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ORIGINAL ARTICLE

Fuzzy methodology application for risk analysis of mechanical system in process industry

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Abstract This research work reviews and expounds application of fuzzy methodology based integrated approach for risk analysis of milling system in Sugar Plant. As sugar plant is a complex process system, therefore, its effective maintenance planning without proper risk identification and prioritization is a major issue. In this research work, conventional FMEA approach was used for prioritizing critical components based on risk priority number (RPN). To remove limitations of conventional FMEA, fuzzy decision support system and fuzzy grey relation analysis were used for estimating RPN scores. These scores were compared with conventional RPN scores for realistic prioritization and decision making. From analysis, twenty-four (24) causes of failures were identified for milling system of sugar plant. Out of those, fourteen (14) causes of failure were found critical to the system. The excessive cyclic loading on shaft, impact loading on tear rod, improper lubrication, foreign particle inclusions, insufficient gaps and pressure between rollers, loose fittings and couplings, wear and tear of nut and bolt were some of the causes of failures with high prioritization. As immediate attention was required, these results were forwarded to the system analyst and management of sugar industry for intelligent and effective maintenance planning and implementation.

Keywords FMEA · Fuzzy FMEA · Fuzzy inference system · Grey relation analysis (GRA)

Abbreviations

FMEA	Failure mode and effect analysis
FRPN	Fuzzy risk priority number
FIS	Fuzzy inference system
CE	Concurrent engineering
RPN	Risk priority number
GRA	Grey relational analysis
TCD	Tons of cane per day
TFN	Triangular fuzzy number

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1 Introduction

India is going through a technological and economic transformation phase. It is estimated that by year 2025, India will be third largest consumer market in world ("The New Indian: The Many Facets of a Changing Customer (2017) [online] https://www.bcg.com/publications/2017/marketing-sales-globalization-new-indian-changing-consumer.aspx (accessed March 20 2017)," n.d.). Due to intense competition of domestic products with international one's, sophisticated machines and systems are used to produce high quality products. This has resulted in real world operating system to become complex, compact and operating at maximum reliability, availability, efficiency and at reduced risk, which is increasing cost of maintaining complex systems. The cost of maintenance of machinery and equipment is estimated in the range of 15–40% of total cost of production (Dunn 1987). This cost can be reduced by effective maintenance planning that will help organization to make financial saving (Eti et al. 2006). For proper maintenance planning identification and prioritization risk is important (Panchal and Kumar 2017). Risk is defined as possibility of loss. It is omnipresent and may or may not happen. Risk analysis founds its application in diverse fields and is used as an important decision support tool. For real world processing systems, high reliability, availability and maintainability respectively, is a big concern (Panchal et al. 2018a; Saini and Kumar 2019). Highly automotive systems, having compact size and high complexity of operation are some of the reason for this issue.

In past, several failures under different conditions: whether gas leakage in Union Carbide Plant, Bhopal 1984; Nuclear disaster, Chernobyl, 1986; Oil pipeline leakage, Nigeria 1998; NTPC Boiler blast, India, 2017 and many more have been observed. It resulted in monetary, human life and environmental losses. Difficulty in risk identification and assessment by maintenance engineers and reliability analyst is one of the reasons for these mishappenings.

India is leading producer of sugar cane in world. India has 5.2 million hectares of area under sugar cane production with a total production of 423 million metric tonnes ("http://agriexchange.apeda.gov.in/MarketReport/Reports," n.d.). Sugar industry in India produce 35.5 million tonnes. Other than sugar produced, cane tops, bagase, molasses and filter muds are by-products of sugar industry. Bagase is used for electricity generation, particle board production, paper production etc. Cane tops are used as good quality fodder. Filter muds are used as fertilizer in agriculture sector. Molasses is used for producing alcohol, acetic acid, citric acid, yeast etc. Sugar Mill consist of milling, clarification, filtration, evaporation, crystallization, separation, refining and cogeneration subsystems respectively. Milling station is one of the important subsystems of plant where cane is loaded, prepared, juice is extracted and bagase is produced. High availability of this subsystem without failure is essential for operation of plant. It depends on high reliability of its constituent systems i.e. gear drive, cast steel shaft, cast iron shell, scrapper and macerator. Failure of any one these elements will make milling system to stand still and lead to monetary losses as all the subsequent operations of the sugar plant are forced to stop. It can also lead to severe accidents that may cause causalities to humans and loss to facility. All these events can be prevented by effective maintenance planning, which makes it an important process. Assessment and prioritization of risk is not only important to assist maintenance planning of the system but also for resolving availability and reliability issues, and for improving safety of resources. Fault tree analysis, petri-nets, cause and effect diagram and Delphi method are some of the popular techniques used for risk identification (Panchal and Kumar 2016; Mangla et al. 2016; Panchal and Srivastava 2019; Moktadir et al. 2018). The risk analysis process using FMEA process is based risk priority number (RPN). It is a product of frequency of occurrence, severity and probability of non-detection. The conventional FMEA is subjected to inherent limitations. The RPN is based on expert's judgement. There are situations when experts are either biased or unable to give proper judgment. In some cases, the relative weights of frequency of occurrence, severity and probability of non-detection are not properly defined (Panchal and Kumar 2017). These situations induce uncertainty in risk analysis process. Risk analysis using knowledge-based, grey system theory based, fuzzy system based FMEA approach may be used to overcome this issue. Many related studies have been done on systems and processes using these approaches. Guimaraes and Lapa (2004) expounded fuzzy inference based risk assessment of nuclear power plant. Kumru and Kumru (2013) applied fuzzy based FMEA approach to improve purchasing process in hospital. Mariajayaprakash and Senthilvelan (2013) proposed integrated methodology of FMEA and Taguchi techniques for risk identification and optimization of sugar mill boiler. Mariajayaprakash and Senthilvelan (2014) further expounded same approach for risk analysis and optimization of screw conveyor in sugar mill boiler. Geramian et al. (2017) applied fuzzy rule based expert system for risk prioritizing. The study was conducted on compact car door producing company in Iran. Panchal et al. (2018b) applied fuzzy and grey relation analysis (GRA) based FMEA approach for risk analysis of ammonia synthesis system. Kumar et al. (2019) analyzed potential risk in adopting green supply chain initiatives in pharmaceutical sector. Panchal and Srivastava (2019) applied fuzzy FMEA and Grey theory-based risk analysis approach for prioritizing failure causes of CNG dispensing system. Srivastava et al. (2019) applied fuzzy rule base system for evaluating fuzzy RPN for water treatment plant.

Considering these studies of risk analysis, in present study, fuzzy methodology based integrated approach of FMEA and GRA has been exemplified for risk analysis of milling plant in sugar mill. This case study helps in achieving various objectives:

(1) Risk identification of systems and subsystems using cause and effect diagram.
(2) Risk prioritization using:
    (a) Conventional FMEA approach.

(b) Fuzzy inference system based FMEA approach.
(c) Fuzzy GRA based approach.

(3) Comparing the results and recommend suggestions.
(4) Correlation and Sensitivity Analysis.

In this paper application of fuzzy based FMEA and GRA approach respectively is used to prioritize the failure cause. The fuzzy based approach is used to remove limitations of conventional FMEA. The reason for selecting fuzzy based GRA approach are:

(1) Simplicity in calculation and understanding.
(2) Use of original data.
(3) Removal of uncertainty arising due to imprecise and ambiguous judgement.

The failure causes for system and subsystem are identified using cause and effect diagram. The paper is structured as, Sect. 2 discuss various approach used for risk analysis, Sect. 3 explain sequential steps used for analysis, Sect. 4 shows the application of proposed integrated approach, Sect. 5 discuss analysis of result obtained and Sect. 6 concludes the research work with research contribution, managerial implication, limitation and future scope of the present work.

2 Literature review

This section summarizes proposed approaches based on FMEA, application of FIS, application of GRA and proposed integrated approaches.

2.1 Approaches based on FMEA

This technique was proposed by US Military for assessment of weapon system reliability in the year 1949. Further this technique was used by NASA for risk assessment of space program (Apollo Mission) in the year 1960. In year 1985, an international standard IEC 60112 was published for FMEA to assess system reliability. This technique is extensively used for risk analysis in aviation, automotive, manufacturing, medical, power plants (nuclear, thermal, hydraulics, wind energy, solar energy etc.), paper plant and food process industries respectively. It is a systematic and knowledge-based approach (Amuthakkannan et al. 2008), which is used to assess possible causes of failure, its frequency, severity on system and detection probability (for systems and sub-systems), so that effective and timely maintenance planning leads to avoidance of failure and improve availability of system. The product of these variables is called risk priority number (RPN), used for risk analysis and prioritization (refer Eq. 1).

$$RPN = O_c \times S_r \times D_n \quad (1)$$

Cause and effect diagram or Fish bone diagram or Ishikawa diagram is an effective technique for assessing cause of failure associated with system under study. The system under study is placed on extreme right end of a horizontal line. The sub-systems or any identified source, are placed at branches protruding out of horizontal line. The failure causes for each sub-system are directed towards it (refer Fig. 1).

2.2 Approaches for overcoming limitation of FMEA

In industrial systems, risk of a system failure is always there (Panchal and Srivastava 2019). Due to its complexity and uncertainty involved in conventional FMEA technique, evidence-based approach, fuzzy methodology-based approach is used for risk analysis. The present research work focuses on integration of fuzzy methodology with conventional FMEA using fuzzy inference system and grey relation approach respectively.

2.2.1 Application of fuzzy inference system

Fuzzy set theory has been used in research work to take care of imprecise and vague judgment resulting in uncertainty. The linguistic variables are used to by expert to represent events that are imprecisely and vaguely defined. For a particular event if an expert is not able to give judgement explicitly, then these linguistic variables are used. Linguistic variables like 'almost none, low, medium high, very high etc.', can be used for transforming subjective knowledge into quantitative terms. This transformation requires a well-defined scale (refer Table 1). These linguistic variables are defined by fuzzy set membership function. There are different types of membership function e.g. triangular, trapezoidal, normal etc. Mostly, triangular and trapezoidal membership functions are used for the sake of their simplicity and ease of computations.

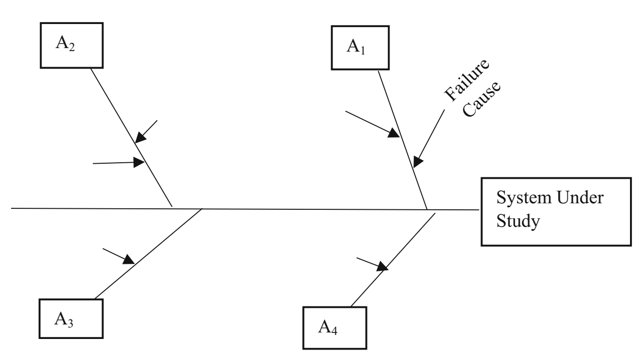

Fig. 1 Cause and effect diagram

Table 1 Linguistic scale

Rating	Meaning	Severity (S_r)	Occurrence (O_c)	Not detection (D_n)
1	Almost none	No breakdown of any component	Failure is very unlikely to happen	Detected 9/10 time
2, 3	Low	Minor breakdown of component which can be fixed with some adjustments	These failures are relatively rare	Detected 7/10 times
4, 5, 6	Medium	Breakdown of components which can be replaced without any harm for the whole machine	Occasional	Detected 5/10 times
7, 8	High	Permanent damage of component but n harmful for machine but not people	More frequent failures	Detected 2/10 times
9, 10	Very high	Hazardous/permanent damage of the component which may cause harm to people	These are common failures	Detected 0/10 times

Triangular membership function (TMF) is defined by Eq. 2.

$$\mu_{\tilde{T}}(x) = \begin{Bmatrix} \frac{x-a}{b-a} & a \leq x \leq b \\ \frac{x-c}{b-c} & b \leq x \leq c \\ 0 & otherwise \end{Bmatrix} \quad (2)$$

where a, b, c is the upper, mean and lower bound respectively and $\tilde{T}$ is TFN represented by (a, b, c).

Trapezoidal membership function is defined by Eq. 3.

$$\mu_{\widehat{Tr}}(x) = \begin{Bmatrix} 0, & (x > d \ or \ x < a) \\ \frac{x-a}{b-a}, & a \leq x \leq b \\ 1, & b \leq x \leq c \\ \frac{d-x}{d-c}, & c \leq x \leq d \end{Bmatrix} \quad (3)$$

where a, b, c, d is the upper, mean (one), mean (two) and lower bound respectively and is TFN represented by (a, b, c, d).

The first step in process is fuzzification of input and output variables by defining membership functions. Then if–then rules are made in rule base (refer Eq. 4).

$$R_i: \ If \ x \ is \ Q_i \ then \ y \ is \ S_i \quad where \ i = 1, 2, 3 \ldots n. \quad (4)$$

If—antecedent that is compared to input, then- precedent that is compared to output. Where, x—input linguistic variable, y—output linguistic variable, Q_i—antecedent linguistic constant, S_i—precedent linguistic constant.

These rules are processed in FIS to get an fuzzified output. Due to simplicity and ease of computation center of area method is used in present research work (refer Eq. 5).

$$\tilde{x} = \frac{\int_{x_1}^{x_2} x\mu_{\tilde{T}}(x)dx}{\mu_{\tilde{T}}(x)dx} \quad (5)$$

where $\mu_{\tilde{T}}(x)$ membership function and $\tilde{T}$ is output fuzzy set.

The output after de-fuzzification will be fuzzy-RPN value. The rules in rule base and FIS serves the purpose of decision support system for the problems involving uncertainty and ambiguity. The process flow for fuzzy decision support system is shown in Fig. 2.

This approach has been used in various applications by the researchers. Xu et al. (2002) applied fuzzy logic based FMEA in the diesel engine system. Guimaraes and Lapa (2004) presented the application of fuzzy FMEA approach for the criticality evaluation of various components of pressurized water reactor chemical and volume control system of a nuclear power plant and also fuzzy inference system for risk analysis in the production of nuclear energy. Further, Yeh and Hsieh (2007) demonstrated the application of fuzzy inference system for a sewage plant. A fuzzy FMEA model for prioritizing the aspects of information security risk was proposed by Silva et al. (2014). Chen et al. (2014) applied integrated approach of fuzzy FMEA and fault tree for prioritization of risk in oxygen enhance combustor. Ilangkumaran et al. (2014) developed an integrated model for assigning the risk priorities/ranking to the risky components of a system in a paper industry. Geramian et al. (2017) exemplified use of fuzzy inference system for risk analysis and prioritization in automobile sector. Panchal et al. (2018a) applied the fuzzy inference system for risk analysis of transmission system of heavy duty vehicle. Mangla et al. (2015) analyzed risk pertinent to adoption of green supply chain practices from industry point of view. Fuzzy AHP approach was used to priority ranking of risk. Mangla et al. (2018) showed the application of fuzzy based FMEA approach in risk analysis of green supply chain (GSC) for better management and sustainable production. Srivastava et al. (2019) exemplified fuzzy based FMEA approach for risk analysis of water treatment plant. Agarwal et al. (2018) applied fuzzy inference based FMEA for risk analysis of water treatment plant.

2.2.2 Application of grey relation method

Grey theory was proposed by Deng (1989). For most of the real-world system, capturing perfect information for model development is impossible. The system information lies

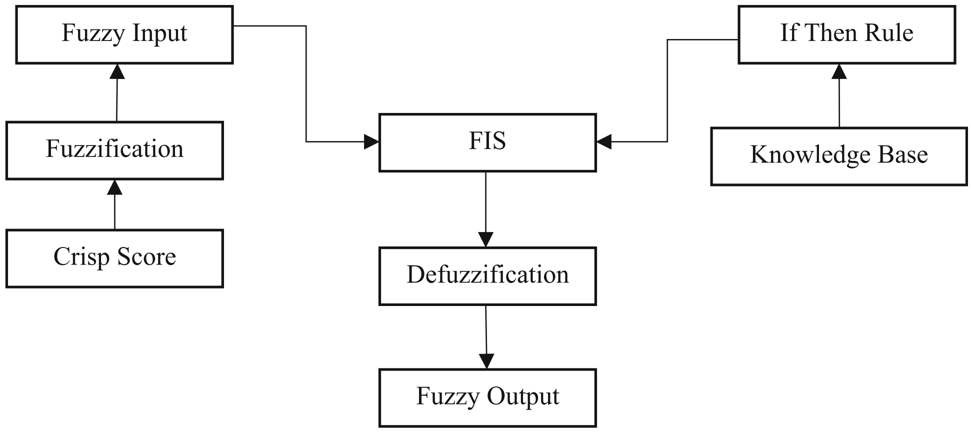

Fig. 2 Fuzzy decision support system

between perfectly white system; for which perfect information is available and perfectly black system; for which no information is available. This system of partial or incomplete information is called as grey system. The grey system theory is one of the powerful tools for solving problems related to prioritization of decision making units (DMU), alternatives, strategies etc. The grey relation analysis (GRA) is part of the grey system. This technique is capable of solving real world problems in diverse fields involving complex interrelationship between attributes, alternatives having incomplete or imprecise information. Multi attribute decision making problems have been solved using GRA technique, like, human resource process (Olson and Wu 2006), facility layout and dispatching rules (Kuo et al. 2008), warehouse location problem (Özcan et al. 2011), selection of advanced manufacturing system (Goyal and Grover 2012), evaluation of innovation competency of aviation cluster in China (Zhu et al. 2012) and resilient supplier selection in electronics supply chain (Rajesh and Ravi 2015). The comparative and standard series in GRA for n decision units is given by Eqs. 6 and 7 respectively (Deng 1989; Panchal and Kumar 2016; Panchal et al. 2018b):

$$Z_0 = [z_0(1), z_0(2), \ldots z_0(k), \ldots z_0(n)] \tag{6}$$

$$Z_i = [z_i(1), z_i(2), \ldots z_i(k), \ldots z_i(n)] \tag{7}$$

where i = 1,2, 3,…, m and k = 1, 2, 3,…, n.

$z_0(k)$ and $z_i(k)$ numbers in standard and comparative series respectively.

$$\text{Comparative Series} = \begin{bmatrix} z_1(1) & z_1(2) & z_1(3) \\ \vdots & \vdots & \vdots \\ z_m(1) & z_m(2) & z_m(3) \end{bmatrix} \tag{8}$$

$$\text{Standard Series} = \begin{bmatrix} z_0(1) & z_0(2) & z_0(3) \\ \vdots & \vdots & \vdots \\ z_m(1) & z_m(2) & z_m(3) \end{bmatrix} \tag{9}$$

$$\Phi = \begin{bmatrix} \Delta_{01}(1) & \Delta_{01}(2) & \Delta_{01}(3) \\ \vdots & \vdots & \vdots \\ \Delta_m(1) & \Delta_m(2) & \Delta_m(3) \end{bmatrix} \tag{10}$$

where Φ is difference of Eqs. 8 and 9 respectively.

The values in these series are defuzzied values of the fuzzy number. In this research work, input variables are defined using trapezoidal fuzzy number. The linguistic variables and corresponding crisp values are shown in Table 2.

The grey relation coefficient (γ) for input variable is calculated by using Eq. 11.

$$\gamma\{z_0(k), z_i(k)\} = \left\{ \underbrace{\min}_{i} \underbrace{\min}_{k} |z_0(k) - z_i(k)| + \zeta \underbrace{\max}_{i} \underbrace{\max}_{k} |z_0(k) - z_i(k)| \right\} \Big/ \left\{ |z_0(k) - z_i(k)| + \zeta \underbrace{\max}_{i} \underbrace{\max}_{k} |z_0(k) - z_i(k)| \right\} \tag{11}$$

The degree of grey relation (Γ) for each risk is calculated by using Eq. 12.

$$\Gamma(z_0, z_i) = \sum_{k=1}^{n} \xi_k \gamma\{z_0(k), z_i(k)\} \tag{12}$$

Table 2 Linguistic variables, symbols and corresponding crisp scores

Linguistic variable	Symbol	Crisp value
Almost none	AN	0.9983
Low	L	2.515
Medium	M	5.015
High	H	7.515
Very high	VH	9.324

where ξ_k is weighting coefficient of for the input variables. It is decided by the expert's judgement or by evaluating it.

2.2.3 Application of integrated approach

Other than the approach mentioned above, there is an increasing trend of integrating various MADM approach for assessing risk prioritization of system. There have been studies of failure analysis on complex system using integrated approach. Tsai and Yeh (2015) proposed a hybrid FMEA and fuzzy inference system for assessing the soldering failures in sources and prioritizing the risk in surface mount assembly. The entropy method was used to evaluate weights of O_c, S_r, D_n. The grey relation approach was used to evaluate the grey relation coefficient and subsequent degree of relationship for prioritizing failures. Zhou and Thai (2016) expounded application of fuzzy FMEA and GRA for relative ranking failure causes for tanker equipment. Mangla et al. (2016) proposed integrated methodology of fault tree analysis and fuzzy AHP for risk assessment in green supply chain of plastic manufacturer. Tian et al. (2018) proposed an integrated approach of fuzzy best–worst, relative entropy and VIKOR (VIsekriterijumska optimizacija i KOm-promisno Resenje) for risk prioritization in grinding wheel system. Moktadir et al. (2018) proposed an integrated framework of Delphi technique and fuzzy AHP. Delphi technique was used for identify risk elements. Fuzzy AHP was used to prioritization of risk.

Milling system is a complex and real-world subsystem of Sugar Mill, where crushing and juicing of sugar cane is carried out. As, all the subsystem are in series configurations, therefore failure at any point will halt the production of sugar. From the reviewed literature, author observe that a number of fuzzy based methodology for risk analysis has been developed for service, process and real time operating systems. But there is either less or no inference of use of fuzzy based FMEA and GRA approach for risk analysis of milling system in sugar mill. The paper seeks to fill this gap by exemplifying this approach for risk analysis of milling system of sugar mill located in northern part of India. The flow chart of research is shown in Fig. 3.

3 Proposed approach

The proposed approach for exemplifying the risk analysis for the present study is shown in Fig. 4.

Steps involved:

- With personal interaction with operators, maintenance analysts and engineer, cause and effect diagram for system under study is made.
- The proper scale is selected and information of O_c, S_r and D_n for FMEA is collected from cross-functional team of experts and log book.
- The RPN values are calculated for conventional FMEA.
- For fuzzy FMEA, input and out-put variables are defined by membership functions, approximated by triangular or trapezoidal fuzzy number. The if–then rules are made in fuzzy inference system (FIS).
- Using these rules output is processed in FIS and converted again into crisp value by using some suitable method. This crisp output will be fuzzy RPN for respective cause of failure. The if–then rule in rule base of FIS will become fuzzy decision support system for any type of input–output variables used in risk analysis.
- The RPN and fuzzy RPN values are prioritized and compared for each cause of failure.

The prioritization is compared by using fuzzy GRA technique. The evaluation process comprises of forming standard and comparative series, forming difference series, calculating grey relation coefficient and subsequently degree of relationship and prioritization causes of failure according to its score. In present research work, two scenarios, equal weights of variable and evaluated weights of variables have been used for estimation of degree of relationship. These are as follow:

(1) *Equal weightage to all the variables* In this case weighing coefficient is taken as 0.33.

(2) *Differential weights* Weight calculation using Wang scale (refer Table 3).

The selection and estimation of weights is important for legitimate results and ranking. The calculation of weights has been done using fuzzy extent analysis approach (Srivastava et al. 2018). For checking the consistency of the results obtained from different stated approach, spearmen rank correlation coefficient has been evaluated. Sensitivity analysis was also performed for priority weights and grey relation coefficient to check the consistency of prioritization results.

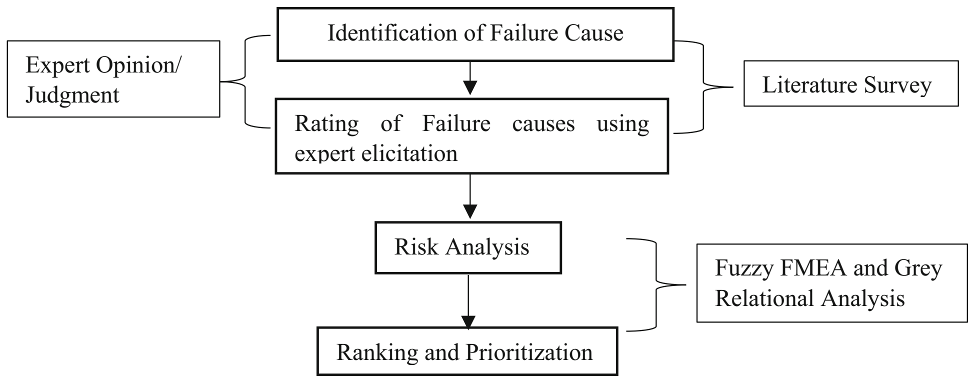

Fig. 3 Flow chart of research

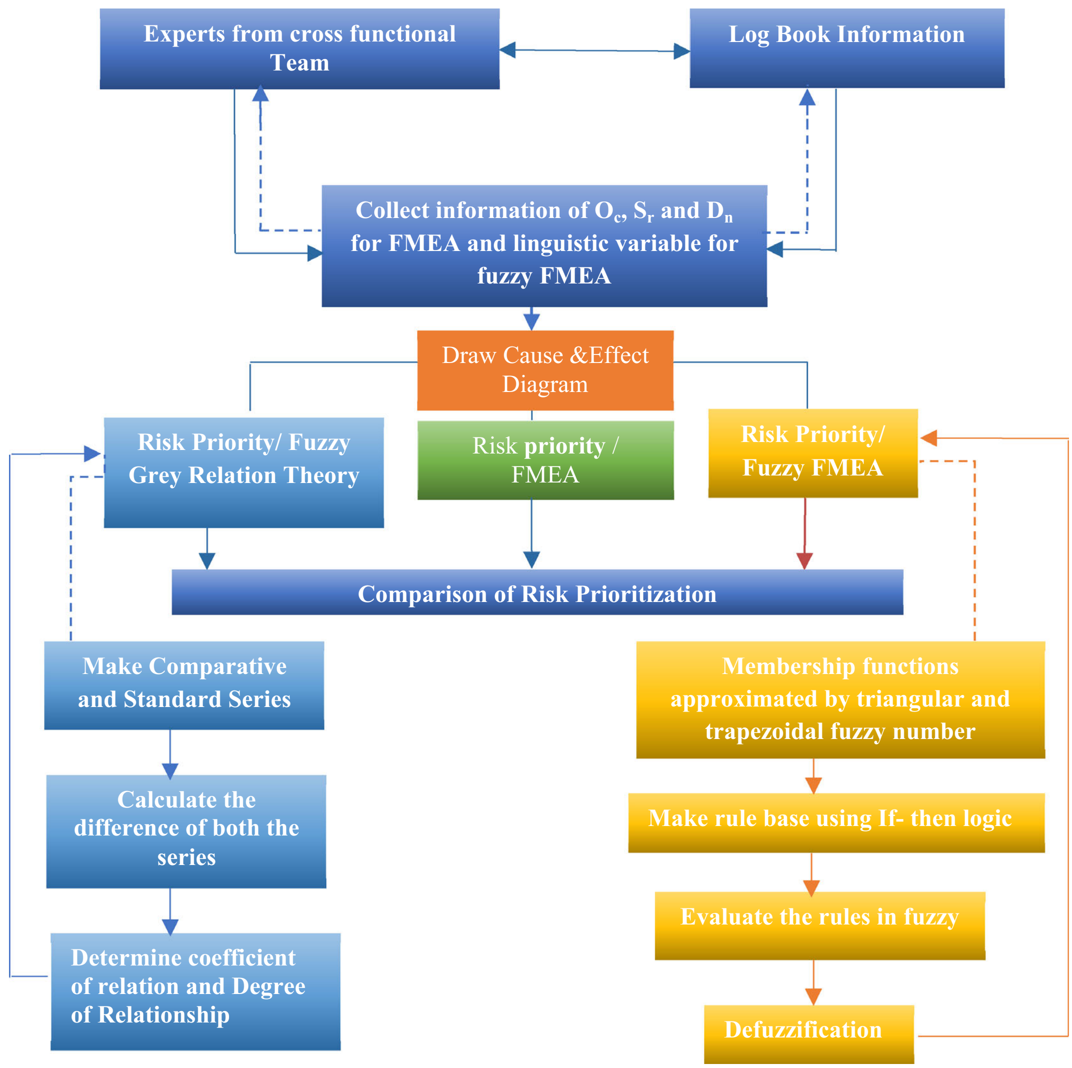

Fig. 4 Proposed methodology

4 Application of the proposed approach

The study was carried out at Sugar Plant, located in northern part of India, having capacity of 2200 TCD (tons of cane per day). The plant has been divided into different sub-systems. These are as follows: (1) Milling plant system, (2) clarification system, (3) evaporation and boiling system, (4) cooling, curing and drying system, (5) boilers, (6) power system, (7) inspection and quality check system. The present study is focused on milling plant system as it is

Table 3 Fuzzy judgement scale for matrix generation (Wang et al. 2007)

Uncertain judgement	Fuzzy score
About equal	(1/2, 1, 2)
About X time more important[a]	(X − 1, X, X + 1)
About X time less important	(1/(X + 1),1/X, 1/(X − 1)
Between Y and Z times more important[b]	(Y (Y + Z)/2, Z)
Between Y and Z times less important	(1/Z, 2/Y + Z, 1/Y)

[a]X = 2, 3,…, 9

[b]Y, Z = 1, 2, 3, …, 9, Y < Z

one of the most important unit of considered sugar plant. For continuous supply of juice for further procedural steps, it is important that all sub–sub-systems of milling plant e.g. gear drive, cast steel shaft, cast iron shell, scrapper, macerator etc. work for long durations. It is only possible if machines or equipment have high reliability and quality. Milling plant system is a complex mechanical system. All other processes or systems are dependent on it. If milling system fails due to failure of any of its sub-systems than it will lead to shut down of whole of the plant Therefore, it is important for maintenance engineer to identify risk level of each sub–sub-system, prioritize it and remove critical cause of failure. This will not only improve system reliability but also its availability. Therefore, it is important to conduct failure analysis of system for high quality and reliability standards for decision making process. The process flow diagram for milling plant is shown in Fig. 5.

4.1 Analysis

The risk analysis was done according to methodology as discussed in Fig. 1. First, the cause and effect diagram was made for assessing the cause of failure for the system (refer Fig. 6).

The FMEA sheet was prepared using cause and effect diagram, linguistic scale for three variables i.e. O_c, S_r and D_n and expert judgement. The experts from maintenance department, milling section were selected for feedback and judgement in present research work. However, the ratings of senior engineer in milling section was used for analysis. A decision support system was formulated using fuzzy logic tool box of Matlab R-2013a. The scores related to O_c, S_r and D_n were used as input. The input variables were defined by five linguistic variable and approximated by TFN, as shown in Fig. 7.

Similarly, output variables were defined by ten linguistic variables and approximated by trapezoidal fuzzy number (refer Fig. 8). After defining membership functions, 125 rules were formulated using if–then logic in FIS. These rules were reduced and applied on fuzzy input to obtain fuzzified output.

This output was converted into crisp value using centroid method (Eq. 5). The FIS with rules were formed using Eq. 6 and is shown in Fig. 9.

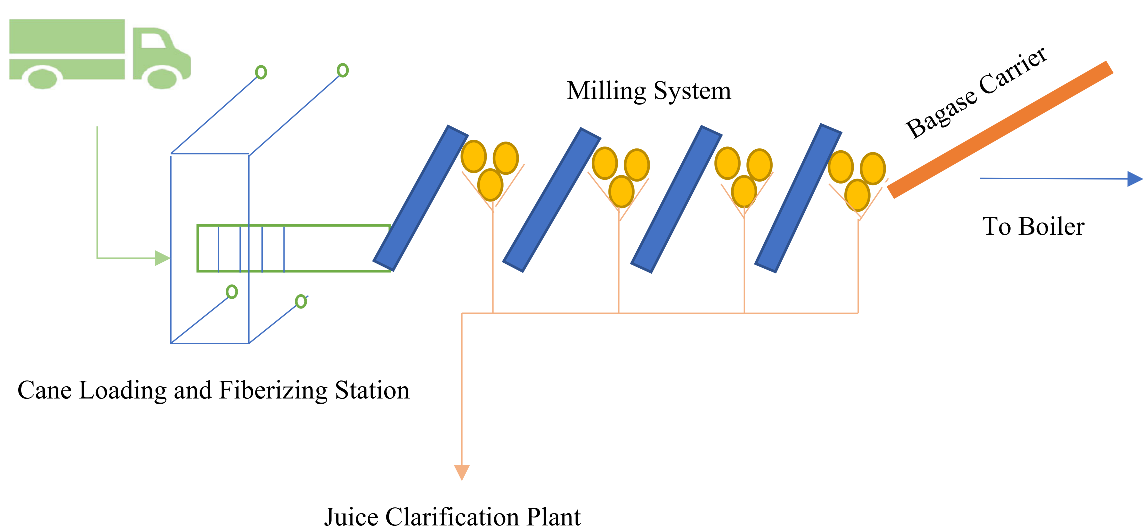

Fig. 5 Process flow diagram

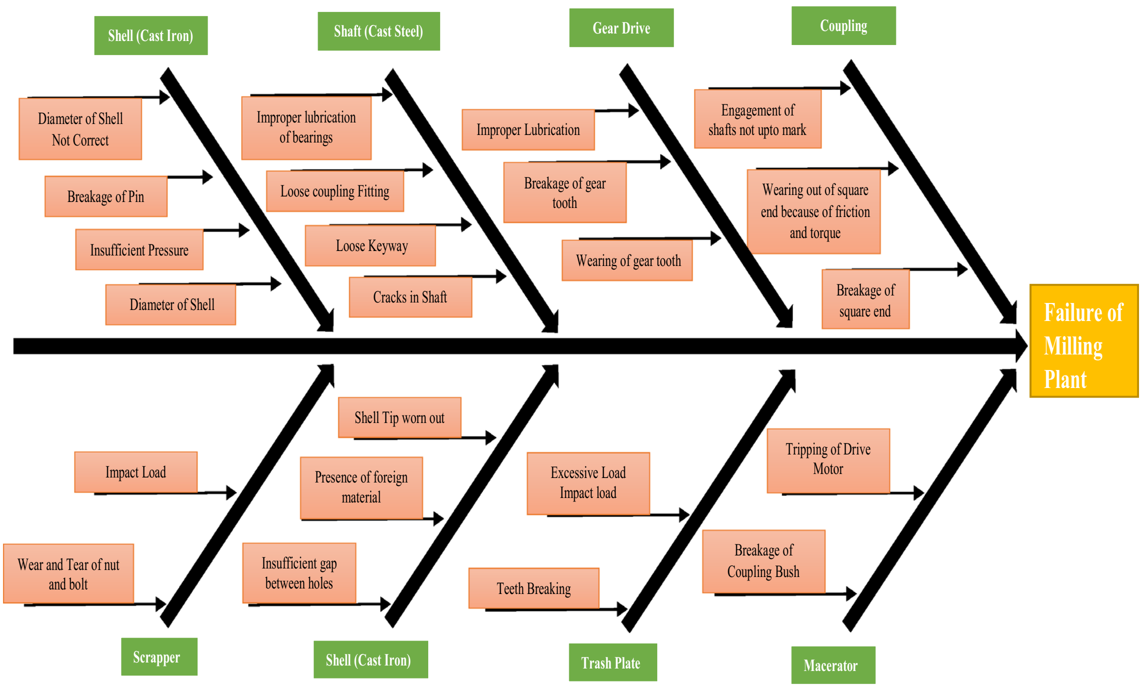

Fig. 6 Cause and effect diagram for milling system

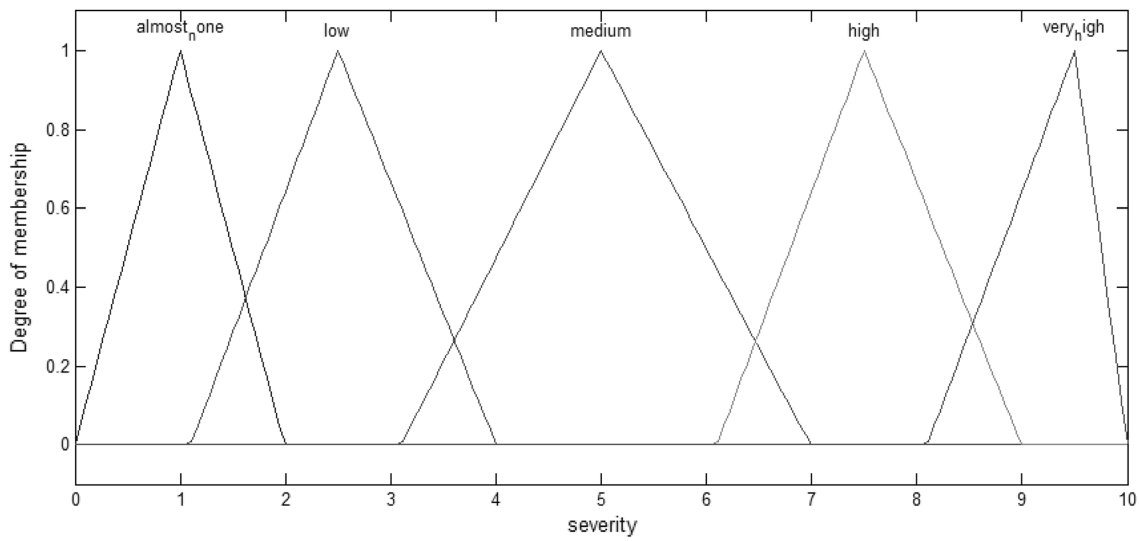

Fig. 7 Membership function for O_c, S_r and D_n

The evaluated weights for variables for GRA analysis, according to Table 2 and fuzzy synthetic extent analysis method (Srivastava et al. 2017) is shown in Table 4.

The RPN scores of risk as evaluated by conventional FMEA, and fuzzy FMEA is shown in Table 5.

The standard, comparative and Φ series as evaluated by Eqs. 10 and 11 respectively is as follow:

$$\text{Comparative Series} = \begin{bmatrix} 5.015 & \cdots & 5.015 \\ \cdots & \cdots & \cdots \\ 7.52 & \cdots & 5.015 \end{bmatrix}$$

$$\text{Standard Series} = \begin{bmatrix} 0 & \cdots & 0 \\ \cdots & \cdots & \cdots \\ 0 & \cdots & 0 \end{bmatrix}$$

$$\Phi = \begin{bmatrix} 5.015 & \cdots & 5.015 \\ \cdots & \cdots & \cdots \\ 7.52 & \cdots & 5.015 \end{bmatrix}$$

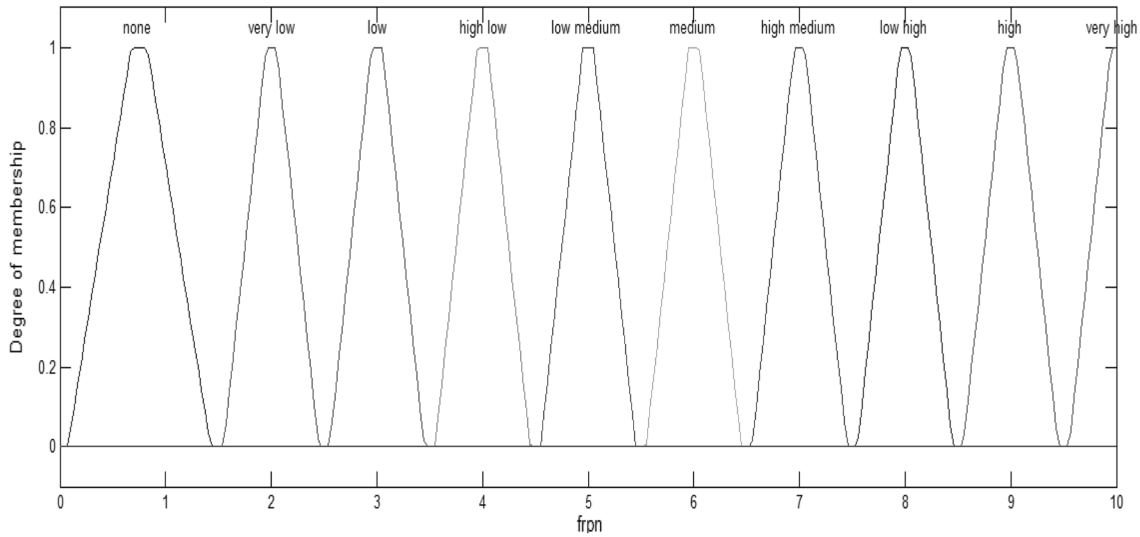

Fig. 8 Membership function for FRPN

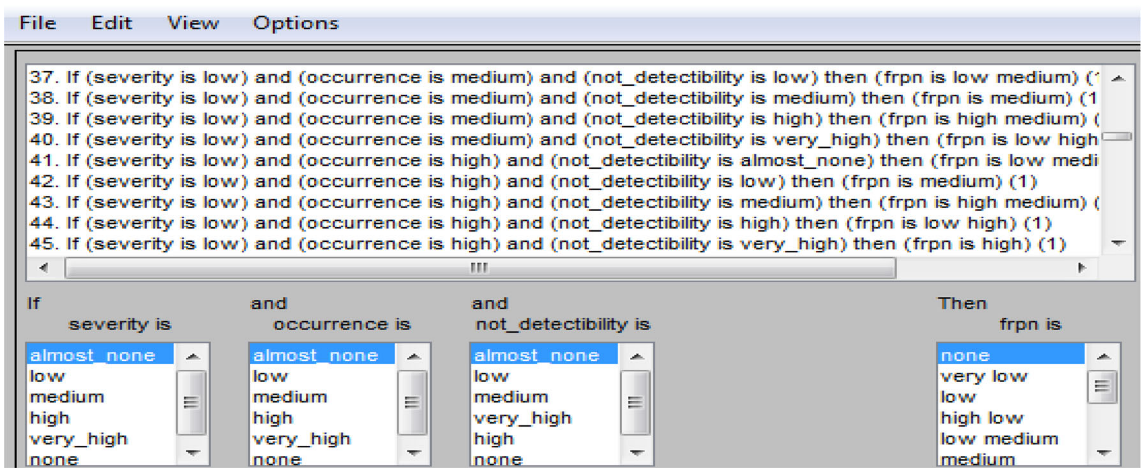

Fig. 9 IF-then rule in fuzzy inference system

Table 4 Evaluated weights

	O_c	S_r	D_n	Weights
O_c	(111)	(0.33 .25 1)	(0.25 0.33 0.5)	0.08
S_r	(234)	(111)	(0.33 0.5 1)	0.29
D_n	(345)	(234)	(111)	0.63

The grey relation coefficient (γ) and degree of relation (Γ) (refer Table 6) is as follow:

The combined ranking is shown in Table 7.

The spearmen correlation coefficient has been calculated and subsequent values are shown in Table 8.

5 Result and discussion

The outcome from the study are as follow:

(1) The risk analysis is done for twenty-six causes of failures. It has been found out that fourteen are critical to system, as their FRPN is greater than the total average FRPN.

(2) From Tables 4 and 5, it is seen that the failure causes CF3 and ShF1 are represented by different linguistic term i.e. [MMM] and [MHH] but have same RPN of 224 respectively. Similar observation is made for failure causes of SF2 and SF4 respectively. Also, failure causes ShF1 and ShF7 are represented by same linguistic term i.e. [MHH] but have different RPN of 224 and 196 respectively. This situation can be confusing for the system analyst.

Table 5 RPN scores assessment by FMEA and fuzzy FMEA

Component	Potential failure mode	Potential effect of failure	Potential cause of failure	O_c	S_r	D_n	RPN	FRPN
Coupling	Loose fitting	Loss of transmission	Engagement of shafts not up-to mark (CF1)	6[M]	5[M]	6[M]	180	7
	Square end of coupling become circular		Engagement of shafts not up-to mark (CF1)	6[M]	5[M]	6[M]	180	7
			Wearing out of square end because of friction and torque(CF2)	6[M]	6[M]	6[M]	216	7
			Breakage of square end(CF3)	4[M]	8[H]	7[H]	224	6
Gear drive	Improper meshing with other gears	Loss of transmission	Wearing of gear teeth (GF1)	6[M]	8[H]	6[M]	288	5
			Improper lubrication (GF2)	4[M]	6[M]	6[M]	144	7
			Inclusion of foreign material in between gear mesh (GF3)	6[M]	6[M]	5[M]	180	7
			Breakage of gear tooth (GF4)	5[M]	8[H]	7[H]	280	6
Shaft (cast steel)	Breakage of shaft	Loss of transmission	Cracks in shaft because of excessive cyclic loads (SF1)	4[M]	8[H]	7[H]	224	6
			Loose keyway (SF2)	6[M]	7[H]	4[M]	168	5
			Loose fitting with coupling (SF3)	5[M]	7[H]	6[M]	210	7
			Improper lubrication of bearings (SF4)	7[H]	6[M]	4[M]	168	5
Shell (cast iron)	Breakage of shell tip	Ineffective grinding of bagase and ineffective production of juice	Shell tip worn out (ShF1)	4[M]	8[H]	7[H]	224	6
			Presence of foreign material between rollers (ShF2)	6[M]	7[M]	4[M]	168	7
			Diameter of shell not up to mark (ShF3)	4[M]	7[M]	5[M]	140	7
	Improper meshing and alignment of rollers		Insufficient gap between rollers (ShF4)	6[M]	6[M]	5[M]	180	7
			Insufficient pressure between rollers (ShF5)	6[M]	6[M]	5[M]	180	7
			Diameter of shell not up to mark (ShF6)	7[H]	5[M]	4[M]	140	5
			Shell tip worn out (ShF1)	4[M]	8[H]	7[H]	224	6
			Breakage of pin due to high stress (ShF7)	4[M]	7[H]	7[H]	196	6.08
Trash plate	Breakage of tie rod or teeth	Improper scrapping	Excessive load/Impact load (TF1)	6[M]	4[M]	4[M]	96	7
			Teeth breaking (TF2)	5[M]	7[H]	7[H]	245	6.07
Scrapper	Breakage of nut and bolts and teeth/ 2 months	Improper scrapping	Wear and tear of nut and bolt(ScF1)	5[M]	6[M]	8[H]	240	8
			Impact load (ScF2)	6[M]	5[M]	6[M]	180	7
Macerator	Jamming of workstation between mill	Less penetration of hot water in compressed bagase/stoppage of mill	Breakage of coupling bush (McF1)	4[M]	7[H]	9[VH]	252	7.08
			Tripping of drive motor(McF2)	8[H]	5[M]	5[M]	200	5

Table 6 Degree of relation

S. no.	Failure causes	γ_o	γ_s	γ_d	Degree of relation, for equal weighting	Degree of relation, for evaluated weighting
1	CF1	1	1	1	0.99	0.9991
2	CF1	1	1	1	0.99	0.9991
3	CF2	1	1	1	0.99	0.9991
4	CF3	1	0.7945879	0.7945879	0.854428	0.8103058
5	GF1	1	0.7945879	1	0.922214	0.9378872
6	GF2	1	1	1	0.99	0.9991
7	GF3	1	1	1	0.99	0.9991
8	GF4	1	0.7945879	0.7945879	0.854428	0.8103058
9	SF1	1	0.7945879	0.7945879	0.854428	0.8103058
10	SF2	1	0.7945879	1	0.922214	0.9378872
11	SF3	1	0.7945879	1	0.922214	0.9378872
12	SF4	0.7945879	1	1	0.922214	0.982667
13	ShF1	1	0.7945879	0.7945879	0.854428	0.8103058
14	ShF2	1	0.7945879	1	0.922214	0.9378872
15	ShF3	1	0.7945879	1	0.922214	0.9378872
16	ShF4	1	1	1	0.99	0.9991
17	ShF5	1	1	1	0.99	0.9991
18	ShF6	0.7945879	1	1	0.922214	0.982667
19	ShF1	1	0.7945879	0.7945879	0.854428	0.8103058
20	ShF7	1	0.7945879	0.7945879	0.854428	0.8103058
21	TF1	1	1	1	0.99	0.9991
22	TF2	1	0.7945879	0.7945879	0.854428	0.8103058
23	ScF1	1	1	0.7945879	0.922214	0.8715186
24	ScF2	1	1	1	0.99	0.9991
25	McF1	1	0.7945879	0.6909091	0.820214	0.7459108
26	McF2	0.7945879	1	1	0.922214	0.982667

(3) Same is the case with CF1, CF2 and CF3; GF2 and GF3; GF4, ShF1 and ShF7 etc.

(4) From Table 7, it has been observed that some fuzzy -RPN (FRPN) rankings are different from the conventional RPN. For example, CF1, CF2 and CF3; GF1, GF2 and GF3; TF1 and TF2; ShF1, ShF6 etc., have different RPN and FRPN rankings respectively.

(5) The excessive cyclic loading on shaft, impact loading on tear rod, improper lubrication, foreign particle inclusions, loose fittings and coupling, insufficient gap and pressure between rollers, wear and tear of nut and bolts and breakage of coupling bush are some of the causes of failure which require immediate attention from maintenance department, as there FRPN is higher in their respective groups.

(6) From Table 7, it has also been observed that most of the prioritizations by GRA are validating FRPN. In some cases, it is even refining the prioritization as done by FRPN.

(7) The spearman correlation coefficient in as shown in Table 8 also shows that the prioritization by fuzzy FMEA and fuzzy GRA are strongly correlated in case of gear drive, shell (cast iron) and shaft (cast steel) with correlation coefficients (r_c) 0.9, 0.6, 0.7857 respectively. In case of Coupling and Trash Plate prioritization by both the approaches are in correlation with r_c of 1. In case of Scrapper and Macerator the value of correlation coefficient (r_c) is − 1, showing no correlation. The coefficient of correlation is not evaluated w.r.t FMEA as it is subjected to uncertainty. Though, for Scrapper and Macerator, FMEA and fuzzy FMEA are showing same prioritization.

The excessive cyclic loading on shaft, impact loading on tear rod, improper lubrication, foreign particle inclusions, insufficient gaps and pressure between rollers, loose fittings and couplings, wear and tear of nut and bolt were some of the causes of failures with high prioritization. It was

Table 7 Combined Result

S. no	Failure causes	FMEA (RPN)	Rank	Fuzzy FMEA (FRPN)	Rank	GRA (degree of relation, for equal weighting)	Rank	GRA (degree of relation, evaluated weights)	Rank
1	CF1	180	3	7	1	0.99	1	0.9991	1
2	CF1	180	3	7	1	0.99	1	0.9991	1
3	CF2	216	2	7	1	0.99	1	0.9991	1
4	CF3	224	1	6	2	0.854428044	2	0.810305781	2
5	GF1	288	1	5	2	0.922214022	2	0.937887208	2
6	GF2	144	4	7	1	0.99	1	0.9991	1
7	GF3	180	3	7	1	0.99	1	0.9991	1
8	GF4	280	2	6	2	0.854428044	3	0.810305781	3
9	SF1	224	1	6	2	0.854428044	2	0.810305781	3
10	SF2	168	3	5	3	0.922214022	1	0.937887208	2
11	SF3	210	2	7	1	0.922214022	1	0.937887208	2
12	SF4	168	3	5	2	0.922214022	1	0.982667036	1
13	ShF1	224	1	6	3	0.854428044	3	0.810305781	4
14	ShF2	168	4	7	1	0.922214022	2	0.937887208	3
15	ShF3	140	5	7	1	0.922214022	2	0.937887208	3
16	ShF4	180	3	7	1	0.99	1	0.9991	1
17	ShF5	180	3	7	1	0.99	1	0.9991	1
18	ShF6	140	5	5	4	0.922214022	2	0.982667036	2
19	ShF1	224	1	6	3	0.854428044	3	0.810305781	4
20	ShF7	196	2	6.08	2	0.854428044	3	0.810305781	4
21	TF1	96	2	7	1	0.99	1	0.9991	1
22	TF2	245	1	6.07	2	0.854428044	2	0.810305781	2
23	ScF1	240	1	8	1	0.922214022	2	0.871518573	2
24	ScF2	180	2	7	2	0.99	1	0.9991	1
25	McF1	252	1	7.08	1	0.820214022	2	0.745910844	2
26	McF2	200	2	5	2	0.922214022	1	0.982667036	1

Table 8 Spearman rank correlation coefficient

	Gear drive			Shaft (cast steel)			Shell (cast iron)		
	FRPN	GRA (EW)	GRA	FRPN	GRA (EW)	GRA	FRPN	GRA (EW)	GRA
FRPN	1	0.9	0.9	1	0.5	0.6	1	0.4761905	0.786
GRA (EW)	0.9	1	1	0.5	1	0.7	0.476	1	0.786
GRA (evaluated)	0.9	1	1	0.6	0.7	1	0.786	0.7857	1

recommended to plan effective maintenance planning for these subcomponents on priority basis.

To check the consistency of the prioritization results, sensitivity analysis was done for priority weights and grey relation coefficient. The priority weights were calculated using fuzzy extant analysis of AHP. The weights calculated for O_c, S_r and D_n were (0.08, 0.298, 0.6211). While doing sensitivity analysis priority weight of O_c was increased by 10–100%. Simultaneously, the weights of S_r and D_n were reduced in same proportion. The sensitivity analysis, shows that the prioritization results for fuzzy GRA are consistent (refer Fig. 10). Also, as the results are consistence, therefore, there is effectively no change in co-relational coefficient.

Further, sensitivity analysis was performed by changing the value of grey relation coefficient (γ). The range of γ is in interval of [0 1]. The sensitivity analysis (refer Fig. 11)

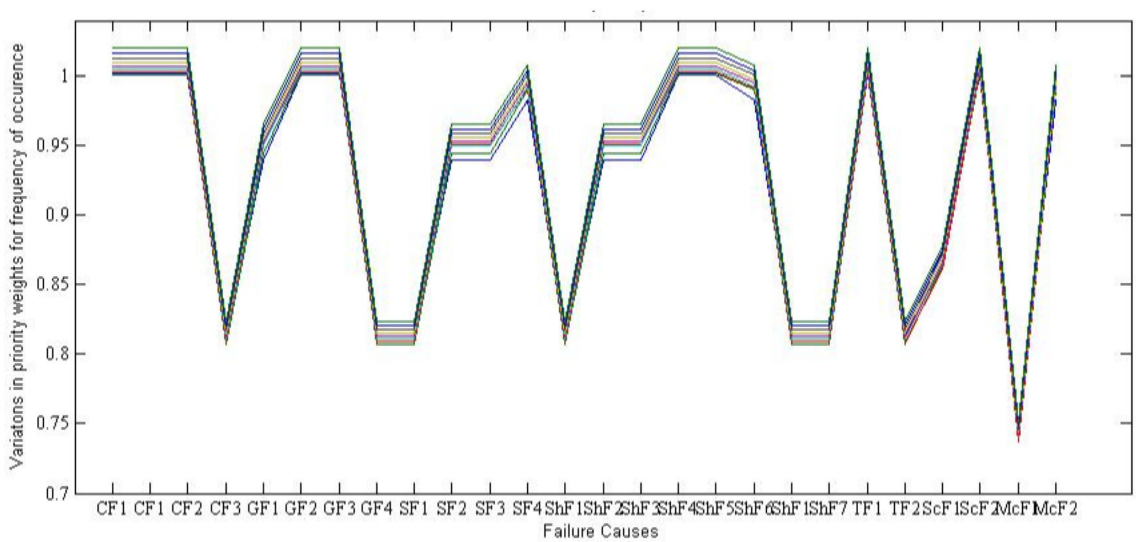

Fig. 10 Sensitivity analysis for priority weights

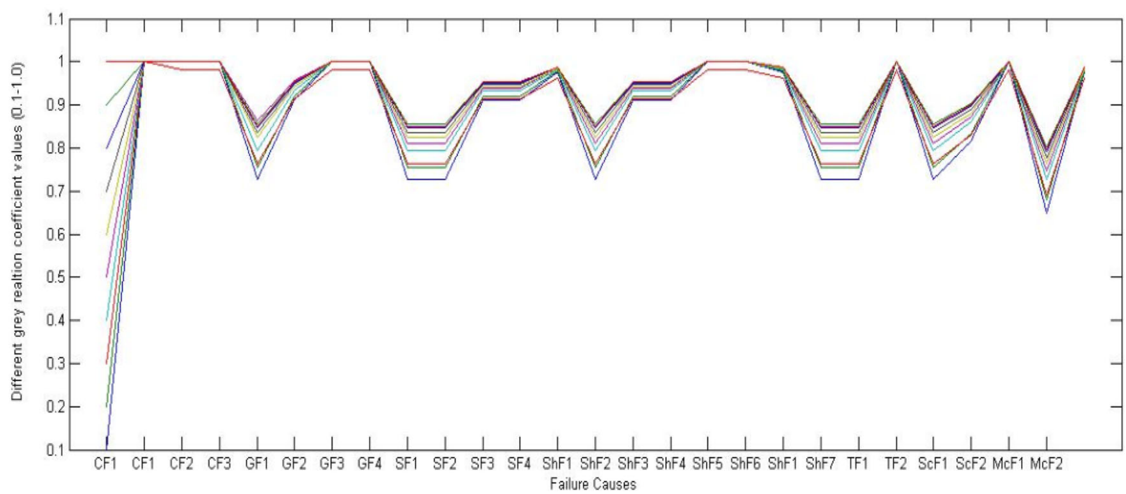

Fig. 11 Sensitivity analysis for grey relation coefficient

also supports the prioritization results as evaluated by using proposed approach.

From Figs. 10 and 11, it is clear that the rankings are consistent. Therefore, there is no effect of variations in priority weights on correlation of the prioritization results.

6 Conclusion

Milling system is sugar plan is a real-world operating system. It consists of number of subsystems like couplings, gear drive, shell, shaft, trash plate, scrapper and macerator. Proper maintenance planning and implementation of such a complex system is a major challenge for system analyst and maintenance engineer. This issue can be resolved by proper identification and prioritization of failure cause or risk. But risk identification and analysis using conventional FMEA approach is susceptible to uncertainty. The reason is biased or wrong expert judgement. These limitations can be removed by incorporating fuzzy methodology-based approach. In present research work fuzzy methodology-based risk analysis approach is used for analysis. The cause and effect diagram is used for identification of risk, fuzzy methodology-based decision support system and fuzzy GRA approach, are used for risk analysis and prioritization. A total of twenty-four causes of failure were identified (refer Table 5), out of which fourteen were found critical to milling system. The priorities obtained from integrated approach were compared with the priorities as calculated by conventional FMEA approach (refer Table 7). The comparative analysis will prove to be helpful to the maintenance engineer and management for effective maintenance planning and implementation.

6.1 Research limitation and managerial implications

The analysis of priorities is based on data and information as collected from all the sources of the sugar plant. There are chances of biased information or data which can affect the priorities. However, author has used combination of triangular and trapezoidal fuzzy number for removing this uncertainty from analysis.

The proposed integrated approach not only identifies and prioritizes risk, but also assist maintenance engineer to assess risk situation and take appropriate steps for improving quality, reliability and maintenance planning of system. Furthermore, to validate the proposed approach, results were shared with maintenance engineer and system analyst has agreement with risk priorities. Once the top management takes decision to implement outcomes of present analysis, detailed verification and validation of proposed approach can be done.

6.2 Future scope of research work

In present research work linguistic term approximated by triangular and trapezoidal membership function have been used to overcome uncertainty and biasing issues in expert judgement. Different combinations of membership functions can be used for analysis in future. More causes of failure can be identified for analysis. An integrated approach of fuzzy decision support system (FDSS) and GRA has been used to prioritize causes of failure. In future, other combinations of multi attribute decision making (MADM) methods can be used for prioritization and results can be compared. The methodology presented in this research paper can be applied to other sub-system of Sugar Plant. Further, it can also be applied to other process industries: Paper Plant, Power Plants, Fertilizer Plants etc.

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