10	2	8	160
	F15	8	2	8	128
	F16	8	2	8	128
	F17	10	2	8	160
Forging	F18	8	2	8	128
	F19	8	2	8	128
	F20	4	2	8	64
	F21	4	2	8	64
	F22	10	2	8	160
	F23	10	2	8	160
	F24	10	2	8	160
	F25	4	2	8	64
Trimming	F26	4	2	6	48
	F27	4	2	6	48
	F28	8	2	6	96
Coining	F29	8	4	8	256
Normalising	F30	10	8	8	640
	F31	10	8	8	640
	F32	10	8	8	640
	F33	10	8	8	640
Grinding	F34	4	2	6	48
	F35	4	2	6	48
Barrelling	F36	6	2	8	96

3.1 Modeling of the fuzzy logic base FMEA

Three factors have been selected as the input parameters for our fuzzy system which is being evaluated in well defined IF-THEN rules prepared in MATLAB Fuzzy logic toolbox. Experts and engineers transform their experience and knowledge into fuzzy IF-THEN rules in language.

The membership function derived from the expert is used to generate the fuzzy rule base. The Rule Viewer of the MatLab that opens during the simulation can be used to access the ‘‘Membership Function Editor’’ and ‘‘Rule Editor’’. ‘Rule Editor’ is used to edit the list of rules that defines the behavior of the system where as ‘Rule Viewer’ is to view the fuzzy inference diagram and a roadmap of the whole fuzzy inference process. The FIS Editor displays information about a fuzzy inference system, in which we can add input variables and arrange it accordingly.



FIS Name: FMECA
FIS Type: mamdani

And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification: centroid

Current Variable
Name: Severity
Type: input
Range: [0 10]

System "FMECA": 3 inputs, 1 output, and 119 rules

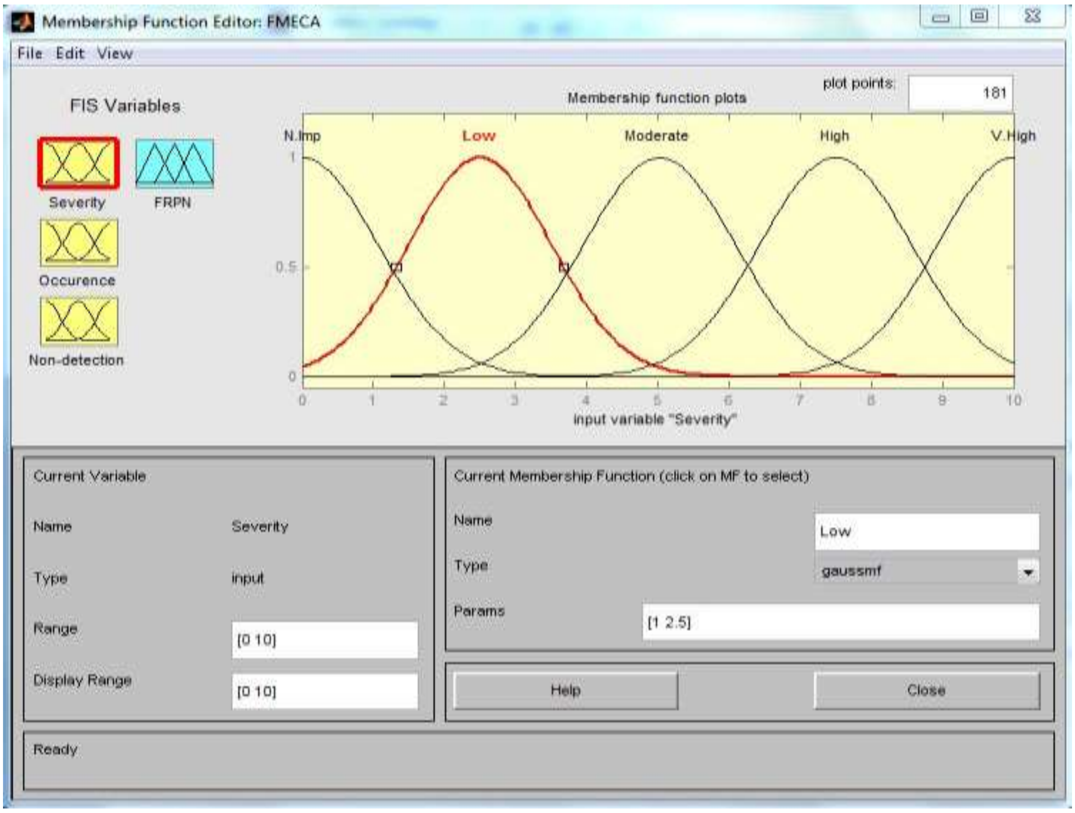
Figure 1. FIS EDITOR

3.2. Input Variables

Severity of Failure
Severity rating is the seriousness of the effect of a failure. According to the degree of the seriousness, severity should be rated on a 1-to-10 scale. This scale is estimated based on the knowledge and expertise of the FMEA team [McDertmott et al., 1996].
Frequency of Occurrence of failure

Occurrence is the chance that one of the specific failures will occur. Sometimes, it could also be described as a probability or a frequency. The same as severity criteria, the likelihood of occurrence is based on a 1-to-10 scale, with 1 being the least chance of occurrence and 10 being the highest chance of occurrence [McDertmott et al., 1996].

Probability of Non-detection of failure
Detection is a relative measure of the assessment of the ability of the current design control to detect either a potential failure mode or the effect of a failure. If there are no current controls, the likelihood of detection will be low, and the item would receive a high rating [McDertmott et al., 1996].



plot points: 181

Current Variable

Name Severity

Type input

Range [0 10]

Display Range [0 10]

Current Membership Function (click on MF to select)

Name Low

Type gaussmf

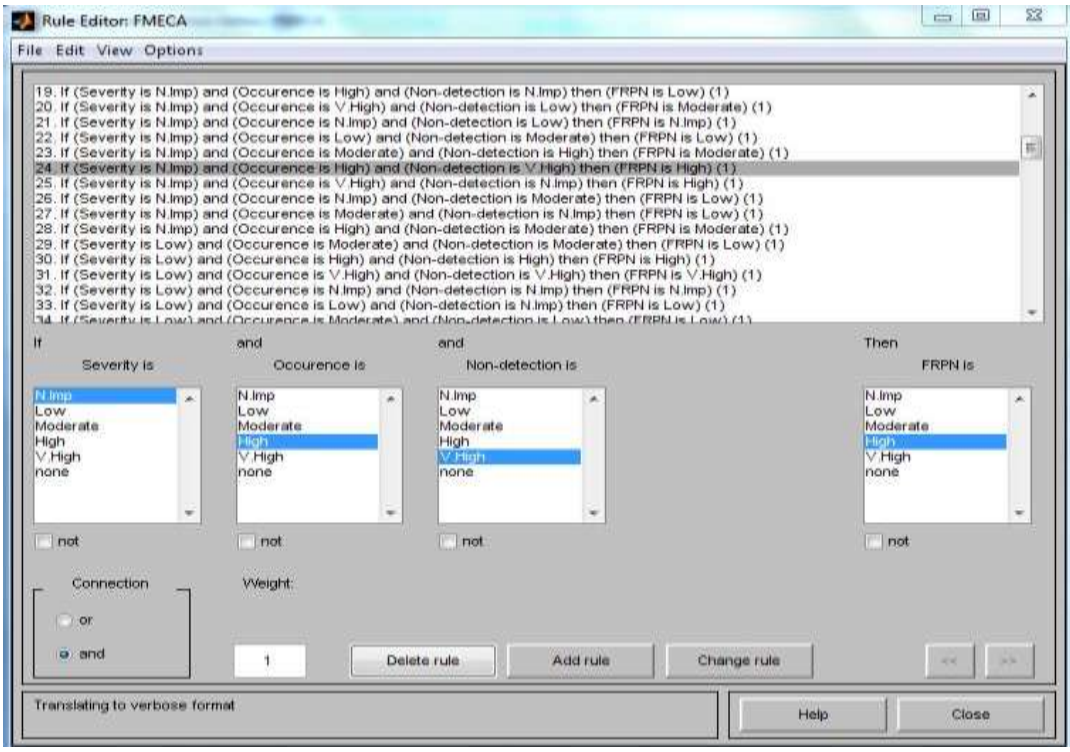
Params [1 2.5]

Ready

Figure 2 Membership Function Editor

3.3 Rule Viewer and Editor

The Rule Viewer is a MATLAB-based display of fuzzy inference program: it is used as diagnostic tool and can show which rules are active or how individual membership function shapes are influencing the results. As shown in figures 3 and 4 one give inputs through the input edit window and directly obtained the output.

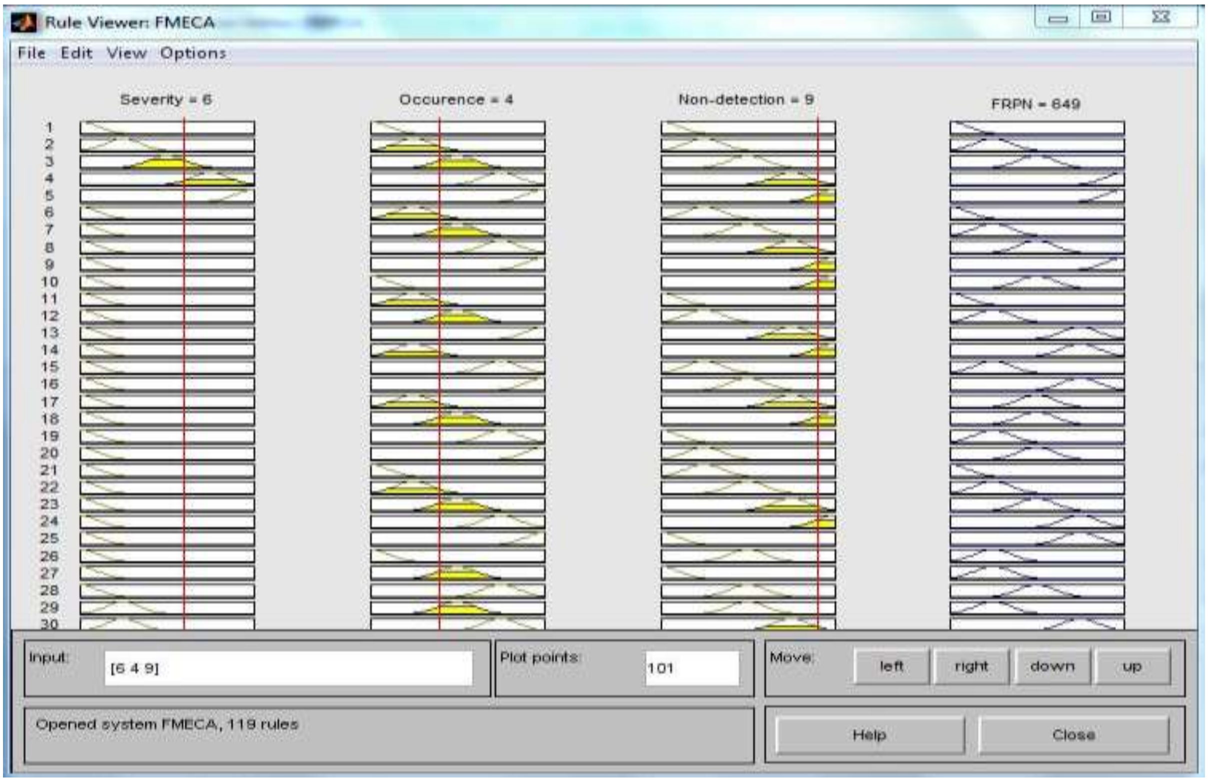


19. If (Severity is N.Imp) and (Occurence is High) and (Non-detection is N.Imp) then (FRPN is Low) (1)
20. If (Severity is N.Imp) and (Occurence is V.High) and (Non-detection is Low) then (FRPN is Moderate) (1)
21. If (Severity is N.Imp) and (Occurence is N.Imp) and (Non-detection is Low) then (FRPN is N.Imp) (1)
22. If (Severity is N.Imp) and (Occurence is Low) and (Non-detection is Moderate) then (FRPN is Low) (1)
23. If (Severity is N.Imp) and (Occurence is Moderate) and (Non-detection is High) then (FRPN is Moderate) (1)
24. If (Severity is N.Imp) and (Occurence is High) and (Non-detection is V.High) then (FRPN is High) (1)
25. If (Severity is N.Imp) and (Occurence is V.High) and (Non-detection is N.Imp) then (FRPN is High) (1)
26. If (Severity is N.Imp) and (Occurence is N.Imp) and (Non-detection is Moderate) then (FRPN is Low) (1)
27. If (Severity is N.Imp) and (Occurence is Moderate) and (Non-detection is N.Imp) then (FRPN is Low) (1)
28. If (Severity is N.Imp) and (Occurence is High) and (Non-detection is Moderate) then (FRPN is Moderate) (1)
29. If (Severity is Low) and (Occurence is Moderate) and (Non-detection is Moderate) then (FRPN is Low) (1)
30. If (Severity is Low) and (Occurence is High) and (Non-detection is High) then (FRPN is High) (1)
31. If (Severity is Low) and (Occurence is V.High) and (Non-detection is V.High) then (FRPN is V.High) (1)
32. If (Severity is Low) and (Occurence is N.Imp) and (Non-detection is N.Imp) then (FRPN is N.Imp) (1)
33. If (Severity is Low) and (Occurence is Low) and (Non-detection is N.Imp) then (FRPN is Low) (1)
34. If (Severity is Low) and (Occurence is Moderate) and (Non-detection is Low) then (FRPN is Low) (1)

Weight: 1

Translating to verbose format

Figure3. Rule Editor

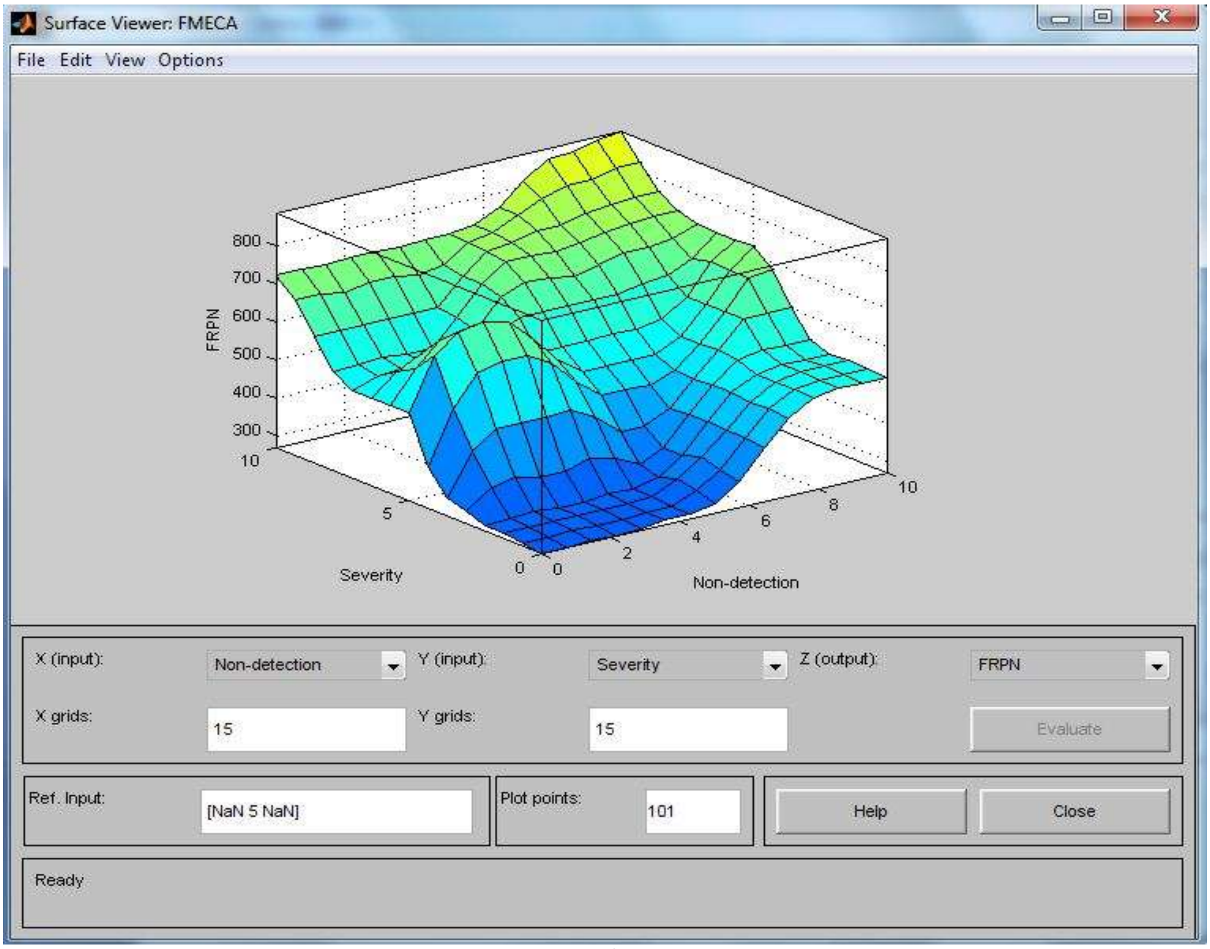


Severity = 6
Occurence = 4
Non-detection = 9
FRPN = 649

Input: [6 4 9]
Plot points: 101

Opened system FMECA, 119 rules

Figure 4. RULE VIEWER



X (input): Non-detection
Y (input): Severity
Z (output): FRPN
X grids: 15
Y grids: 15
Ref. Input: [NaN 5 NaN]
Plot points: 101

Ready

Figure 5 Surface Viewer

3.3 Surface Viewer

Upon opening the Surface Viewer, you see a three-dimensional curve that represents the mapping from severity and Non-detection. Because this curve represents a two-input one-output, you can see the entire mapping in one plot. It helps to view the dependency of one of the outputs on any one or two of the inputs (Fuzzy user guide 2012).

4. Results and Conclusion

Table 3 present the traditional RPN output and Fuzzy RPN (FRPN) output of forging shop with change in failure priority ranking. The numerical values of FMEA parameters are obtained by using the traditional methodology. Then RPN number for each failure cause is evaluated by multiplying all the three factors .The resulting RPN number and Fuzzy risk priority ranking is presented in 4th and 6th columns of Table3.

The results so obtained are presented that the ranking of priority of various failure causes obtained from the traditional FMEA is altered. Potential Failure cause number F30, F31, F32 and F33 is same both in traditional ranking and fuzzy ranking but when we see failure cause F9 and F10, it turned out to be one of the most critical failure causes in terms of RPN, while, after conducting fuzzy criticality assessment using FIS it ranks only at the 11th and 12th place respectively. At the same time, Potential Failure cause F17 and F22 becomes the most critical one because of high rank.

TABLE 3. COMPARISION BETWEEN TRADITIONAL RPN AND FUZZY RPN RANKING

S.no	Potential failur cause	Traditional RP output	Ranking traditional	FRPN output	Fuzzy Ranking
1	F1	96	24	500	31
2	F2	240	12	720	22
3	F3	80	27	425	32
4	F4	160	13	648	23
5	F5	256	7	732	17
6	F6	256	8	732	18
7	F7	256	9	732	19
8	F8	256	10	732	20
9	F9	320	5	816	11
10	F10	320	6	816	12
11	F11	64	28	551	26
12	F12	64	29	551	27
13	F13	160	14	833	5
14	F14	160	15	833	6
15	F15	128	20	735	13
16	F16	128	21	735	14
17	F17	160	16	833	7
18	F18	128	22	735	15
19	F19	128	23	735	16
20	F20	64	30	551	28
21	F21	64	31	551	29
22	F22	160	17	833	8
23	F23	160	18	833	9
24	F24	160	19	833	10
25	F25	64	32	551	30

26	F26	48	33	349	33
27	F27	48	34	349	34
28	F28	96	25	594	24
29	F29	256	11	732	21
30	F30	640	1	904	1
31	F31	640	2	904	2
32	F32	640	3	904	3
33	F33	640	4	904	4
34	F34	48	35	349	35
35	F35	48	36	349	36
36	F36	96	26	589	25

According to the analysis of the results produced by the traditional FMEA and the fuzzy FMEA methods, this research shows that a more accurate, reasonable ranking can be achieved by the application of FMEA based on fuzzy theory. It is concluded from the study that fuzzy logic-based approach not only resolves the limitations associated with traditional methodology for RPN evaluation of failure causes in reliability analysis of system but also offers added advantages. In addition, the fuzzy rule base can also be revised or updated when more information of a process is available. As a result, the proposed assessment method will be continuously improved.

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