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Research paper

Fuzzy-FMEA risk evaluation approach for LHD machine – A case study

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ABSTRACT

Improvement of productivity has become an important goal for mining industries in order to meet the expected targets of production and increased price competitiveness. Productivity can be improved in different ways. The effective utilization of men and machinery is one such way. Equipment is prone to numerous unexpected potential failures during its operation. Failure Mode and Effect Analysis (FMEA) is one of the suitable techniques of reliability modeling used to investigate the failure behavior of a complex system. In conventional FMEA, the risk level of failures, a ranking of failures and prioritization of necessary actions is made on the basis of estimated Risk Priority Number (RPN). While this approach is easy and uncomplicated, there are a few flaws in acquiring the best approximation of the failure. The estimation of RPN is made by multiplying the Severity (S), Occurrence (O) and Detection (D) alone and irrespective of the degree of importance of each input. Hence, a new risk management approach known as the Fuzzy rule base interface system was proposed in this research in order to mitigate the failures. Fuzzy FMEA is designed in order to acquire the highest Fuzzy RPN value which will be used as the focus of enhancements to reduce the probability of occurrence of some kind of failure for a second time. This study focused on the Root Cause Analysis (RCA) of underground mining machinery such as Load-Haul-Dumper (LHD). 16 potential risks of various sub-system breakdowns were identified in Fuzzy FMEA. The highest value of RPN 168 (for potential failure mode-F9) was obtained for the electrical subsystem (SSE), as was the highest FRPN 117 (F9). There is a difference between the RPN and FRPN values. The FRPN value is obtained from Fuzzy field generation with consideration of the degree of importance of the given input data. In addition, the recommendations were made based on the analysis to reduce the uneven occurrence of failures.

1. Introduction

In today's time of intense global competition, every industry is constantly looking to enhance their production levels by producing products. From past reports, recorded production and productivity levels of Indian underground mines over the years were not satisfactory and the record previous years is not encouraging, perhaps due to less mechanization because of a range of reasons, such as bad managerial practices, improper operation and maintenance activities, unreliable machinery utilization, lack of real-time condition monitoring and delay in timely response to identifying problems during the operation of the equipment. As a result of this, a significant loss in the performance of the equipment can be observed. In order to acquire a profitability index, the system needs to be maintained in an efficient and effective manner. Hence, there is a requirement for identifying, ranking and prioritizing the failure modes of equipment.

Many researchers have argued that Reliability Centered Maintenance (RCM) and FMEA are the two most significant techniques which should be applied for most maintenance problems (Bloom, 2006; Mobley & Smith, 2002; Moubray, 1992; Stamatis, 2003; Seyed-Hosseini, Safaei, & Asgharpour, 2006; Waeyenbergh & Pintelon, 2002). RCM defines the functions and desired standards of equipment with respect to its maintenance strategies. FMEA identifies the potential failure mode and to determine their impact (Braaksma et al., 2013). Initially, RCM was developed by the US branch of defense thirty years ago, for the purpose of successful the completion of a mission (Nowlan & Heap, 1978). The use of RCM presents a reason for preventive maintenance (PM) exercises and can be used to estimate the impacts of operational and maintenance costs. As indicated by (Teoh & Case, 2005), a critical part of the RCM approach is FMEA and this was created in 1949 by the American Army to assess the effect of framework and equipment breakdowns on mission achievement and the security of workers and equipment. FMEA can be characterized as "a technique for reliability investigation expected to recognize breakdowns influencing the working of a system and empower needs for an activity to be set" (Bowles & Pelaez, 1995). FMEA is the subjective evaluation of hazards,

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and is mostly dependent on the judgment of specialists (Moubray, 1992).

FMEA is an appropriate method for determining design dependability by considering potential reasons for breakdowns and their effects in a complex system. FMEA based risk management analysis can be adopted to prevent undesirable events and to avoid customer dissatisfaction in the industry (Wang, 2008). Industries may have numerous reasons to develop a FMEA report. A good FMEA report can be beneficial by providing, for example, a predominant item dependability, fewer structure changes, enhanced quality figure, ceaseless enhancement in item and process plans, and lower producing costs. The conventional FMEA investigation is typically performed by a specialist in the respective field. The components of FMEA are: recognizing the methods of disappointment and the ensuing issues; surveying the actions which allow flaws occur; evaluating the seriousness of the results of the deficiencies; computing a proportion of the hazard; positioning the shortcomings based on the hazard; checking the viability of the activity, and utilizing an updated proportion of hazard (Ahsen, 2008). While this methodology is straightforward, there are a few weaknesses in getting a decent gauge of disappointment evaluations. To remedy this, another hazard evaluation framework dependent on the fuzzy set hypothesis and fuzzy principle base hypothesis is proposed.

Fuzzy set theory is a way to deal with exchanging the vulnerability of hypothetical relations into numerical systems. In accordance with a pattern has been developing in FMEA writing which utilizes fuzzy linguistic terms for depicting the three hazard factors S, O, and D. Many of the researchers assumed that fuzzy FMEA approach is the great foundation for obtaining accurate responses (Gargama & Chaturvedi, 2011; Keskin & Özkan, 2009). The vast majority of the current investigations into fuzzy FMEA writing by utilizing "If – Then" rules. This paper portrays the exact and sensible positioning of the needs of different disappointment modes by the usage of regular FMEA and proposed Fuzzy FMEA approaches.

2. Conventional Failure Mode and Effect Analysis (FMEA)

Failure Modes and Effects Analysis (FMEA) is a systematic technique of identifying, analyzing and preventing product and process problems before they occur. Its main and highlight activities that eradicate or decrease the probability of the possible breakdown event and document the reports of the advancement. The plan and philosophy of FMEA was first created by the airplane business in the 1960s for the improvement of security and reliability requirements. FMEA was also treated as an efficient way to identify and prevent product and process difficulties prior to them arising. Preferably this technique should be conducted at the stage of product design and development, despite the fact that carrying out an FMEA on pre-existing items or procedures may also yield benefits. This helps to reduce the cost of the enrichment of the product and process, as it organizes activities that reduce the possibility of the occurrence of failure (Rakesh. et al., 2013).

2.1. The procedure of FMEA

Performing FMEA begins with the selection of a machine to be analyzed. The relationship between the machine and its working environment should be clearly understood in order to decide on the effects and reasons for potential failures. After the scope for FMEA has been decided, the plan of further investigation is as follows:

i. Categorize the subsystems from the selected system/machine based on the failure type.
ii. Analyze the functioning of a component and its sub-components. Each function should in fact be determined and the breakdown criteria of the function should be characterized entirely.
iii. Identify the breakdown modes of the element. For each breakdown mode, the accountable breakdown system and their occurrences are resolved.
iv. Develop control designs that recognize disappointing systems, modes, and impacts. The viability of each arrangement is assessed by identification of the ranking.
v. Assess the general hazards of a breakdown mode. The general hazard is estimated by the Risk Priority Number (RPN), which can be calculated by multiplying the severity, occurrence and detection parameters. A high RPN indicated a high hazard of that breakdown. Restorative procedures have to be taken to decrease the hazard.
vi. Finally, the aftereffects of FMEA are recorded utilizing an identical set-up.

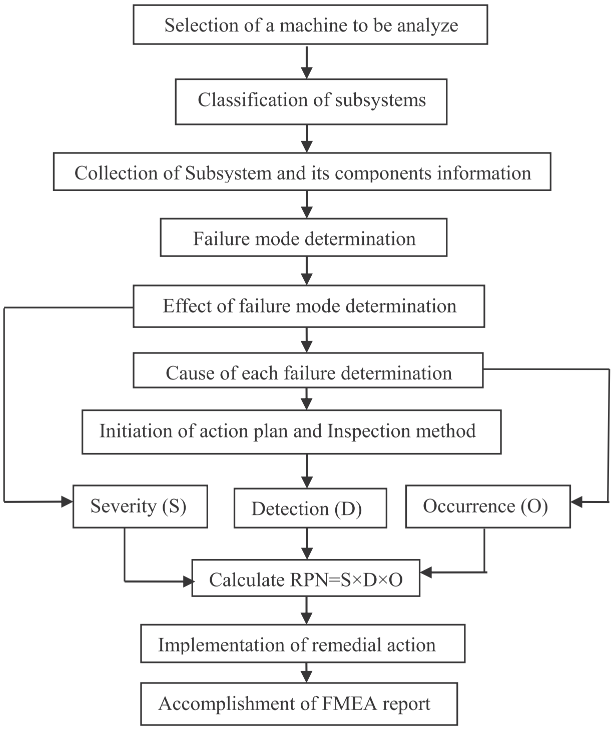


Fig. 1. Flow chart for the sequential procedure of FMEA analysis.

The sequential procedure of present analysis with the application of FMEA is demonstrated as follows (Fig. 1) (Arvanitoyannis & Varzakas, 2009).

2.2. Potential failure modes and effects

Potential Failure Mode is characterized as a system, sub-system or component which may possibly fail before meeting the designed targets. The primary potential breakdown may trigger the occurrence of secondary failure (i.e., breakdown of lower level component) due to lack of spontaneous attention of the maintenance crew to repair or replace the failed part. Every potential breakdown mode for the specific component and its function ought to be recorded. The assumption is made that the breakdown can happen, but may not necessarily happen.

Imminent Failure Effect is characterized as the impact of the breakdown mode, and should be based on the evaluation or analyses of the system response following failure. It may have physical or health and safety consequences and it needs to be clearly stated that it could impact safety or non-cooperation to the system (Maiti, 2005; Bubbico, Cave, & Mazzarotta, 2004).

2.3. Risk indexed parameters

The FMEA technique is not only used to identify the potential breakdown mode, but also used to prioritize the failure modes based on an assessment of risk indexed parameters. In general, prioritization of critical failure can be determined through calculation of Risk Priority Number (RPN) value. This can be achieved by multiplying the indexes of O, S, and D of each failure.

(i) Severity (S)

The seriousness assesses the criticalness of the impact of the potential hazard occurring. The S score is assessed against the impact of the effect brought about by the failure mode.

(ii) Occurrence (O)

Occurrence estimates the recurrence of a potential risk(s) that will occur for a given circumstance or a framework. The probability score is evaluated against the probability that the effect happens as a result of a failure mode.

(iii) Detection (D)

Detectability is the likelihood of the breakdown being identified before the effect of the breakdown to the procedure or framework being evaluated is distinguished. The D score is appraised against the capacity to recognize the result of the breakdown mode.

(iv) Risk Priority Number (RPN)

RPN is the result of the rating of three data sources (Severity, Occurrence and Detection). This can be utilized at the time of risk assessment of a failure.

RPN = Severity (S) x Occurrence (O) x Detection (D).

RPN gives direction to ranking the potential breakdowns and identifying the recommended actions for outline or process changes which would reduce Severity or Occurrence. Risk Indexed Parameter (S, O, and D) Rankings for RPN Estimation are given in Table 1.

2.4. Drawbacks of conventional FMEA

The goal of FMEA is to discover and prioritize the possible breakdown types through calculating the RPN values. FMEA based RPN evaluations are popular for evaluating all kinds of product and process investigations (Sharma et al., 2005). This technique is still in use due to its accuracy and ease of use. However, unfortunately, numerous drawbacks are associated with its sensible implementation in actual working situations in production or process industries.

The critical disadvantages include:

i. In RPN analysis, the same kind of identical values can be obtained for different data set points of S, O, and D; however, the risk assessment might be completely different (Sachdeva, Kumar, & Kumar, 2009).
ii. The qualified significance between the three parameter ratings.
iii. The dissimilarity of hazard illustrations among the breakdown modes having identical RPN (Sharma et al., 2005).

For example the risk indexed factors for the machinery components X and Y are S = 6, O = 2, D = 5 and S = 3, O = 4, D = 5. Since RPN is the product of S, O and D, both components have a similar RPN value i.e., RPN = 60. However, the degree of risk factor for these components may not be same. The other difficulty of RPN grading is that it ignores the qualified significance between S, O and D. As a result, these three parameters are assumed to have identical consequences, but in actual realistic appliances, qualified significance between the factors should exist. Similarly, for example state component 1, with risk indexed parameters of S = 5, O = 4, and D = 5, might have the lowest value of RPN i.e. 100. Whereas, the other alternative component 2, with

Table 1
Risk indexed parameter (S, O, and D) Rankings for RPN estimation (Chin, Chan, & Yang, 2008).

Effect	Severity level	Probability of occurrence	Detection (D) criteria	Rating/scale
Hazardous	When a potential failure mode effects	Very high: failure is almost unavoidable (>1 in 2)	Controls actions are not available (Not possible)	10
Very high	When a potential failure mode effects	Very high: failure is almost unavoidable (1 in 3)	Extremely low possibility of noticing the breakdown (Very remote)	9
High	System inoperable due to destructive failure	High: repeated failure, A process that has often failed (1 in 8)	Low possibility of noticing the breakdown (Remote)	8
Moderately high	System inoperable due to harsh failure	High: repeated failure, A process that has often failed (1 in 20)	Low possibility of noticing the reasons for the occurrence of breakdown (Low)	7
Moderately low	System inoperable with minor or notable failure	Moderate: infrequent failures with little impact (1 in 80)	Low chance of detecting a possible cause and consequent failure mode (Low)	6
Low	System inoperable with minor or prominent failure	Moderate: infrequent failures with little impact (1 in 400)	Reasonable possibility of noticing the reasons for the occurrence of breakdown (Moderate)	5
Very low	System operable with relatively few failures	Low: relatively few failures are associated with similar processes (1 in 2000)	Reasonably high possibility of noticing the possible reasons for occurrence of breakdown (Moderately high)	4
Very remote	System operable with relatively few failures	Low: relatively few failures are associated with similar processes (1 in 15,000)	High probability to notice the potential reasons for the occurrence of breakdown (High)	3
Remote	No effect	Remote: failure is implausible (1 in 1,50,000)	Very high probability of noticing the potential reasons for occurrence of breakdown (Very high)	2
None	No effect	Remote: failure is implausible (1 in 15,00,000)	Required controls are available to detect a failure mode (Assured controls)	1

moderately high risk indexed parameters of S = 6, O = 8, D = 4, has RPN = 192. There is a huge difference between both RPN values of the components; however, it is necessary to prioritize corrective action for component 1.

Important efforts have been made within FMEA to overcome the inadequacy of conventional RPN. Particularly fuzzy modeling with a fuzzy If-then rule base, has been recommended in order to overcome the disadvantages. In the investigation of the Fuzzy based FMEA model, a specialist can describe the risk indexed factors such as S, O and D using a fuzzy linguistic path (Bowles & Pelaez, 1995; Chen, 1985).

3. Fuzzy Failure Mode Effect Analysis (Fuzzy-FMEA)

3.1. Significance of the fuzzy logic technique

Fuzzy logic is an appropriate technique which is used to estimate the output response from given input data. There are a wide variety of reasons why business commentators use a fuzzy logic system, these being, among others (Kusumadewi, 2002):

i. The Fuzzy logic concept is very easy to understand. The fundamentals of the mathematics are also uncomplicated in the Fuzzy Interface System.
ii. This is flexible and can tolerate the data if any inappropricy exists in the datasets.
iii. This technique is able to model complex non-linear functions in a short period of time.
iv. This approach can also build up the experience of specialists without the need of additional training.
v. This technique will work on the basis of simple natural language.

3.2. Fuzzy FMEA methodology

According to (Wang, 2008) fuzzy methodology is a significant theory which deals with the breakdown of information. In Fuzzy-FMEA the risk indexed parameters such as Severity (S), Occurrence (O) and Detection (D) are fuzzified with suitable membership functions. This is a knowledge-based approach and can be created with proficiency and knowledge in the form of Fuzzy IF-THEN rules (Tay & Lim, 2006). More sensible and suitable knowledge-based model can be built using expert knowledge and decisions. The fuzzy conclusion is then de-fuzzified to acquire the RPN value. The concepts connected with fuzzy, i.e. Fuzzification, Fuzzy rule base, and De-fuzzification are shown in Fig. 2.

Fig. 3. A typical LHD system at a workshop for maintenance.

(i) Fuzzification

Fuzzification is a process used to transform input parameters into membership degree quantities, which express the input parameters in the form of qualitative linguistic terms (Sharma et al., 2005). Specialist decisions and knowledge can be utilized to describe the degree of membership function for a particular variable. Along with Fuzzification, a fuzzy logic controller acquires input information, known as the fluffy variable, and examines it as outlined by client characterized diagrams called membership functions.

(ii) Fuzzy rule base

The fuzzy rule base explains the level of criticality of a system for each combination of input variables. In general, the combination of input variables can be created in linguistic form, for example, by using rule-based logic like “if – then”, “or – else” etc. This can be created in two different ways namely, (i) Familiarity and proficiency of a specialist (ii) Process of the Fuzzy based model (Yang, 2007). Experts judgment and experience can be used to define the degree of membership function for a variable.

(iii) De-fuzzificationDe-fuzzification is a process of looking at standard results after they have been normally included and that they will be the final output responses of the fuzzy controller. During de-fuzzification, the controller exchanges the fluffy yield into response information (Sharma et al., 2005).

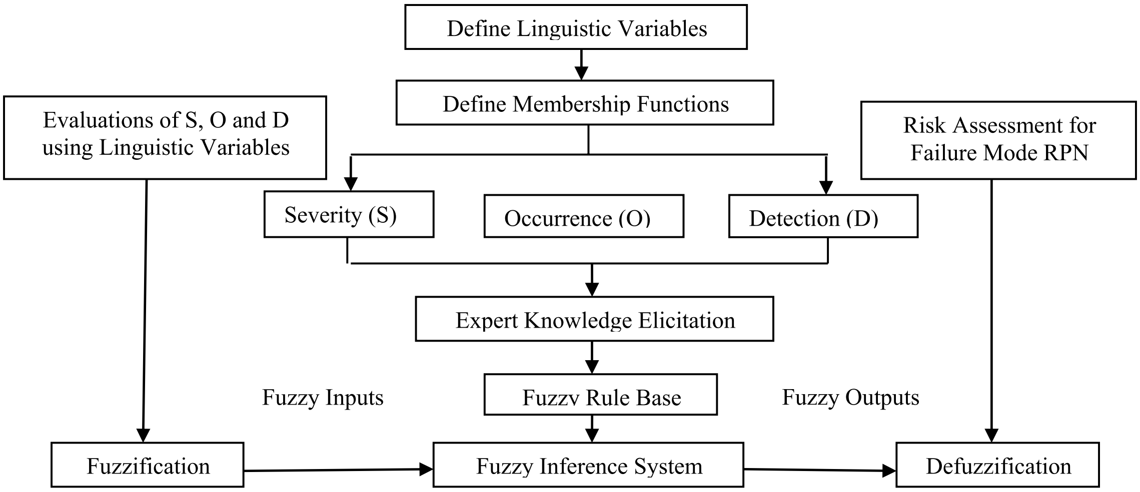


Fig. 2. Flow chart of Fuzzy-FMEA Technique.

Table 2
Root cause analysis of the complex system considered.

Sub system	Potential Failure Mode	Reason for Potential Failure Mode	Effect of Potential Failure Mode	Recommended action
SSBr	Brake pedal broken (F1)	Wear and tear, lubrication and lack of daily inspection	Prone to accidents	Brake system need to be cleaned every 1000 h
SSTy	Tyre punctures (F2)	Poor underfoot conditions, overloading, improper inflation	The machine was stopped for repair	Remove and send to re-buttoning agencies
	Tyre burst (F3)	Incorrect fitment, excessive torque, concerning or rim spin, incorrect or defective rim conditions	The machine was stopped for repair	Remove the tyre and replace with a new one
SSH	Directional solenoid connector spool damage (F4)	Metal particles trapped in spool	Flush entire hydraulic system post failure of any hydraulic component	Hydraulic oil needs to be cleaned & flushed every 1500 hrs
	Cylinder bearing damaged (F5)	Wear and tear	The hydraulic system will be damaged	Check for greasing and if require remove and replace with a new one
	Lift cylinder piston became bent and hydraulic oil leakage (F6)	Piston rod eye broken and during lowering the boom, piston rod bent	Poor operating condition and Deterioration	Life of the piston rod is not tracked. Strengthen the design in a new type
	Cracks on the cylinder (F7)	Lubrication, wear and tear	Cylinder damage	Training to be conducted for maintenance crew about Contamination Control
SSE	Engine mounting bracket (Rear Supporting Blocks) broken (F8)	Continuous impact and stress concentrated on the weak portion of the supporting block	Misalignment with adjacent components led to breakage of torque converter regulator	Replace with a modified design bracket
	Steering function not working (F9)	Internal failure of the directional spool due to aging	Machine directions are not possible to control	Replace steering main valve
SSEl	Cable drum sprocket, chain fail (F10)	Lack of greasing, wear and tear	The machine is not operable	Greasing should be done on a daily basis
	Cable reel fail (F11)	Improper maintenance, aging factor	The machine is not operable	Remove and replace with a new one
SSTr	Transmission oil leakage (F12)	Breakage of torque converter regulating valve	The engine dropped slightly from its mounting position	Replace with a new regulating valve
SSM	Swing lever eye broken (F13)	The machine ran without greasing for the last 8 consecutive shifts and machine is regularly operated by operators	The machine is not operable	Operator refresher training to be conducted and greasing of the machine must be done every day
	Boom broken (F14)	Overloading, Lifting cylinder breakage and poor welding at the joints	Production stoppages	Remove and replace with a strengthened one
	Bucket broken (F15)	Poor welding at the joints	Production stoppages	To be welded at the required sections
	Knuckle joint broken (F16)	Broken due to poor design, week strength, and overload	Production stoppages	Remove and replace with a strengthened one

Table 3
General structure of risk indexed parameters and RPN metrics.

Sub system	Failure type	Severity (S)	Occurrence (O)	Detection (D)	RPN
SSE	F1	X11	X12	X13	RPN1
SSBr	F2	X21	X22	X23	RPN2
SSTy	F3	X31	X32	X33	RPN3
.	.	.	.	.	.
.	.	.	.	.	.
SSH	F9	X91	X92	X93	RPN9
SSM	F10	X101	X102	X103	RPN10

Table 4
Estimated values of risk indexed parameters and RPN metrics.

Sub system	Failure Type	Severity (S)	Occurrence (O)	Detection (D)	RPN
SSBr	F1	2	6	3	36
SSTy	F2	8	8	2	128
	F3	7	8	1	56
SSH	F4	2	9	2	36
	F5	3	8	6	144
	F6	2	8	6	96
	F7	2	4	6	48
SSE	F8	7	4	2	56
	F9	4	6	7	168
SSEl	F10	8	3	4	96
	F11	8	2	4	64
SSTr	F12	3	8	3	72
SSM	F13	5	4	1	20
	F14	9	3	2	54
	F15	9	4	2	72
	F16	8	3	2	48

4. Case study

The field study was carried out in an Indian underground metal mine located in the North East of the country. The extraction of metal is performed by drilling and blasting and the extracted ore is transported through LHD systems from the point of the mined area to the primary crushing process point. It is also known as a scoop cable car or loaders in underground mining operation. A typical LHD machine is shown in Fig. 3.

5. Results and discussion

5.1. Conventional FMEA

In this investigation the Sandvick brand LHD machine LH517 make was considered for the risk analysis. Two years of breakdown details were taken into consideration for the analysis. On the basis of the type of failure, the machine was classified into seven subsystems (Table 2), i.e. Subsystem of Engine (SSE), Subsystem of Braking (SSBr), Subsystem of Tyre (SSTy), Subsystem of Hydraulics (SSH), Subsystem of Electrical (SSEl), Subsystem of Transmission and Subsystem of Mechanical (SSM) (Raju, Govinda, & Murthy, 2018). All the functional failures of the LHD machine with potential failure modes of Fi,j are given in Table 4. RPN values of conventional FMEA were computed (Table 5) with the product of S, O and D metrics. On the other hand, an "If – Then" rule base is created using fuzzy inference (FIS), which after de-fuzzification generates the fuzzy risk priority number (FRPN). The development of the Fuzzy-FMEA assessment model was made by utilizing MATLAB 7.0 software. Some parts of the potential failures of the LHD system are provided in Fig. 4 and a fishbone diagram for Root Cause Analysis (RCA) of the LHD is provided in Fig. 5.

The proposed Fuzzy-FMEA approach provides information on possibility of occurrence of the various potential failure modes with identical RPN values. This helps to reduce the burden of the prioritization of RPN rankings. In general, it was assumed that all the risk indexed parameters are equally important. The value of RPN with "n" number of failure modes is estimated from the following expression (Zafiropoulos & Dialynas, 2005; Zimmermann, 1996):

$$\text{RPN} = \prod_{i,j=1}^{n} X_{ij} \tag{1}$$

Where $1 \le i \le n$; $1 \le j \le n$;

Let ‘Xij’ indicate the position of S, O, and D of failure mode ‘Fi’, where $i = 1, 2, 3 \ldots n$ and $j = 1, 2, 3 \ldots n$.

Xij accurately receives the positions of 1–10 sequentially. The quantitative scale of ranking for S, O and D are given in Tables 1–3.

The prioritization of risk indexed parameters are evaluated with a three-stage process;

i. Critical Failure Mode Index (CFMI)

CFMIi,j = min [max (S11. S12, S13⋯S1n-1,S1n), max (O11, O12, O13⋯O1n-1, O1n) and
max (D11, D12, D13 … D1n-1, D1n)]

ii. Risk Priority Code (RPC)

RPCi,j = Ni,jWhere Ni,j indicates the number of samples or failures in the row consequent to “i,j” for which Xi,j ≥ CFMIi,j

iii. Critical Breakdown Mode (CBM)

CBMi = The breakdowns consequent to max. Ni,j.

The ranking of S, O, and D are assigned on the basis of expert decisions in a range of 1–10 scale. RPN values were calculated for each individual potential failure mode with the multiplication of risk indexed parameters (S, O, and D). The general structure of risk indexed parameters and RPN metrics are given in Table 3 and the estimated

Table 5
Comparison of conventional FMEA and Fuzzy FMEA RPN values.

Sub system	Failure type	Conventional FMEA RPN	C-RPN ranking	Fuzzy FMEA RPN	F-RPN ranking
SSBr	F1	36	14	78.3	11
SSTy	F2	128	3	108	4
	F3	56	9	76.1	12
SSH	F4	36	15	67.6	15
	F5	144	2	142	1
	F6	96	4	142	2
	F7	48	12	93.7	5
SSE	F8	56	10	69.1	14
	F9	168	1	117	3
SSEl	F10	96	5	87.9	6
	F11	64	8	87.9	7
SSTr	F12	72	6	76.1	13
SSM	F13	20	16	32	16
	F14	54	11	80	8
	F15	72	7	80	9
	F16	48	13	80	10

Replacement of Bucket Attachment (Boom)
Hose Failure
Electric Control Failure
Tyre Failure/Puncture
Bucket Attachment System Failure
Steering Direction Main Spool
Lift Cylinder Rod Broken
Engine Supporting Block Broken

Fig. 4. Some potential failed parts of an LHD system.

metrics of RPN corresponding to the risk indexed parameter rankings are given in Table 4.

5.2. Fuzzy-FMEA

In this analysis, three factors were considered as input factors for the fuzzy system. These were evaluated using well defined "If – Then" rules prepared in the MATLAB Fuzzy logic toolbox. The membership function was derived, initially, to produce the fuzzy rule base. The MATLAB Rule Viewer was kept open throughout the reproduction procedure and can be utilized to get to the Membership Function Editor and Rule Editor. The function Rule Editor is used to edit the list of rules, which characterizes the conduct of the framework. Input variables/membership functions can be added using the Fuzzy Interface System (FIS) Editor.

The outputs of the RPN fuzzy values are categorized into nine interval classes: Hazardous/Very High –V.H, High-H, Moderate-M, Moderately Low-ML, Moderately High-MH, Low-L, Very Low-V.L, Remote-R, Remotely High-RH and Remotely Low-RL. The membership function of the output variable and its parameters can be determined based on the type of curve used (Fig. 6).

The resulting fuzzy input is evaluated using the fuzzy rules (IF-THEN rule). The input variables used are S, O and D, with five levels (Hazardous/Very High (V.H), High (H), Moderate (M), Low (L) and None (N)) to obtain 125 fuzzy rule base combinations. The combination of this FMEA fuzzy rule base is as in the example below

Combination of the rule base in fuzzy FMEA:

i. IF Severity is L and Occurrence is M and Detection is L THEN FRPN is L
ii. IF Severity is H and Occurrence is H and Detection is H THEN FRPN is H Critical
iii. IF Severity is H and Occurrence is H and Detection is V.H THEN FRPN is M
iv. IF Severity is L and Occurrence is V.H and Detection is V.H THEN FRPN is L
v. IF Severity is M and Occurrence is M and Detection is M THEN FRPN is H Critical
vi. IF Severity is L and Occurrence is M and Detection is M THEN FRPN is V.H Critical
vii. IF Severity is L and Occurrence is M and Detection is M THEN FRPN is H
viii. IF Severity is H and Occurrence is V.H and Detection is V.H THEN FRPN is M
ix. IF Severity is M and Occurrence is L and Detection is L THEN FRPN is V.H Critical
x. IF Severity is V.H and Occurrence is L and Detection is H THEN FRPN is H

xi. IF Severity is H and Occurrence is M and Detection is H THEN FRPN is M
xii. IF Severity is L and Occurrence is H and Detection is H THEN FRPN is M
xiii. IF Severity is M and Occurrence is L and Detection is V.H THEN FRPN is N
xiv. IF Severity is V.H and Occurrence is L and Detection is V.H THEN FRPN is L
xv. IF Severity is V.H and Occurrence is L and Detection is H THEN FRPN is M
xvi. IF Severity is H and Occurrence is L and Detection is V.H THEN FRPN is L

The formulation of the fuzzy rule ("If – Then" rule) is done by considering the severity value is to be most decisive input for the fuzzy RPN value, so if the Severity (S) value is Very High (VH) then the fuzzy RPN value is also Very High (VH), regardless of the value obtained for Occurrence (O) and Detection (O). The resulting fuzzy RPN value indicates the priority level of risk to be addressed. High fuzzy RPN values indicate that the risk should have greater priority. The calculation of the RPN fuzzy value is performed using MATLAB.

(i) Input Variables

The utilized input variables in the analysis were the Severity, Occurrence and Detectability of a failure mode (Fig. 7). In general, the term severity describes the severity/risk/hazard level of the failed part/component. In accordance with the level of significance, severity ranking should be allotted in a 1 to 10 point scale. The level in the severity scale can be estimated on the basis of the familiarity and proficiency of the FMEA specialist. Occurrence is the probability of an exact failure happened during a considered time period. This can be estimated on the basis of the frequency of the occurrence of a breakdown. Occurrence ranking is also given a severity ranking using a 1 to 10 point scale. The value 10 represents the highest probability of occurrence and similarly and, 1 the lowest probability of occurrence. Detectability defines the likelihood of the detection of a failure mode and it can also be expressed as the ability of a person to detect the potential breakdown mode and its consequence (Rengith & Madhavan, 2018). Detectability can also be estimated using a 1 to 10 point scale. The lowest value of dectectability can be assigned when there is no current control action for the failure mode. These parameters can be used to estimate the risk priority number (RPN). The criticality of the component can be decided on the basis of the prioritization of a failure mode (Zadeh & Desoer, 1965).

(ii) Rule Editor and Rule Viewer

The Rule Editor is a MATLAB-based logic unit which helps to add the rules in a linguistic form. The dependency of the output parameter should be dependent upon the given linguistic format input data. The training process was performed in MATLAB based fuzzy analysis for the created combination of input rules (Fig. 8).

Rule viewer is generally used to exhibit the image of the response in the MATLAB Fuzzy interface system. It is also used to demonstrate how the rules are fuzzyfied and how the individual membership function shapes are influencing the results, as shown in Fig. 9. Figs. 6 and 7 show that one enters inputs through the input edit window and the output is then obtained.

(iii) Rule Viewer and Surface Viewer

The Surface viewer (Fig. 10) helps to view the dependency of the output on one or two of the inputs, such as severity and detection (Rengith & Madhavan, 2018). In this analysis, the presented surface viewer is a three dimensional mapping view with severity, detection and FRPN. From the plot it was noticed that the maximum amount of dependency of FRPN (142) was obtained for the severity (3) and detection (8) risk indexes.

5.3. Comparison of conventional FMEA and fuzzy FMEA results

The priority ranking of conventional FMEA and Fuzzy based FMEA for the analyzed machine is shown in Table 5. The prioritization of the

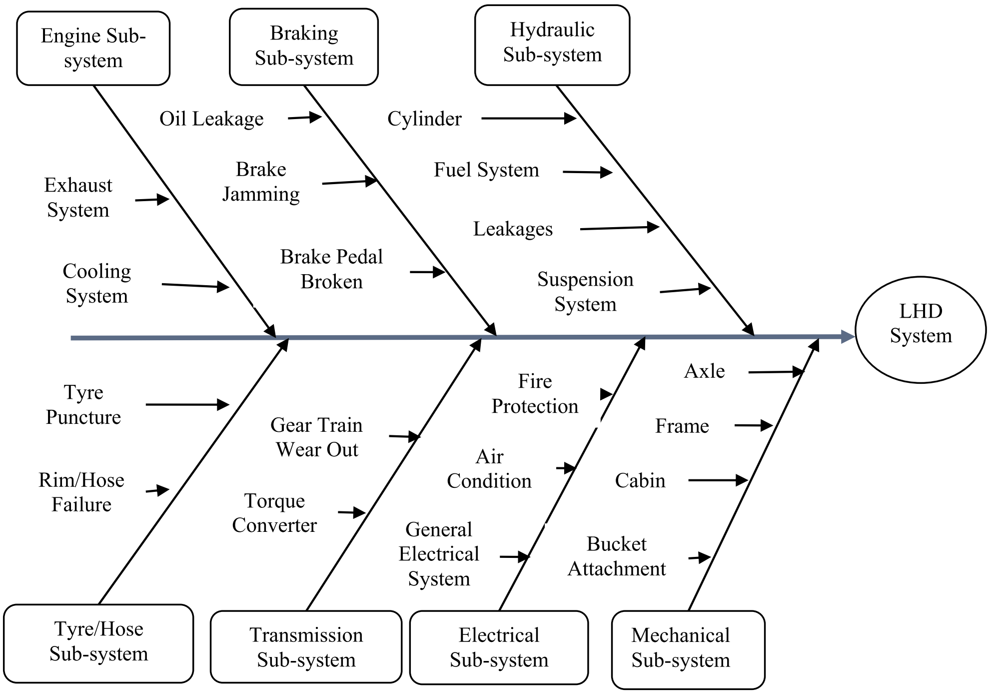
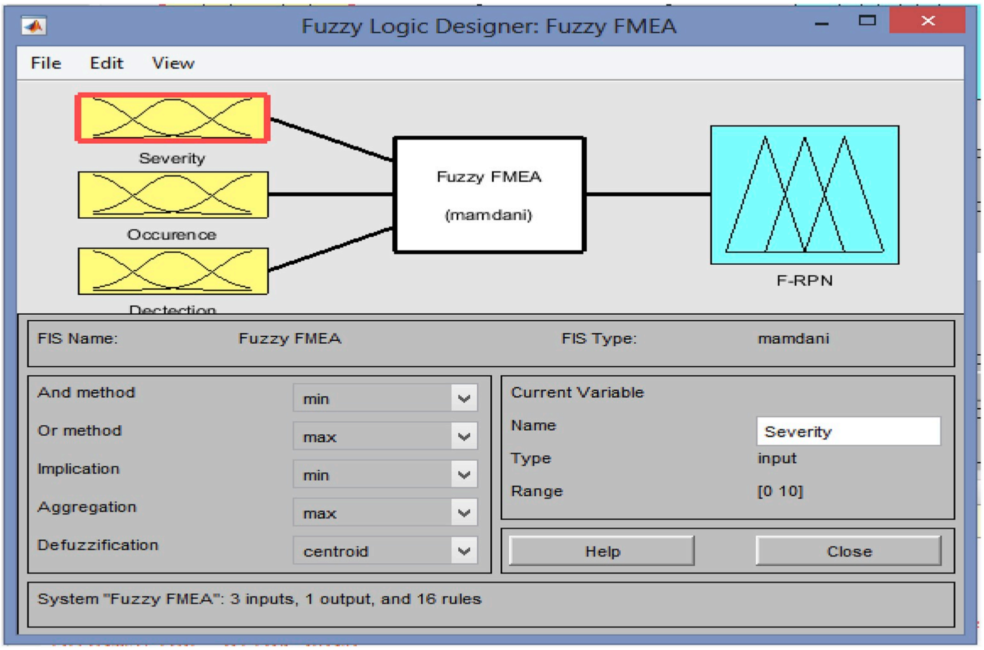


Fig. 5. Fishbone diagram for the Root Cause Analysis (RCA) of the LHD system.

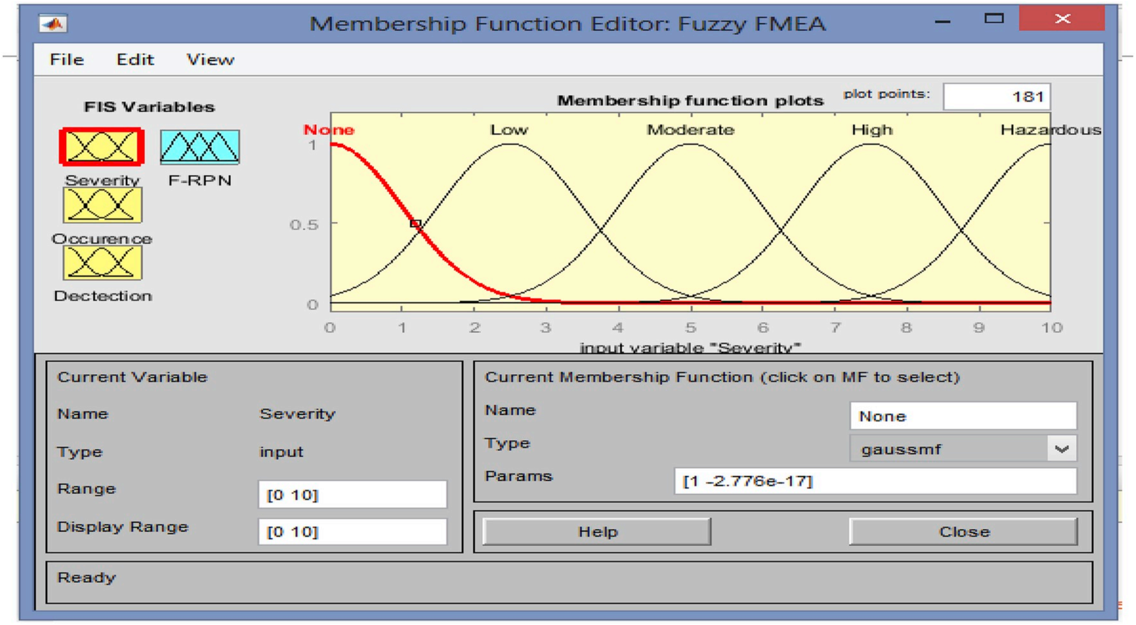


FIS Name: Fuzzy FMEA
FIS Type: mamdani
And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification: centroid

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

System "Fuzzy FMEA": 3 inputs, 1 output, and 16 rules

Fig. 6. FIS editor.



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: None
Type: gaussmf
Params: [1 -2.776e-17]

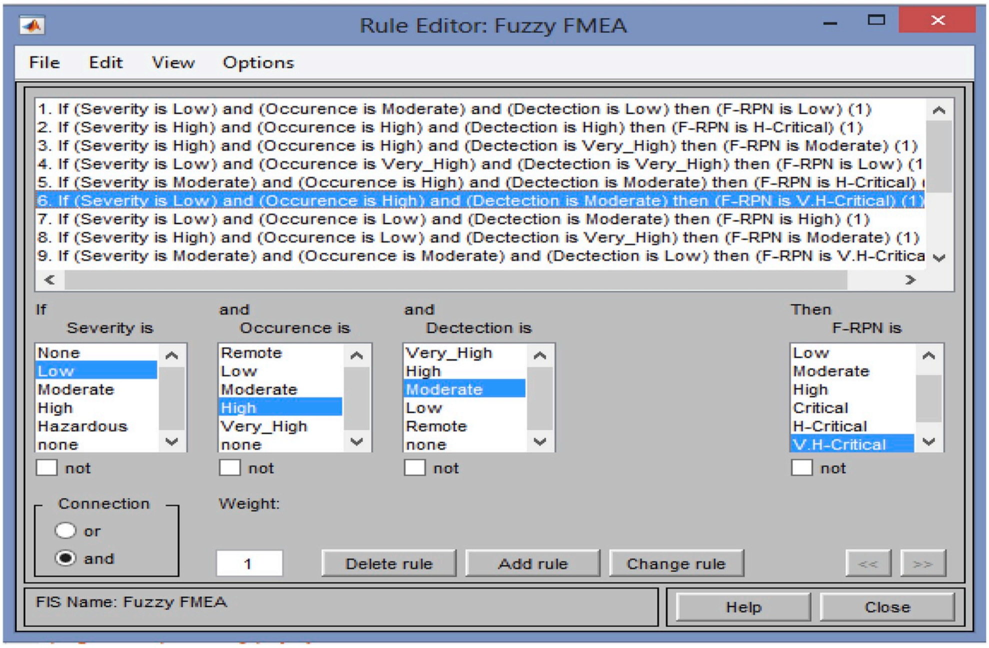
Ready

Fig. 7. Membership function editor.

failure modes or rankings of C-RPN and F-RPN was made on the basis of computed RPN results. These were predicted by the product of risk indexed parameters such as S, O and D in the conventional FMEA approach. MATLAB based RPN values were obtained directly from the fuzzy interface.

6. Conclusions

Reliable equipment must remain in good condition over time and free from breakdowns. The unexpected occurrence of breakdowns are a major cause for a drop in performance of capital intensive equipment. These breakdowns occur due to a wide variety of reasons, such as bad managerial practices, in-efficient maintenance and operational actions and harsh working environments. Hence, there is a requirement to analyze the failure behavior of a system in order to identify the key influencing factors on the equipment performance. In this research failure behavior of LHDs was analyzed within each individual potential failure mode. This analysis provides information on several aspects, such as the present working condition of the machines, reasons for the occurrence of failure modes, influence of failure modes on equipment performance and reliable life etc. Also, these investigations assess the forecasting of necessary managerial practices or control measures like possible design modifications and the replacement of components to ensure the required level of availability and utilization. Results of the

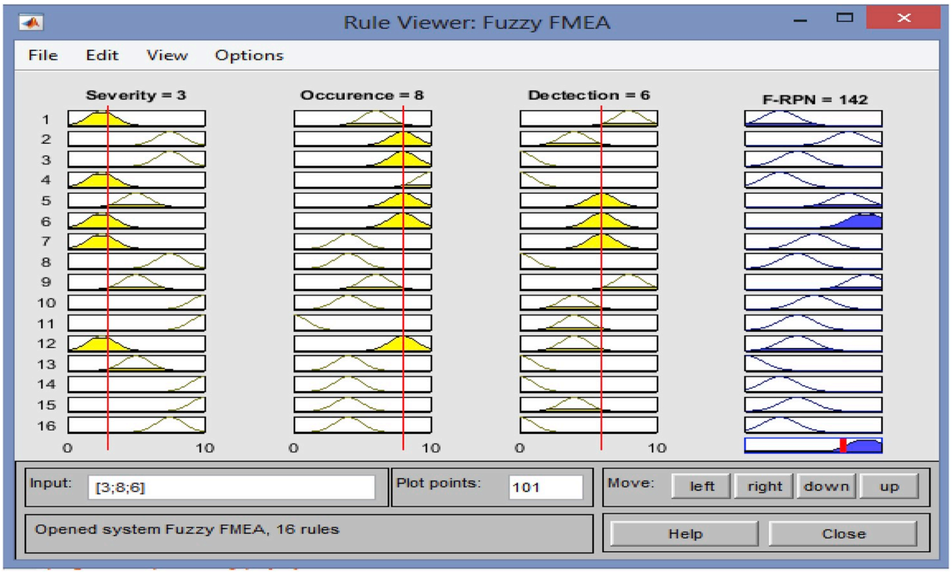


1. If (Severity is Low) and (Occurence is Moderate) and (Dectection is Low) then (F-RPN is Low) (1)
2. If (Severity is High) and (Occurence is High) and (Dectection is High) then (F-RPN is H-Critical) (1)
3. If (Severity is High) and (Occurence is High) and (Dectection is Very_High) then (F-RPN is Moderate) (1)
4. If (Severity is Low) and (Occurence is Very_High) and (Dectection is Very_High) then (F-RPN is Low) (1
5. If (Severity is Moderate) and (Occurence is High) and (Dectection is Moderate) then (F-RPN is H-Critical)
6. If (Severity is Low) and (Occurence is High) and (Dectection is Moderate) then (F-RPN is V.H-Critical) (1)
7. If (Severity is Low) and (Occurence is Low) and (Dectection is Moderate) then (F-RPN is High) (1)
8. If (Severity is High) and (Occurence is Low) and (Dectection is Very_High) then (F-RPN is Moderate) (1)
9. If (Severity is Moderate) and (Occurence is Moderate) and (Dectection is Low) then (F-RPN is V.H-Critica

Weight: 1

FIS Name: Fuzzy FMEA

Fig. 8. Rule editor.



Input: [3;8;6]

Plot points: 101

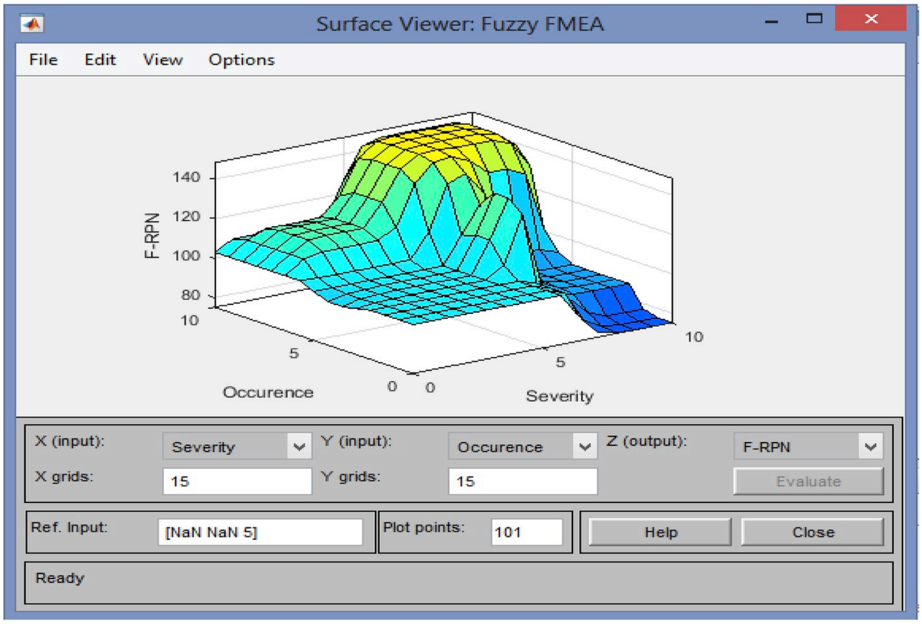
Opened system Fuzzy FMEA, 16 rules

Fig. 9. Rule viewer.

calculations and analysis are explained as follows:

i. From the results (Table 4) of conventional FMEA it was noticed that the highest level of RPN value was obtained for SSTy (128; F2-3), SSH (144; F5-2) and SSE (168; F9-1) sub-systems. RPN value provides guidance for failure mode prioritization and can be utilized to minimize the severity level and failure mode occurrence. It will also be useful when recommending necessary modification actions for the improvement of a design or process. It was concluded that a significant level of severity and maximum probability of occurrence of potential breakdowns are the reasons for greater levels of RPN value. If the RPN value is high, then the effect of the failure mode is more critical. This effect reduces the life of the equipment and overall mine production. This can be improved by conducting Preventive Maintenance (PM) with in time intervals, and by providing proper training and awareness on each individual component to the maintenance and operating crew.

ii. The MATLAB based Fuzzy rule base system was used in this study for data analysis and validation. Fuzzy-FMEA technique can also help to prioritize the failure modes accurately if two or more have an equal ranking. From the results (Table 5), a similar kind of RPN value was found for the failure modes of F9, F5, F11, F13 and F14 (i.e.,1, 2, 8, 16,11) and the rank 1 was assigned for the highest value of RPN. The failure modes with highest RPN values were treated as critical parts and therefore, it was suggested that the highest value of RPN needs to be paid attention by undertaking necessary repair or replacement actions to improve the lifespan of the equipment. In some cases replacement of the component may also be required when it is not possible to repair the failed parts at the time of PM. These failures are called censored failures and these components must be replaced at the time of Corrective Maintenance (CM) with appropriate high strength components.



X (input): Severity
Y (input): Occurence
Z (output): F-RPN
X grids: 15
Y grids: 15
Ref. Input: [NaN NaN 5]
Plot points: 101
Ready

Fig. 10. Surface viewer.

iii. In this investigation, Fuzzy-FMEA technique was proposed in order to prioritize the potential failure mode rankings. This technique can also assess the hazard and criticality of machine components by characterizing the MATLAB database of Fuzzy IF-THEN guidelines. This technique considers vague and ambiguous data in the assessment procedure. It was concluded that a rule-based Fuzzy FMEA analysis provides strong evidence that the proposed methodology is logically useful for prioritizing RPN values. This analysis not only determined the restrictions connected with the conventional FMEA approach for RPN, it also estimated the reasons for the occurrence of potential failure modes in a complex repairable system. In addition, the fuzzy rule base should also be amended or updated when more failure information exists.

Conflict of interest

None declared.

Ethical Statement

Authors state that the research was conducted according to ethical standards.

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