CrossMark

ORIGINAL ARTICLE

Qualitative analysis of CNG dispensing system using fuzzy FMEA–GRA integrated approach

Dilbagh Panchal[1] · **Priyank Srivastava[2]**

Abstract This research work reviews different risk analysis approach and expounds the application of fuzzy integrated multi criteria decision making framework for qualitative analysis of compressed natural gas dispensing system. Qualitative analysis of system is its risk identification and prioritization. This analysis is done by exemplifying integrated approach of failure mode and effect analysis (FMEA), fuzzy FMEA and fuzzy grey relational analysis (GRA) respectively. The conventional FMEA prioritizes risk on the basis of risk priority number (RPN). The uncertainty issue from analysis has been removed by integrating fuzzy methodology with conventional technique. The rule base in fuzzy inference system is used for calculating fuzzy RPN. The effect of weightage of each variable has been considered in fuzzy GRA for risk prioritization. A total of 43 risks have been identified and seven are assessed critical to system. The regulator malfunction of metering skid, internal leakage of compressor, motherboard failure of dispenser, internal pipe leakage and air filter choking of priority panel and plug leakage of cascade have been identified as critical risk in present study. This outcome of the proposed framework will act as decision support system for the system analyst and maintenance engineer to identify and prioritize risk, subsequently assisting them for better maintenance planning.

Keywords FMEA · FIS · Fuzzy FMEA · Fuzzy GRA · CNG

Abbreviations
FMEA   Failure mode and effect analysis
RPN   Risk priority number
FRPN   Fuzzy risk priority number
GRA   Grey relational analysis
FIS   Fuzzy inference system
CNG   Compressed natural gas
PM   Particulate matter
ISO   International Standards Organization
IS   Indian Standard
NASA   National Aeronautics and Space Administration

✉ Dilbagh Panchal
panchald@nitj.ac.in

Priyank Srivastava
priyanksrivastava_me@yahoo.in

[1] Department of Industrial and Production Engineering, Dr. B.R Ambedkar National Institute of Technology, Jalandhar, Punjab 144011, India

[2] Department of Mechanical Engineering, Amity University, Noida, Uttar Pradesh 201313, India

1 Introduction

World is facing lots of challenges in front of environmental pollution and its protection. It has initiated strict norms and regulation for gas emission due to burning of fuel. This has necessitated use of fuels that have low carbon dioxide (CO_2), nitrogen oxide (NO_x), sulphur dioxide (SO_2) and particulate matter (PM) emission. Compressed natural gas (CNG), is one such alternative fuel that has low emissions of the above-mentioned gases and PM. The use of CNG instead of gasoline reduces environmental pollution, as there is reduction of 26% CO_2 emission thereby reducing

greenhouse effect considerably. The use of CNG as alternative automotive fuel has increased in recent years. There are different standards of CNG for different purpose. IS:15958 applies to CNG as fuel for automotive purpose and ISO: 16923:2016 for CNG dispensing system. CNG is a form of natural gas (mainly methane CH_4) compressed at high pressure. CNG is considered a safe automotive fuel alternative as it doesn't burn below 5% and above 15% composition respectively, when mixed with air. Though, the hazards at dispensing station are high. Being lighter than air, there is always a possibility of leakage due to faulty sub-systems of dispensing station. As CNG is inflammable, its leakage can lead to fire and explosion hazard at dispensing station. This can affect components of system, process, monitory functions, personals and people repectively. Therefore, proper maintenance of CNG dispensing station is essential. For proper maintenance planning, identification of causes of failure and their prioritization is essential. Risk can be defined situation of exposure to danger that can be initiated by failure event. Risk analysis is essential:

1. To improve safety level of various operating system.
2. To identify component whose probability of failure is high.
3. To optimize maintenance planning.
4. To support emergency planning.

Identification of risk using FMEA is a proactive approach that can reduce facility, monetary and human life loss in case of future catastrophic failure. The FMEA approach is subjected to intrinsic limitations. It is a group activity that depends on experience, knowledge and preference of cross-functional team of experts. There is always a chance of error or biasness in judgement that can lead to uncertainty. Fuzzy methodology can be used to overcome this limitation. The present research expounds the application of fuzzy integrated approach of FMEA and GRA. A case from CNG dispensing station has been selected for exemplifying the proposed framework, as it is a complex system comprising of various sub-components. These sub components are connected in combined series and parallel configurations, which makes its risk analysis pertinent for proper maintenance planning. The paper is structured as, Sect. 2 discuss previous research work in area of risk analysis of system, Sect. 3 which expounds flowchart/sequential steps followed for analysis, Sect. 4 discuss different techniques used for risk prioritization, Sect. 5 discuss the process flow of CNG dispensing station and subsequent analysis according to research methodology, Sect. 6 discuss analysis of result obtained, Sect. 7 discuss outcome of study and managerial implication of the present work.

2 Literature review

In an industrial system, risk of a system failure is always there. Therefore, for maintaining high availability of a system it is necessary to eliminate or minimize various types of risk. FMEA is a systematic technique that is used for risk analysis of complex systems by identifying possible future failures and its prioritization. The risk mainly depends on three factors, occurrence, severity and detection. Occurrence (O_c) indicates frequency of failure over span of time. Severity (S_r) indicates adverse effect of a failure. Non-detection (D_n) indicates the likelihood of the failure traceability. Different mathematical models have been developed for failure analysis of the system. Amuthakkannan et al. (2008) applied FMEA and other quality control tools for upgrading the software quality used for improving the performance of an internal combustion engine. Arabian-Hoseynabadi and Tavner (2010) applied FMEA approach for improving quality and reliability of wind turbine system. Hekmatpanah et al. (2011) implemented FMEA to improve quality of products in an Iranian Oil Company. Gaula and Sharma (2015) implemented FMEA to analyse the effect of maintenance strategies on throughput of a typical flexible manufacturing cells (FMC's). Feili et al. (2013) demonstrated the application of FMEA approach for risk analysis in geothermal power plant. The conventional Failure Mode and Effect Analysis is susceptible to intrinsic faults and these drawbacks are as follow.

a. It is a group decision activity and is performed by a cross functional team. There is every chance of a biased opinion.
b. It is dependent on raw data from various sources that are often vague and imprecise.

To overcome limitation of conventional FMEA, fuzzy methodology can be integrated with it and be applied in diverse fields Srivastava et al. (2017). Xu et al. (2002) applied fuzzy logic based FMEA in the diesel engine system. Fuzzy integrated FMEA and GRA approach was used for risk analysis of water treatment plant (Panchal and Kumar 2016a, b) and further for real industrial system (Panchal and Kumar 2017a, b). An approach was used for criticality analysis of components of sub-system of nuclear power plant by Guimaraes and Lapa (2004). Das et al. (2011) implemented an aggregative fuzzy risk analysis for the flood incident management. There have been studies of failure analysis on complex system using integrated approach. Chen et al. (2014) applied integrated approach of fuzzy FMEA and fault tree for prioritization of risk in oxygen enhance combustor. Du et al. (2014) proposed fuzzy FMEA approach using evidential reasoning

(ER) and the technique for order preference by similarity to ideal solution (TOPSIS). 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. Tang (2015) proposed a framework for decision making based on GRA and Dempster AND Shaffer theory. Zhou and Thai (2016) expounded application of fuzzy FMEA and GRA for relative ranking failure causes for tanker equipment. Ighravwe and Oke (2017) implemented fuzzy-grey-weighted aggregate sum product assessment methodical approach for multi-criteria analysis of maintenance performance systems. Panchal et al. (2018a, b) expounded the application of GRA for validating results of fuzzy RPN of transmission system in heavy motor vehicle.

It is clear from the preceding section that FMEA is a powerful tool for risk analysis. The uncertainty can be removed by using fuzzy methodology. This prioritization results from fuzzy GRA can be used for checking, comparing and validating the results as obtained by FMEA and fuzzy FMEA. From the reviewed literature, author observes that there is either no or less inference of use of this methodology for risk analysis of CNG dispensing system. The paper seeks to fill this gap by applying this methodology for risk analysis of above mentioned system located in northern part of India.

3 Research methodology

The research methodology for the present study is shown in Fig. 1.

Steps Involved:

- With personal interaction with operators, maintenance analysts and engineer, cause and effect diagram for system under study is made.
- A 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 linguistic terms, approximated by triangular or trapezoidal fuzzy membership function. 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 from the prioritization as obtained by fuzzy GRA approach. The degree of relationship is measure of prioritization. It is evaluated by establishing comparative, standard and difference series and evaluating grey relation coefficient.

4 Methods and approach

This section discusses various approach used for risk analysis and prioritization.

4.1 Cause and effect diagram

Cause and effect diagram, also called as fish-bone 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 (Fig. 2).

4.2 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. 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; Panchal and Kumar 2016a, b), 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 (Eq. 1).

$$RPN = O_c \times S_r \times D_n \tag{1}$$

4.3 Fuzzy FMEA

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 and can be used for transforming subjective knowledge

Fig. 1 Research methodology

Select the case and collect all the information from log book and experts

Determine all Potential Failure Modes and their effects and their current control

Define Scale O_c, S_r and D_n on linguistic scales and express judgement on linguistic scale

Evaluate O_c, S_r and D_n rating for each failure mode

Generate membership functions for risk output

Obtain crisp number for O_c, S_r and D_n by de-fuzzification of fuzzy sets

Calculate RPN and prioritize

Generate Rule Base and evaluate FRPN and Prioritize

Establish Comparative and Standard Series

Calculate Grey Relation Coefficient and degree of relationship

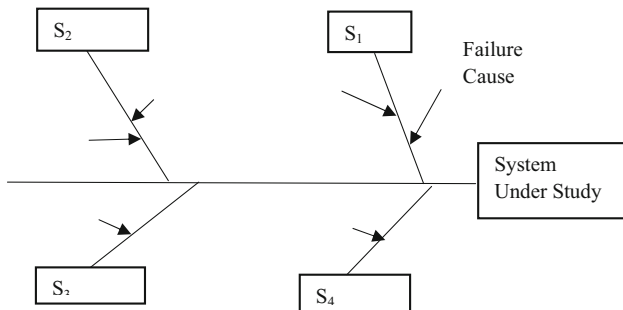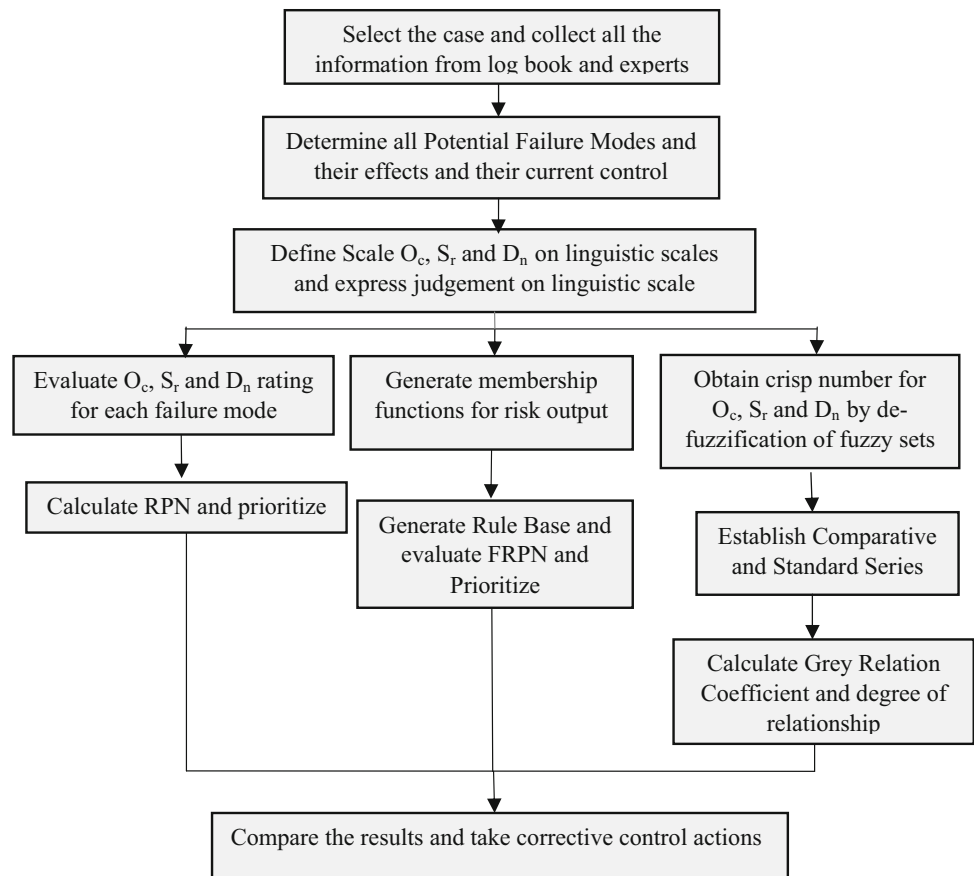Compare the results and take corrective control actions

Fig. 2 Cause and effect diagram

into quantitative terms. This transformation requires a well-defined scale (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. Triangular membership function (TMF) is defined by Eq. 1.

$$\mu_{\tilde{T}}(x) = \begin{cases} \dfrac{x-a}{b-a} & a \le x \le b \\ \dfrac{x-c}{b-c} & b \le x \le c \\ 0 & otherwise \end{cases} \tag{2}$$

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

Similarly, Trapezoidal membership function is defined by Eq. 3.

$$\mu_{\widetilde{Tr}}(x) = \begin{cases} 0, & (x > d \ or \ x < a) \\ \dfrac{x-a}{b-a}, & a \le x \le b \\ 1, & b \le x \le c \\ \dfrac{d-x}{d-c}, & c \le x \le d \end{cases} \tag{3}$$

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 (Panchal and Kumar 2016a, b; Panchal et al. 2018a, b).

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 (Eq. 4).

Table 1 Fuzzy linguistic scale for variable

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

$$\tilde{x} = \frac{\int_{x_1}^{x_2} x\mu_{\tilde{T}}(x)dx}{\mu_{\tilde{T}}(x)dx} \tag{4}$$

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

The output after de-fuzzification will be fuzzy-RPN value as evaluated by Eq. 5.

$$\text{Crisp value of TFN} = \frac{(a + 4b + c)}{6} \tag{5}$$

The process flow for fuzzy decision support system is shown in Fig. 3.

4.4 Grey relation analysis

Grey theory was proposed by Deng (1989). For most of the real-world system, capturing perfect information for model development is impossible. The grey system theory is one of the powerful tool 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. MCDM problems have been solved using GRA technique, like, human resource process (Olson and Wu 2006), facility layout and dispatching rules (Kuo et al. 2008), supplier selection for vehicle components based on green supply chain (Li and Zhao 2009) warehouse location problem (Özcan et al. 2011), selection of advanced manufacturing system (Goyal and Grover 2012), evaluation of innovation competency of aviation (Zhu et al. 2012), resilient supplier selection (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 et al. 2018a, b):

Fig. 3 Fuzzy decision support system
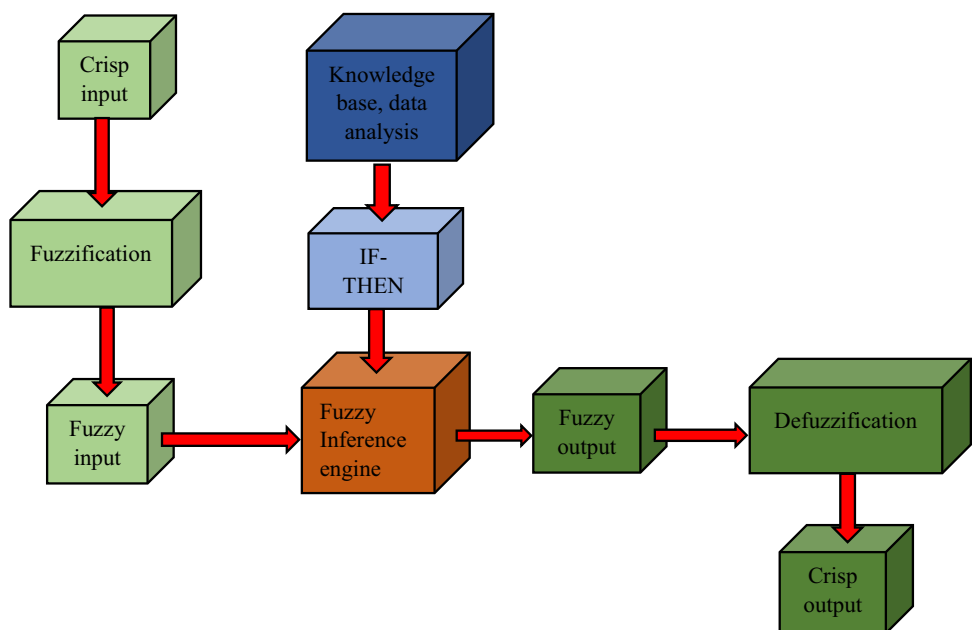
$$Z_0 = [z_0(1), z_0(2), \ldots\ldots\ldots z_0(k)\ldots\ldots z_0(n)] \quad (6)$$

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

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.

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

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

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

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

The values in these series are defuzzied values of the fuzzy number. The grey relation coefficient (γ) for input variable is calculated by using Eq. 11.

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

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

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

where, ξ_k is weighting coefficient of for the input variables. It is decided by the expert's judgement. In present research work, weighting coefficients are calculated using Wang

Table 2 FuzzyJudgement Scale for Matrix Generation (Wang et al. 2007)

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

*X = 2,3, …. 9
[#]Y, Z = 1,2,3…., 9, Y < Z

scale (Table 2), and weights are calculated using fuzzy extent analysis (Panchal and Kumar 2017a, b; Srivastava et al. 2018).

The selection and estimation of weights is important for legitimate results and ranking.

5 Case description and analysis

The process flow diagram is shown in Fig. 4.

The description of the components in Fig. 4 is tabulated in Table 3.

5.1 Analysis

The cause and effect diagram has been shown in Fig. 5. Due to limitation of space only eighteen (18) causes failure have been shown.

After identification of failure causes, expert rating for risk for three input variables was recorded and subsequently RPN calculated according to the steps as discussed in methodology. For evaluation of fuzzy RPN, input and output variables were approximated by triangular and trapezoidal fuzzy numbers respectively (Fig. 6 and 7), and subsequently decision support system was prepared using Matlab R-13a (Eq. 4).

A total of 125 if–then rules were prepared and reduced to eliminate chances of duplicity. The output of decision support system is fuzzy RPN. The output of FMEA and fuzzy FMEA has been shown in Table 4.

The degree of relationship for fuzzy GRA has been evaluated using Eq. from 8–12. The standard, comparative and Φ series as evaluated by Eqs. 8, 9 and 10 respectively is as follow:

$$\text{Comparative Series} = \begin{bmatrix} 5.015 & \ldots & 0.9983 \\ \ldots & \ldots & \ldots \\ 9.324 & \ldots & 9.324 \end{bmatrix}$$

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

$$\Phi = \begin{bmatrix} 5.015 & \ldots & 0.9983 \\ \ldots & \ldots & \ldots \\ 9.324 & \ldots & 9.324 \end{bmatrix}$$

The grey relation coefficient (γ) and degree of relation (Γ) (Table 5) is as follow:

The prioritization from all the approaches has been shown in Table 6.

Storage Cascade
3000 WL (2 No's)

Car Dispenser
200 Kg/cm² @ 15 Kg/min (1)

Bus Dispenser
200 Kg/cm² @ 75 Kg/min (2)

Priority Panel

Gas Compressor –1

3 Stage Reciprocating Compressor (600 SCMH)

Gas Compressor – 2

3 Stage Reciprocating Compressor (600 SCMH)

N.GAS Inlet Pressure 19 Kg/cm³

Station Isolation Valve & Metering Skid
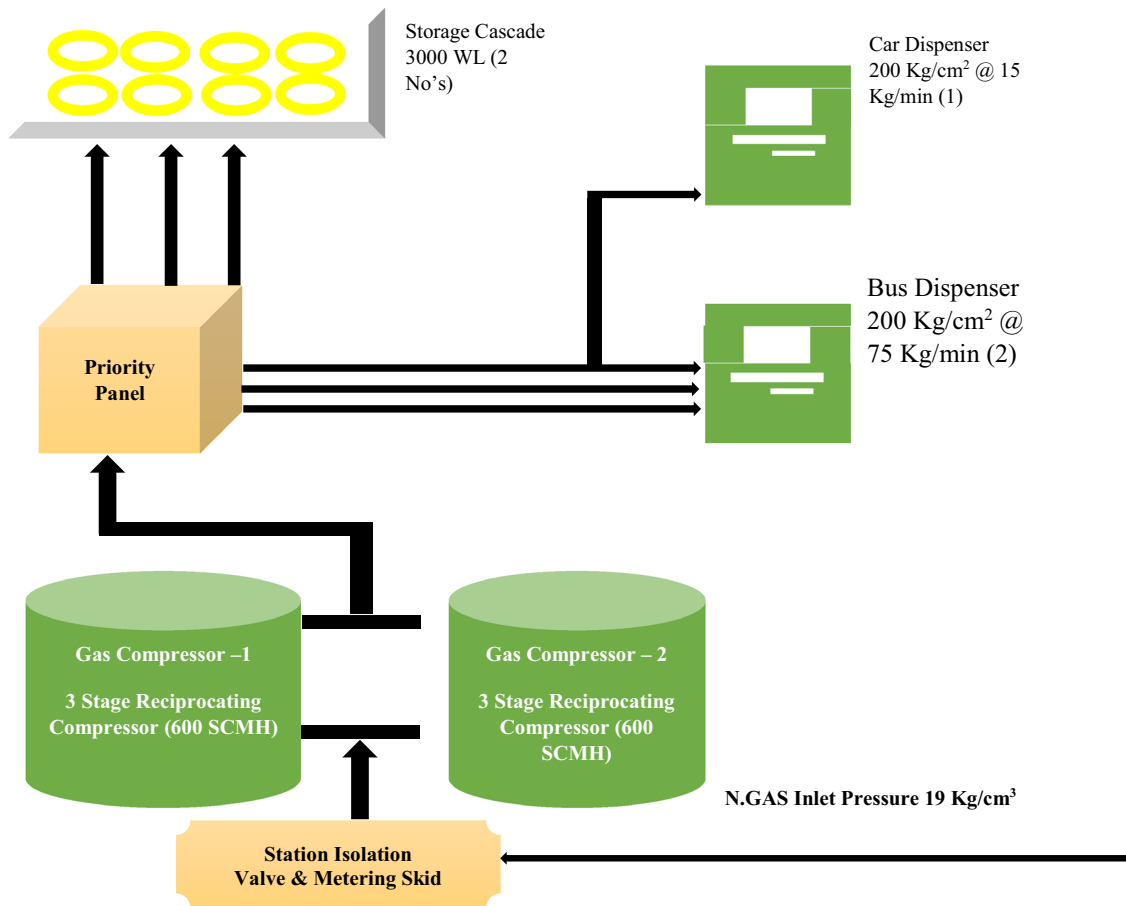
Fig. 4 Process flow chart

Table 3 Component description

Component	Function
Metering Skid	A metering skid includes several flowmeters and meter provers. Its main function is to regulate the pressure and filter the gas. The metering skid is also used in case of emergencies and when there is a need of shutting down the gas station
Compressor	The basic function of the compressor is to increase the pressure of a gas by reducing its volume. There are three types of compressors which are commonly used- Rotary, reciprocating and centrifugal pumps. In the IGL CNG filling stations, reciprocating pumps are used
Priority Panel	The priority panel is designed to control the filling sequence of Stationary cascade, dispenser and mobile cascade. They control the flow of CNG between the compressor and storage tanks
Cascade	A cascade is high pressure storage tank or system of tanks which is used to fill smaller cylinders with less pressure
Dispenser	The dispenser is the interface of the CNG filling station with the customer. To make it easier to use and understand, it is designed similar in appearance and operation to conventional dispensers for liquid fuel. These dispensers work on 'Coriolis' principle which is used to measure the mass flow rate of a liquid travelling through a tube

6 Result and discussion

Qualitative analysis for risk shows a crucial part to bridge up the space amongst the process and operational conditions by providing pre-emptive maintenance strategy and suggesting precaution. Currently, the aim is to reduce or prevent the risk conditions in CNG filling stations where

the subcomponents are metering skid, compressor, dispenser, priority panel and cascade. The results are as follow:

1. The results elucidate average RPN values for metering skids by traditional FMEA is 27.2, by fuzzy is 3.975 and by GRA is 0.761. It is found that at least four and

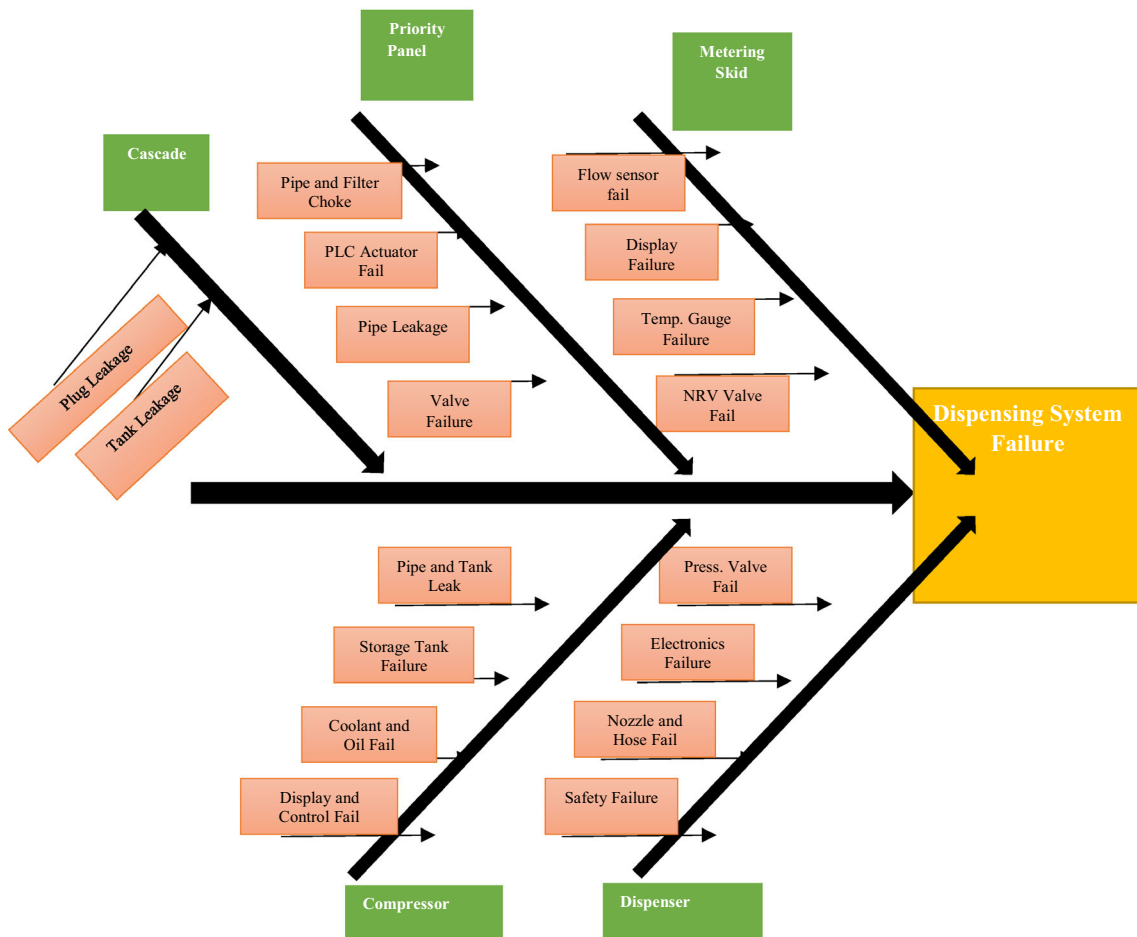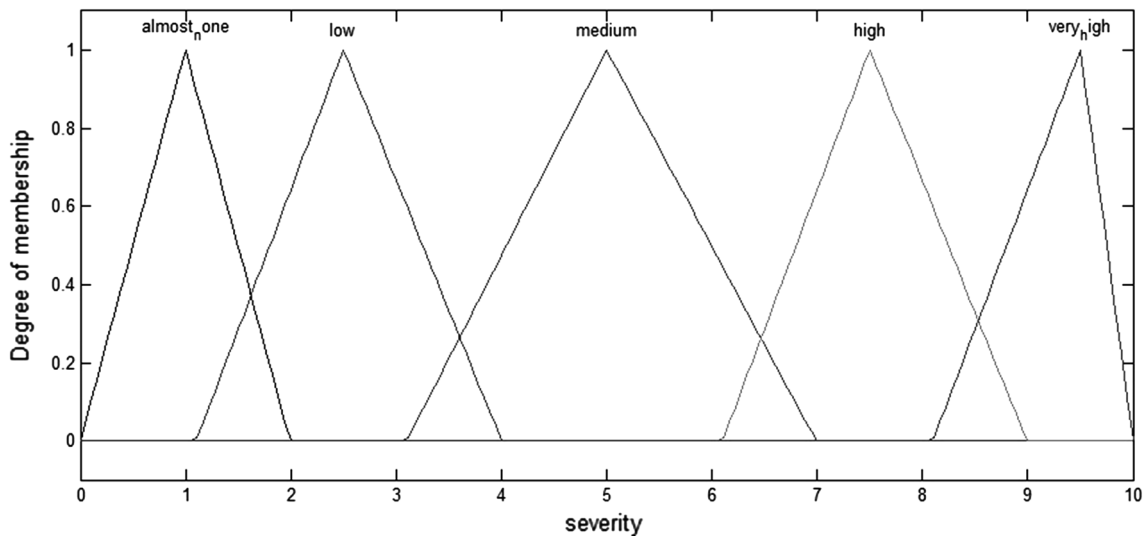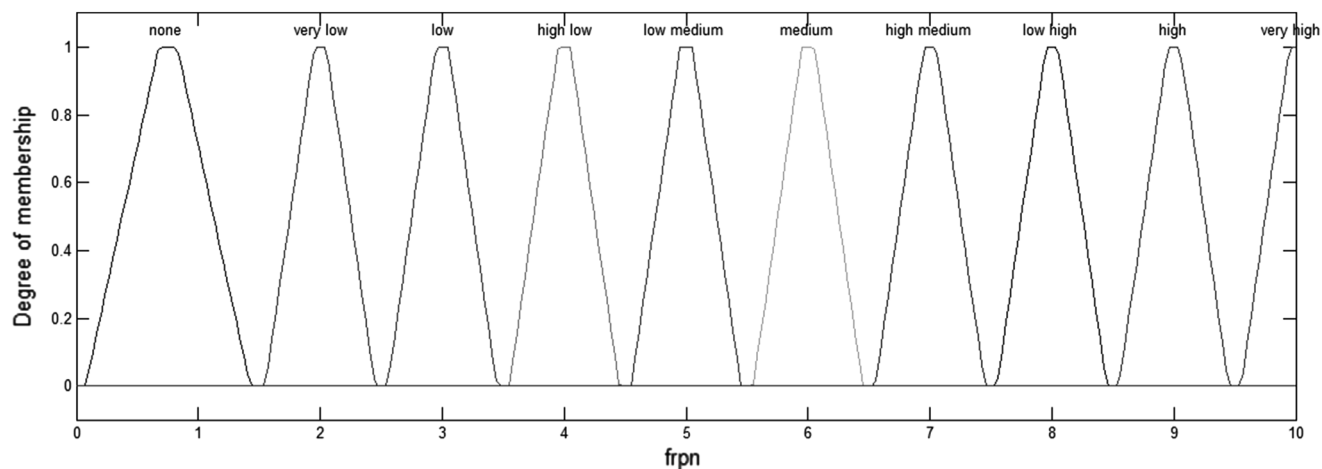**Fig. 5** Fish-bone/cause and effect diagram

Fig. 6 Membership function for O_c, S_r and D_n

at most six failure causes have values more than the average value as evaluated by conventional FMEA, fuzzy FMEA and fuzzy GRA approach respectively.

2. The average RPN values for compressor by traditional FMEA is 147, by fuzzy is 4.479 and by GRA is 0.653466. It is found that at least three and at most

Fig. 7 Membership function for FRPN

eight failure causes have values more than the average value as evaluated by conventional FMEA, fuzzy FMEA and GRA approach respectively.

3. The average RPN values for dispenser by traditional FMEA is 67.1, by fuzzy is 5.3 and by GRA is 0.659. It is found that at least three and at most four failure causes have values more than the average value as evaluated by conventional FMEA, fuzzy FMEA and GRA approach respectively.

4. The average RPN values for priority panel by traditional FMEA is 113.714, by fuzzy is 4.107 and by GRA is 0.6711. It is found that at least one and at most five failure causes have values more than the average value as evaluated by conventional FMEA, fuzzy FMEA and GRA approach respectively.

5. The average RPN values for cascade by traditional FMEA is 95.25, by fuzzy is 5 and by GRA is 0.5988. It is found that It is found that at least one and at most four failure causes have values more than the average value as evaluated by conventional FMEA, fuzzy FMEA and GRA approach respectively.

The fuzzy method represents an extensive concern while bearing with the failures. The failure ranking comparison elucidates that traditional FMEA has uncertainty and ambiguity in the assessment while the fuzzy approach provides more stable solution. This is justified as follow:

1. It can be noticed from failure mode CS2 (Internal Pipe Leakage), DS3 (Failure of Motherboard), DS5 (Flow Sensor Failure), PP2 (Air Filter Choke), PP7 (Actuator Failure), CA3 (Tank Leakage/Tank Corrosion) and CA4 (Burst Disk Failure) in which the value of RPN are similar. Fuzzy FMEA along with fuzzy GRA approach can convincingly assess the expert's judgements and accordingly improve the significance of FMEA technique. The rule base analysis is substituted by the fuzzy GRA. The evaluated weights for Oc, S_r and D_n and integrating it with the proposed methodology, makes it realistic, applied and flexible.

2. There is an issue of clustering because of assignment of multiple belief to single RPN, using rule base approach.

3. It has been noticed that MS7 in metering skid has a less importance in fuzzy GRA and a greater importance in rule-based method. Failure modes like CS5, CS4, DS6, DS7, PP4, CA2 and CA3 have greater importance in the fuzzy GRA method and lower importance in rule-based method.

4. By the use of projected methodology failure, it is being evaluated that the following failure needs safety improvement action in order to promote a safer surrounding:

   MS10 Metering Skid's Regulator Malfunction results in Pulsating Flow
   CS2 Compressor's internal pipe leakage results in loss of pressure and gas leakage
   CS3 Compressor's internal valve failure results in valve closing
   DS3 Failure in Dispenser's motherboard results in complete breakdown
   PP1 Internal Pipe Leakage in Priority Panel results in Gas leakage
   PP2 Priority Panel's air filter choke results in particulate matter contamination
   CA1 Cascade's plug leakage results in low output

7 Conclusion

Fuzzy FMEA and MADM approach is applied to CNG dispensing unit. The possible failure modes have been diagnosed and analysed for their effects, detection methods

Table 4 RPN, FRPN

Sub-components	Failure code	Cause of failures	O	S	D	RPN	FRPN
Metering skid	MS1	Suction line filter choke	6	8	1	48	3
	MS2	Slam shut of valve not opening	2	1	4	8	5
	MS3	Flow sensor fail	2	1	2	4	5
	MS4	Display error	1	3	1	3	0.75
	MS5	Display hang	4	8	1	32	3
	MS6	Transmitter failure	1	5	4	20	5
	MS7	NRV valve failure	1	10	5	50	5
	MS8	Temperature gauge failure	8	1	1	8	3
	MS9	Pressure gauge failure	9	1	1	9	4
	MS10	Regulator malfunction	5	3	6	90	6
Compressor	CS1	Inlet filter choke	10	8	1	80	5
	CS2	Internal pipe leakage	9	10	7	630	5
	CS3	Internal valve failure	7	9	8	504	8
	CS4	Insufficient coolant	1	7	1	7	0.75
	CS5	Pressure gauge failure	3	1	1	3	2
	CS6	Tank leakage	3	9	4	108	5
	CS7	Tank corrosion	1	10	9	90	5
	CS8	Cable worn-out	2	9	3	54	4
	CS9	Display problem	4	2	1	8	4
	CS10	PLC failure	3	7	4	84	5
	CS11	Gasket damage in engine	5	9	4	180	5
	CS12	Insufficient engine oil	1	8	2	16	5
Dispenser	DS1	Nozzle failure	10	10	1	100	5
	DS2	Fill and vent hoses leakage	7	9	2	126	6
	DS3	Failure of motherboard	5	3	4	60	6
	DS4	Pressure regulator valve failure	3	10	5	150	5
	DS5	Flow sensor failure	4	3	5	60	6
	DS6	Pressure safety valve failure	1	10	2	20	5
	DS7	Outlet block failure	1	9	2	18	5
	DS8	Display error	8	5	1	40	5
	DS9	Safety check error	5	5	1	25	5
	DS10	Probe spring failure	8	9	1	72	5
Priority Panel	PP1	Internal pipe leakage	7	10	8	560	5
	PP2	Air filter choke	8	2	3	48	5
	PP3	Isolation valve leakage	1	6	7	42	5
	PP4	PLC failure	1	8	1	8	0.75
	PP5	SOV valve failure	3	6	4	72	5
	PP6	Pipe choke	2	9	1	18	3
	PP7	Actuator failure	2	6	4	48	5
Cascade	CA1	Plug leakage	10	2	6	120	5
	CA2	Cylinder wall failure	1	9	9	81	5
	CA3	Tank leakage/tank corrosion	1	10	9	90	5
	CA4	Burst disc failure	10	1	9	90	5

and their root causes. The conventional and fuzzy RPN are being calculated with the input analysed and discussed from the experts. The use of etymological expressions permits the experts to provide a noteworthy worth for the risk factors under consideration. The fuzzy GRA approach allows the practitioner to fix on the significant factor for the study and provides a weight to the results that provide precious inferences for the prioritization.

Table 5 Grey relation coefficient and degree of relationship

Failure code	γ_o	γ_s	γ_d	Degree of relationship (Γ)
MS2	0.5844399	0.4661506	1	0.691193206
MS3	0.787794	1	0.584923	0.783534683
MS4	0.787794	1	0.7886721	0.853845249
MS5	0.9985886	0.7895518	1	0.934309384
MS6	0.5844399	0.4661506	1	0.691193206
MS7	0.9985886	0.5862058	0.584923	0.728069861
MS8	0.9985886	0.405986	0.584923	0.672231995
MS9	0.4645302	1	1	0.815217926
MS10	0.4044805	1	1	0.794495746
CS1	0.5844399	0.7895518	0.584923	0.648156837
CS2	0.4044805	0.4661506	1	0.629092109
CS3	0.4044805	0.405986	0.4648353	0.425774446
CS4	0.4645302	0.405986	0.4648353	0.446496625
CS5	0.9985886	0.4661506	1	0.834109326
CS6	0.787794	1	1	0.92677111
CS7	0.787794	0.405986	0.584923	0.599490142
CS8	0.9985886	0.405986	0.4047119	0.610044008
CS9	0.787794	0.405986	0.7886721	0.669800709
CS10	0.5844399	0.7895518	1	0.791393264
CS11	0.787794	0.4661506	0.584923	0.618131046
CS12	0.5844399	0.405986	0.584923	0.529315876
DS1	0.9985886	0.4661506	0.7886721	0.761183465
DS2	0.4044805	0.405986	1	0.610451205
DS3	0.4645302	0.405986	0.7886721	0.558247524
DS4	0.5844399	0.7895518	0.584923	0.648156837
DS5	0.787794	0.405986	0.584923	0.599490142
DS6	0.5844399	0.7895518	0.584923	0.648156837
DS7	0.9985886	0.405986	0.7886721	0.742542561
DS8	0.9985886	0.405986	0.7886721	0.742542561
DS9	0.4645302	0.5862058	1	0.687011251
DS10	0.5844399	0.5862058	1	0.728390168
PP1	0.4645302	0.405986	1	0.631173385
PP2	0.4645302	0.405986	0.4648353	0.446496625
PP3	0.4645302	0.7895518	0.7886721	0.677088486
PP4	0.9985886	0.5862058	0.4648353	0.686629528
PP5	0.9985886	0.4661506	1	0.834109326
PP6	0.787794	0.5862058	0.584923	0.655328008
PP7	0.787794	0.405986	1	0.742726569
CA1	0.787794	0.5862058	0.584923	0.655328008
CA2	0.4044805	0.7895518	0.584923	0.58605574
CA3	0.9985886	0.405986	0.4047119	0.610044008
CA4	0.9985886	0.405986	0.4047119	0.610044008
MS2	0.4044805	1	0.4047119	0.589071332

The benefits of integrated approach are as follow:

- Experts experience and knowledge are thoroughly combined for usage in the risk analysis.
- The judgement of expert is conveyed easily in form of linguistic variable.

- Fuzzy integrated approach can overcome uncertainties, thereby making analysis more realistic, flexible and practical.
- Fuzzy GRA approach can alternatively be used without framing 'if–then' rules which otherwise requires

Table 6 Combined ranking

Sub-components	Failure code	RPN	Rank	FRPN	Rank	Degree of Relationship	Rank
Metering skid	MS1	48	3	3	4	0.691193206	7
	MS2	8	7	5	2	0.783534683	5
	MS3	4	8	5	2	0.853845249	2
	MS4	3	9	0.75	5	0.934309384	1
	MS5	32	4	3	4	0.691193206	7
	MS6	20	5	5	2	0.728069861	6
	MS7	50	2	5	2	0.672231995	8
	MS8	8	7	3	4	0.815217926	3
	MS9	9	6	4	3	0.794495746	4
	MS10	90	1	6	1	0.648156837	9
Compressor	CS1	80	7	5	2	0.629092109	6
	CS2	630	1	5	2	0.425774446	12
	CS3	504	2	8	1	0.446496625	11
	CS4	7	11	0.75	5	0.834109326	2
	CS5	3	12	2	4	0.92677111	1
	CS6	108	4	5	2	0.599490142	9
	CS7	90	5	5	2	0.610044008	8
	CS8	54	8	4	3	0.669800709	5
	CS9	8	10	4	3	0.791393264	3
	CS10	84	6	5	2	0.618131046	7
	CS11	180	3	5	2	0.529315876	10
	CS12	16	9	5	2	0.761183465	4
Dispenser	DS1	100	3	5	2	0.610451205	6
	DS2	126	2	6	1	0.558247524	8
	DS3	60	5	6	1	0.648156837	4
	DS4	150	1	5	2	0.599490142	7
	DS5	60	5	6	1	0.648156837	4
	DS6	20	8	5	2	0.742542561	1
	DS7	18	9	5	2	0.742542561	1
	DS8	40	6	5	2	0.687011251	3
	DS9	25	7	5	2	0.728390168	2
	DS10	72	4	5	2	0.631173385	5
Priority panel	PP1	560	1	5	1	0.446496625	6
	PP2	48	3	5	1	0.677088486	4
	PP3	42	4	5	1	0.686629528	3
	PP4	8	6	0.75	3	0.834109326	1
	PP5	72	2	5	1	0.655328008	5
	PP6	18	5	3	2	0.742726569	2
	PP7	48	3	5	1	0.655328008	5
Cascade	CA1	120	1	5	1	0.58605574	3
	CA2	81	3	5	1	0.610044008	1
	CA3	90	2	5	1	0.610044008	1
	CA4	90	2	5	1	0.589071332	2

expertise. It can be easily modified to meet system requirement.

- Assigning weights to the variables in study, makes risk analysis more realistic.

- The integrated approach obtains risk priorities in simple and straightforward manner.
- The integrated approach in form of decision support system assist system analyst in decision making.

The outcomes are useful for maintenance engineer and system analyst for assessing risk and planning for effective maintenance policy. The present methodology can be applied to other processing system like Petrochemical Plant, Chemical Plant, Aerospace Industries, Fertilizer Plant, Power Plant, where there is use of inflammable fuel or working substance.

References

Amuthakkannan R, Kannan SM, Selladurai V, Vijayalakshmi K (2008) Software quality measurement and improvement for real-time systems using quality tools and techniques: a case study. Int J Ind Syst Eng 3(2):229–256

Arabian-Hoseynabadi OH, Tavner PJ (2010) Failure modes and effects analysis (FMEA) for wind turbines. Int J Electr Power Energy Syst 32(7):817–824

Chen Z, Wu X, Qin J (2014) Risk assessment of an oxygen-enhanced combustor using a structural model based on the FMEA and fuzzy fault tree. J Loss Prev Process Ind 32:349–357

Das S, Sadiq R, Tesfamariam S (2011) An aggregative fuzzy risk analysis for flood incident management. Int J Syst Assur Eng Manag 2(1):31

Deng J (1989) Introduction to grey system theory. J Grey Syst 1(1):1–24

Du Y, Mo H, Deng X, Sadiq R, Deng Y (2014) A new method in failure mode and effects analysis based on evidential reasoning. Int J Syst Assur Eng Manage 5(1):1–10

Feili HR, Akar N, Lotfizadeh H, Bairampour M, Nasiri S (2013) Risk analysis of geothermal power plants using failure modes and effects analysis (FMEA) technique. Energy Convers Manag 72:69–76

Gaula AK, Sharma RK (2015) Analyzing the effect of maintenance strategies on throughput of a typical FMC (3-M, 1-R). Int J Syst Assur Eng Manag 6(2):183–190

Goyal S, Grover S (2012) Applying fuzzy grey relational analysis for ranking the advanced manufacturing systems. Grey Syst Theory Appl 2(2):284–298

Guimaraes AC, Lapa CMF (2004) Effects analysis fuzzy inference system in nuclear problems using approximate reasoning. Ann Nucl Energy 31(1):107–115

Hekmatpanah M, Shahin A, Ravichandran N (2011) The application of FMEA in the oil industry in Iran: the case of four litre oil canning process of Sepahan Oil Company. Afr J Bus Manag 5(7):3019

Ighravwe DE, Oke SA (2017) A fuzzy-grey-weighted aggregate sum product assessment methodical approach for multi-criteria analysis of maintenance performance systems. Int J Syst Assur Eng Manag 8(2):961–973

Ilangkumaran M, Shanmugam P, Sakthivel G Visagavel (2014) Failure mode effect analysis using fuzzy AHP process. Int J Product Qual Manag 14(3):296–313

Kuo Y, Yang T, Huang G (2008) The use of grey relational analysis in solving multiple attribute decision-making problems. Comput Ind Eng 55(1):80–93

Li X, Zhao C (2009) Selection of suppliers of vehicle components based on green supply chain. In: 16th International Conference on industrial engineering and engineering management, 2009. IE&EM'09. IEEE, pp 1588–1591

Olson DL, Wu D (2006) Simulation of fuzzy multi attribute models for grey relationships. Eur J Oper Res 175(1):111–120

Özcan T, Çelebi N, Esnaf Ş (2011) Comparative analysis of multi-criteria decision-making methodologies and implementation of a warehouse location selection problem. Expert Syst Appl 38(8):9773–9779

Panchal D, Kumar D (2016a) Integrated framework for behaviour analysis in a process plant. J Loss Prev Process Ind 40:147–161

Panchal D, Kumar D (2016b) Stochastic behaviour analysis of power generating unit in thermal power plant using fuzzy methodology. OPSEARCH 53(1):16–40

Panchal D, Kumar D (2017a) Stochastic behaviour analysis of real industrial system. Int J Syst Assur Eng Manag 8(2):1126–1142

Panchal D, Kumar D (2017b) Risk analysis of compressor house unit in thermal power plant using integrated fuzzy FMEA and GRA approach. Int J Ind Syst Eng 25(2):228–250

Panchal D, Jamwal U, Srivastava P, Kamboj K, Sharma R (2018a) Fuzzy methodology application for failure analysis of transmission system. Int J Math Oper Res 12(2):220–237

Panchal D, Mangla SK, Tyagi M, Ram M (2018b) Risk analysis for clean and sustainable production in a urea fertilizer industry. Int J Qual Reliab 35(7):1459–1476

Rajesh R, Ravi V (2015) Supplier selection in resilient supply chains: a grey relational analysis approach. J Clean Prod 86:343–359

Srivastava P, Khanduja D, Agrawal VP (2017) A framework of fuzzy integrated MADM and GMA for maintenance strategy selection based on agile enabler attributes. Math Ind Case Stud 8(1):5

Srivastava P, Khanduja D, Agrawal VP (2018) Integrating agile thinking into maintenance strategy performance analysis. Int J Process Manag Benchmark 8(2):228–245

Tang H (2015) A novel fuzzy soft set approach in decision making based on grey relational analysis and Dempster-Shafer theory of evidence. Appl Soft Comput 31:317–325

Wang L, Chu J, Wu J (2007) Selection of optimum maintenance strategy based on a fuzzy analytic hierarchy process. Int J Prod Econ 107(1):151–163

Xu K, Tang LC, Xie M, Ho SL, Zhu ML (2002) Fuzzy assessment of FMEA for engine systems. Reliab Eng Syst Saf 75:17–29

Zhou Q, Thai VV (2016) Fuzzy and grey theories in failure mode and effect analysis for tanker equipment failure prediction. Saf Sci 83:74–79

Zhu Y, Wang R, Hipel KW (2012) Grey relational evaluation of innovation competency in an aviation industry cluster. Grey Syst Theory Appl 2(2):272–283