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CASE STUDIES

Development of a risk-based maintenance decision making approach for automotive production line

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Abstract Automotive industries require effective and reliable maintenance strategies to ensure high levels of availability and safety. Risk-based maintenance approach is a useful tool for maintenance decision making with the aim of reducing the overall risk in operating activities. In this paper, a Failure Mode and Effect Analysis (FMEA) model as one of the risk assessment techniques is developed with subjective information derived from domain experts. To overcome the drawbacks of traditional FMEA for risk priority number (RPN) estimation, a linguistic fuzzy set theory, through effective decision attributes in complex automotive equipment is conducted. The main attributes of this approach include the effect of experts' traits, scales variation, using various membership functions and defuzzification algorithms on reliable Fuzzy-RPN (FRPN) estimation. The result of the proposed model revealed that altering membership functions and defuzzification algorithms had no significant effect on the FRPN estimation, but their values are highly affected by the number of scales. The sensitivity analysis showed that experts' traits have no sensible impact on experts' opinion for FRPN estimation, while the detectability index has more impact on FRPN variation. The result of risk classification number showed that the maintenance decision making could be included for the failure modes with the highest RPN values as a priority, which it would be useful to achieve the high level of availability and safety.

Keywords Automotive industry · Fuzzy set theory · Maintenance decision making · RPN value · Sensitivity analysis

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1 Introduction

Reliability and safety issues are increasingly concerning in process industries, which have significant contribution satisfying the demand and increase the quality toward sustainable production (Verma et al. 2010; Soltanali et al. 2018; Di Bona et al. 2018). Risk analysis is one of the most important technique for evaluating the reliability and safety of production systems under Failure Modes and Effects Analysis (FMEA) technique (Carbone and Tippett 2004; Bahill and Smith 2009). FMEA plays a key role to deal with the ensuring minimum risks (Hsu and Chen 1996; Keskin and Özkan 2009; Sharma and Sharma 2015). Besides, it is a regular employed procedure to achieve the continuous quality progress through prevention of failures and reducing their severity and occurrence, regarding maintenance decision making (Woodhouse 2005; Bona et al. 2018).

In this regards, the so-called Risk-Based Maintenance (RBM) approach under systematic FMEA model has been used to develop effective maintenance strategies towards appropriate decision making in a wide range of industries including Geothermal power plants (Feili et al. 2013), Medical industry (Cagliano et al. 2011), Oil industry (Hekmatpanah et al. 2011), Nuclear power plants (Kang et al. 2009), Food industry (Bertolini et al. 2006), Water utility sector (Pollard et al. 2004), Automotive, Aerospace, and Manufacturing industries (Press 2003). Despite many advantages of the traditional FMEA in detecting the critical bottlenecks and its ability to maintenance decision making process under Risk Priority Number (RPN), it has been criticized for a number of shortcomings and limitations which have been stated by others (Liu et al. 2015b; Chanamool and Naenna 2016), including:

1. Making the same RPN with different combinations of risk factors (Occurrence (O), Severity (S), and Detection (D)).
2. The above risk factors are assumed to be equally important. In other words the relative importance of O, S and D is ignored, which is more likely exists, when considering a practical application of FMEA.
3. It is difficult to precisely estimate the three risk factors. Much information in the FMEA could be claimed in a linguistic way, such as likely, important, very high and etc.

To overcome the aforementioned limitations of the traditional FMEA, many efforts have been made. Consequently, the fuzzy set theory (known as Fuzzy-FMEA) as a computational intelligence has been developed (Kirkire et al. 2015).

1.1 Literature review of Fuzzy-FMEA

The fuzzy set theory based FMEA approach has been used in a variety of engineering fields to eliminate the mentioned drawbacks. A Fuzzy-FMEA approach was proposed by Yazdi et al. (2017) for aircraft landing system. The comparison of results with the traditional FMEA revealed that the fuzzy developed model can yield a reasonable and credible priority ranking of failure modes. In another research, Zhou and Thai (2016) developed a fuzzy theory in FMEA for shipping tankers' failure prediction. The fuzzy set theory was used to calculate the fuzzy risk priority numbers. Their results confirmed that the practical proposed model can improve the accuracy of prediction, and hence it may be used to better decision-making regarding inspection and maintenance activities.

A case study of steam valve system was considered to propose a Fuzzy-FMEA by Liu et al. (2016). All information about the risk factors of O, S and D and their relative weights in linguistic terms were nominated by fuzzy numbers. In another study, traditional and Fuzzy-FMEA models of risk analysis in a sterilization unit of a large hospital have been presented by Dağsuyu et al. (2016). Their results revealed that both of proposed models have a high accuracy for the risk assessment and effective for the prioritization of failure modes. Liu et al. (2015a) established a novel risk assessment methodology by combining the fuzzy decision-making trial and evaluation laboratory, to rank the failures risk in the traditional FMEA. They emphasized that the traditional FMEA does not consider the indirect relations between failure modes of a system and it is insufficient for complex systems with many subsystems. Failure analysis was also performed employing fuzzy membership function by Helvacioglu and Ozen (2014) to find out the critical failures during yacht design.

Therefore, it can be concluded that the fuzzy theory based FMEA models has great potential to overcome the drawbacks of the traditional models and estimate the RPN, more precisely. In these models, often the Triangular (Trimf) and Trapezoidal (Trapmf) are considered as the core membership functions (MFs) and the center of gravity (Centroid) technique is assumed as main defuzzification algorithm. Whereas, the other type of functions and algorithms are not surveyed to estimate the Fuzzy-RPN (FRPN). In this study, as main contribution, the impact of various membership functions and defuzzification algorithms were investigated to estimate the FRPNs. Subsequently, three types of fuzzy scales were performed to examine their ability for RPN clustering. Besides, the impact of experts' traits through a sensitivity analysis was investigated to obtain a more reliable estimation of FRPN for their application towards maintenance decision making.

Furthermore, one of the main objective of this study is to decide and suggest some appropriate maintenance actions to help managers to achieve a higher reliability and safety guarantee in process industry, especially automotive industry. In such industry, the FMEA models are mainly categorized as Design-FMEA (DFMEA) and Process-FMEA (PFMEA). These models may be used for component, system, process, vehicle, or customer (Press 2003; Semp et al. 2006). For instance, a PFMEA model with lean approach has been used to fix problems and identify the critical failures in an automotive company (Banduka et al. 2016). In another study, Banduka et al. (2016) applied a PFMEA model on a sample of suppliers for an automotive production company in the UK. This research aimed to response the concerns and inhibitors of users and evaluate the PFMEA model as a problem prevention technique to reflect best performance in automotive operations. Besides,

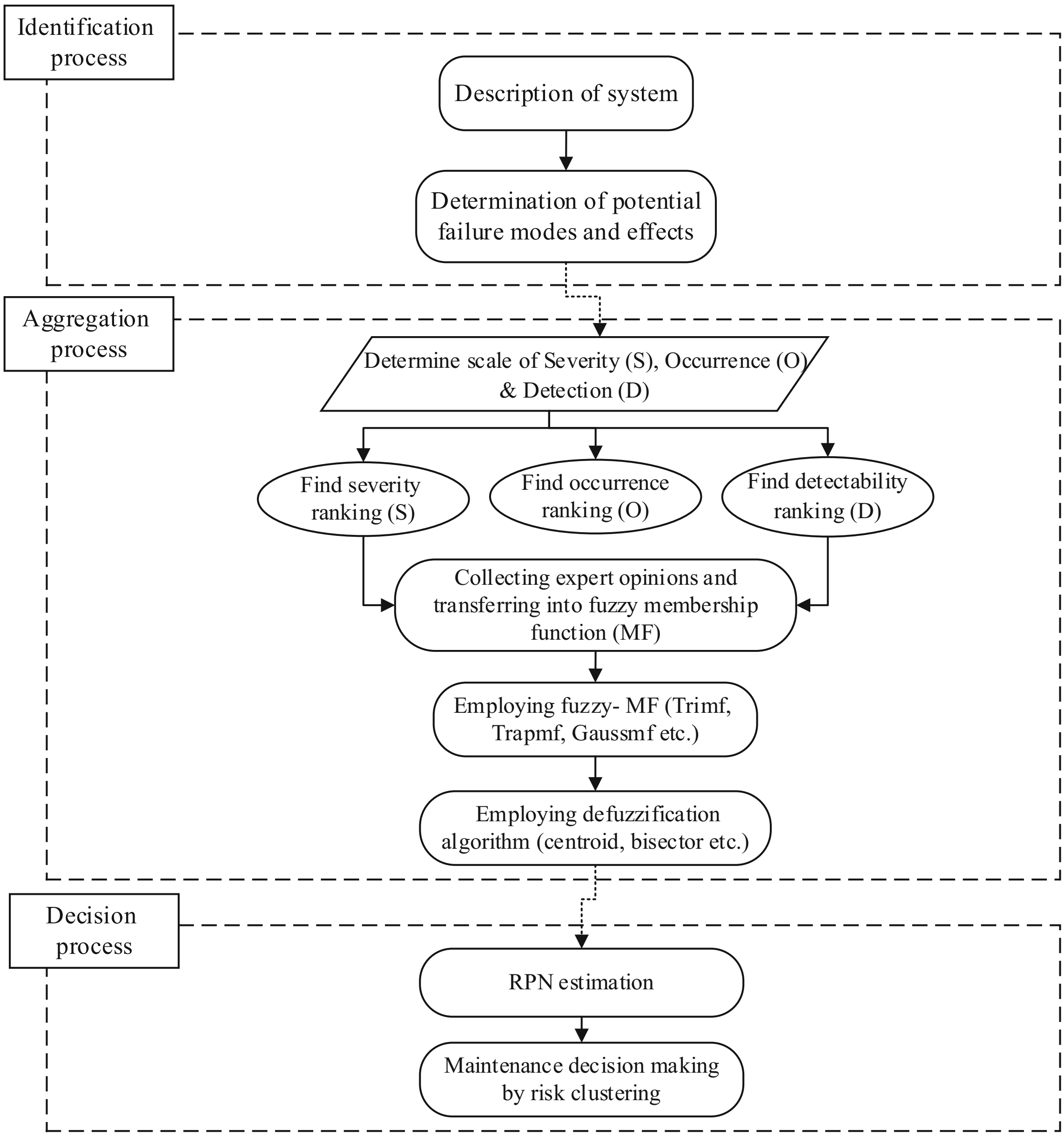

Fig. 1 The framework of the proposed Fuzzy-FMEA model

a DFMEA model was introduced to design a comfortable automotive driver seat by Kolich (2014). The results showed that this systematic approach could highlight the main potential seating comfort failure modes, reduce their risk, and bring capable designs to life. Therefore, it is concluded that the FMEAs approaches are useful tool and can help designers and engineers for improving the products and services in automotive industries (Vinodh and Santhosh 2012; Johnson and Khan 2003).

Despite the successful application of such approaches in design and process phases, the viewpoint of maintenance decision making to help engineering mangers has not been investigated in automotive sector, particularly in production operations. For this purpose, this study aimed to develop an RBM approach to select the effective maintenance tasks under developed fuzzy theory based FMEA model on a complex equipment in an automotive production line.

2 Methodology

As seen in Fig. 1, a systematic framework is proposed to implement the Fuzzy-FMEA model. Primary identification of system, aggregation process and decision process are the three key stages in the proposed model. Firstly, in the

Table 1 Linguistic scale for risk parameters

Linguistic term	Severity of effect (S)	Probability of occurrence (O)	Detectability (D)
Remote (R)	A failure has little or no impact on the system, and the operator probably will not notice {1}	A failure will be detected almost certainly by the inspection automatically of the whole process {1}	A failure will be detected almost certainly by the inspection automatically of the whole process {9, 10}
Low (L)	A failure causes slight annoyance to operator, and no deterioration on system{2, 3}	A failure will be detected until the review inspected or test but not automatically {2, 3}	A failure will be detected until manual inspection or test carried out {7, 8}
Moderate (M)	A failure causes slight deterioration in system performance and a high level of operator dissatisfaction {4, 5, 6}	A failure will be detected until manual inspection or test carried out {4, 5, 6}	A failure will be detected until the review inspected or test but not automatically {4, 5, 6}
High (H)	A failure causes significant deterioration or in operation on the system {7, 8}	A failure will be detected only with thorough inspection or test, and it is not feasible to be done {7, 8}	A failure will be detected only with thorough inspection or test, and it is not feasible to be done {2, 3}
Very high (VH)	A failure causes extremely impact on system, production loss and/or serious injury to operators {9, 10}	A failure will be detected hardly because of no known measure to solve {9, 10}	A failure will be detected hardly because of no known measure to solve {1}

Table 2 Score rating according to experts' trait

Item	Categorize	Score	Item	Categorize	Score
Education	Ph.D	5	Profession position	Higher-ranking academic	5
	Master	4		Low-ranking academic	4
	Bachelor	3		Engineer	3
	Associate	2		Technician	2
	Diploma	1		Worker	1
Age	More than 40	4	Job tenure	More than 20 years	5
	36–39	3		16–20	4
	30–35	2		10–15	3
	< 30	1		6–9	2
				≤ 5	1

identification process, the main functions of system is described and subsequently, the potential failure modes and their effects are found. Followed by, in the aggregation process, expert judgments are conducted to find the three risk parameters; S, O and D of failure mode. Also, their judgments are transferred to the fuzzy membership function and then the defuzzification procedure is performed to convert the experts' judgments to corresponding crisp possibility. Finally in the decision process, RPN is calculated and suitable maintenance actions through risk clustering method are suggested.

2.1 Definition of severity (S), occurrence (O) and detection (D)

Linguistic scale of risk parameters and score rating according to expert's traits are provided in Tables 1 and 2. These factors were determined using linguistic expression and various scales were offered by Yazdi et al. (2017). In traditional FMEA, the risk numbers are used to prioritize the failures modes. The S, O, and D indices could be divided into five-linguistic term including Remote (R), Low (L), Moderate (M), High (H) and Very high (VH) (Table 1). This attitude will help the FMEA team to prioritize the failure mods and their effects (Guimarães and Lapa 2007). Due to the various opinion, information, experience, and intellectual attributes of FMEA specialists for each indices, a combination of expert opinions should be used for this purpose (Preyssl 1995). On the other hand, the FMEA team in terms of age, expertise, skill, experience, knowledge level, etc. are almost heterogeneous (Helvacioglu and Ozen 2014; Yazdi and Soltanali 2018). The main expert's traits are described in Table 2. To calculate the RPN, first the S, O, and D indices are obtained by affecting the weighted score of expert's traits, then RPN is calculated by Eq. (1).

$$S = \sum_{i=1}^{4} w_i S_i, \quad O = \sum_{i=1}^{4} w_i O_i, \quad D = \sum_{i=1}^{4} w_i D_i, \quad RPN = S.O.D \tag{1}$$

where w is the weighted score of ith expert's traits.

2.2 Rating stage

In order to transfer the linguistic expressions to their corresponding fuzzy numbers, Chen and Hwang (1992) presented an eight group of scales with different expressions. Also, a scale one including two-linguistic expressions and scale eight including the 13-linguistic expressions were proposed by Nicolis and Tsuda (1985). Further, a numerical approximation was proposed by Gupta and Bhattacharya (2007). Recently, Yazdi et al. (2017) offered a transferring six-scale which includes five-linguistic expressions for finding the severity and occurrence indices.+ Towards improving the Fuzzy-FMEA model as an alternative to RPN estimation in the present study, to define the S, O, and D indices, three modes of 3-scale, 5-scale, and 10-scale were evaluated along with four types of membership function (MF) including: Triangular-shaped (Trimf), Trapezoidal-shaped (Trapmf), Π-shaped (Pimf) and Gaussian (Gauss2mf) (see Tables 3, 4 and 5).

2.3 Aggregation process

In this section, aggregation process of expert judgments was assigned to achieve a reliable decision, because each expert might have a variety of opinions about failure modes. This process is conducted via the following steps (Hsu and Chen 1996):

1. Calculating degree of similarity between opinion of every two experts S ($\tilde{A}$, $\tilde{B}$) Eq. (2):

$$S(\tilde{A}, \tilde{B}) = 1 - \frac{1}{J}\sum_{i=1}^{J} |a_i - b_i| \tag{2}$$

where J is the parameters of the membership function; a_i and b_i are also the parameters of the membership function.

2. Computing the Relative Agreement (RA) degree, (AA (E_u)) of expert's opinion Eq. (3):

$$AA(E_u) = \frac{1}{J-1} \sum_{v=1, u\neq v}^{J} S(\tilde{R}_u, \tilde{R}_v) \tag{3}$$

3. Computing the Relative Agreement (RA (E_u)) degree, of expert's opinion Eq. (4):

$$RA(E_u) = \frac{AA(E_u)}{\sum_{u=1}^{J} AA(E_u)} \tag{4}$$

4. Calculating the consensus coefficient degree of expert's opinion (CC (E_u)) Eq. (5):

$$CC(E_u) = \beta \cdot W(E_u) + (1-\beta) \cdot RA(E_u) \tag{5}$$

where W is the weight of each experts, β is relaxation factor ($0 \leq \beta \leq 1$) wherever it can be used for sensitivity analysis to determine sensible effect of expert's traits on experts' opinion.

5. Computing the final result of expert's opinions ($\tilde{R}_{AG}$) Eq. (6):

$$\tilde{R}_{AG} = CC(E_1) \otimes \tilde{R}_2 \oplus CC(E_2) \otimes \tilde{R}_2 \oplus \cdots \oplus CC(E_m) \otimes \tilde{R}_M \tag{6}$$

where $\oplus$ is a fuzzy sum operation and $\otimes$ is a fuzzy scalar multiply operation.$\tilde{R}_{AG}$ is a fuzzy set in which the defuzzification method must be used to calculate explicit RPN values. For this purpose, five algorithms including centroid, bisector, smallest of maximum (SOM), middle of maximum (MOM) and largest of

Table 3 Fuzzy 3-scale with 4 membership function for S, O and D

Rank	Linguistic expression	MF function	Fuzzy number
1, 2, 3	Low (L)	Trapmf	(0.0, 0.0, 0.2, 0.04)
		Trimf	(0.0, 0.2, 0.04)
		Gauss2mf	(0, 0, 0.07, 0.22)
		Pimf	(0.0, 0.0, 0.22, 0.38)
4, 5, 6, 7	Medium (M)	Trimf	(0.2, 0.5, 0.8)
		Trapmf	(0.23, 0.47, 0.53, 0.77)
		Gauss2mf	(0.10, 0.47, 0.10, 0.53)
		Pimf	(0.23, 0.47, 0.53, 0.77)
8, 9, 10	High (H)	Trapmf	(0.6, 0.8, 1.0, 1.0)
		Trimf	(0.6, 0.8, 1.0)
		Gauss2mf	(0.07, 0.08, 0.0, 1.0)
		Pimf	(0.62, 0.78, 1.0, 1.0)

Table 4 Fuzzy 5-scale with 4 membership function for S, O and D

Rank	Linguistic expression	MF function	Fuzzy number
1	Very low (VL)	Trapmf	(0.0, 0.0, 0.1, 0.2)
		Trimf	(0.0, 0.1, 0.2)
		Gauss2mf	(0.0, 0.0, 0.03, 0.11)
		Pimf	(0.00, 0.00, 0.11, 0.19)
2, 3	Low (L)	Trapmf	(0.1, 0.2, 0.3, 0.4)
		Trimf	(0.05, 0.25, 0.45)
		Gauss2mf	(0.03, 0.19, 0.03, 0.31)
		Pimf	(0.11, 0.19, 0.31, 0.39)
4, 5, 6	Medium (M)	Trapmf	(0.3, 0.4, 0.6, 0.7)
		Trimf	(0.20, 0.50, 0.80)
		Gauss2mf	(0.03, 0.39, 0.03, 0.61)
		Pimf	(0.31, 0.39, 0.61, 0.69)
7, 8	High (H)	Trapmf	(0.6, 0.7, 0.8, 0.9)
		Trimf	(0.55, 0.75, 0.95)
		Gauss2mf	(0.03, 0.69, 0.03, 0.81)
		Pimf	(0.61, 0.69, 0.81, 0.89)
9, 10	Very high (VH)	Trapmf	(0.8, 0.9, 1.0, 1.0)
		Trimf	(0.8, 0.9, 1.0)
		Gauss2mf	(0.03, 0.89, 0.00, 1.00)
		Pimf	(0.81, 0.89, 1.00, 1.00)

Table 5 Fuzzy 10-scale with 4 membership function for S, O and D

Rank	LE	MF	Fuzzy number	Rank	LE	MF	Fuzzy number
1	Very low (VL)	Trimf	(0.0, 0.1, 0.2)	6	More or less high (MH)	Trimf	(0.5, 0.6, 0.7)
		Trapmf	(0.01, 0.09, 0.11, 0.19)			Trapmf	(0.51, 0.59, 0.61, 0.69)
		Gauss2mf	(0.03, 0.09, 0.03, 0.11)			Gauss2mf	(0.03, 0.59, 0.03, 0.61)
		Pimf	(0.01, 0.09, 0.11, 0.19)			Pimf	(0.51, 0.59, 0.61, 0.69)
2	Low (L)	Trimf	(0.1, 0.2, 0.3)	7	Fairly high (FH)	Trimf	(0.6, 0.7, 0.8)
		Trapmf	(0.11, 0.19, 0.21, 0.29)			Trapmf	(0.61, 0.69, 0.71, 0.79)
		Gauss2mf	(0.03, 0.19, 0.03, 0.21)			Gauss2mf	(0.03, 0.69, 0.03, 0.71)
		Pimf	(0.11, 0.19, 0.21, 0.29)			Pimf	(0.61, 0.69, 0.71, 0.79)
3	Fairly low (FL)	Trimf	(0.2, 0.3, 0.4)	8	High (H)	Trimf	(0.7, 0.8, 0.9)
		Trapmf	(0.21, 0.29, 0.31, 0.39)			Trapmf	(0.71, 0.79, 0.81, 0.89)
		Gauss2mf	(0.03, 0.29, 0.03, 0.31)			Gauss2mf	(0.03, 0.79, 0.03, 0.81)
		Pimf	(0.21, 0.29, 0.31, 0.39)			Pimf	(0.71, 0.79, 0.81, 0.89)
4	More or less low (ML)	Trimf	(0.3, 0.4, 0.5)	9	Very high (VH)	Trimf	(0.8, 0.9, 1.0)
		Trapmf	(0.31, 0.39, 0.41, 0.49)			Trapmf	(0.81, 0.89, 0.91, 0.99)
		Gauss2mf	(0.03, 0.39, 0.03, 0.41)			Gauss2mf	(0.03, 0.89, 0.03, 0.91)
		Pimf	(0.31, 0.39, 0.41, 0.49)			Pimf	(0.81, 0.89, 0.91, 0.99)
5	Medium (M)	Trimf	(0.4, 0.5, 0.6)	10	Extremely high (VH)	Trimf	(0.9, 1.0, 1.0)
		Trapmf	(0.41, 0.49, 0.51, 0.59)			Trapmf	(0.91, 0.99, 1.00, 1.00)
		Gauss2mf	(0.03, 0.49, 0.03, 0.51)			Gauss2mf	(0.03, 0.99, 0.00, 1.00)
		Pimf	(0.41, 0.49, 0.51, 0.59)			Pimf	(0.91, 0.99, 1.00, 1.00)

LE Linguistic expression, *MF* membership function maximum (LOM) were applied. The computer code was developed in MATLAB-vR-2017b (MathworksInc, US) programming environment.

3 Results and discussion

3.1 The empirical case study

In order to implement the proposed framework, the fluid filling system, as the most critical and complex equipment, in an automotive production line was considered. The fluid filling system is in charge of filling, leveling and leakage tests in paths and pipes of vehicles by producing pressure and/or vacuum. Figure 2a and b shows the process description and structural diagram of the fluid filling system, respectively. The system consists of six critical blocks including initialization block, ready block, pressure and vacuum block, filling block, process end and lubrication blocks. The initialization block is in charge of process pressure, if the filling system tank is under pressure, the process will equalize/release the pressure. Subsequently, the system is ready to perform filling process (Ready block). There are two pumps (including vacuum and filling pumps) as well as a pressure control set to measure pressure/vacuum level. The pressure block is used to inject air into the system and, examine the pressure to ensure the filing system is free of any leakage. Followed by, the vacuum block performs the evacuation of system and checks for any vacuum leaks for a proper vacuum level in the filling system. After setting the vacuum and pressure, the filling block performs the fillings with different liquids and their leveling. For ongoing operation of the rotary equipment especially pumps, the lubrication is performed during the filling process which provided through a lubrication tank. At last, the operator can unclamp and remove the filling head from vehicle (Process end block). Figure 2b displays the main systems of a fluid filling process including the hydraulic-pneumatic circuit, the electronic circuit and the filling head set.

In addition, the potential functional failures, failure modes and effects of the fluid filling system are presented in Table 6. As seen, a fluid filling system is divided into three major sub-systems with 23 failure modes (Fm). The pumps, especially the vacuum pump, operate more often and they are active in all of filling process. Therefore, they are subjected to a higher occurrence of failures. On the other hand, failure effect defines the degree of impressionable subsystems from failure mode consequences. In other words, some failure modes in the fluid filling system may lead not only to equipment disability but also to downtime in the whole production line.

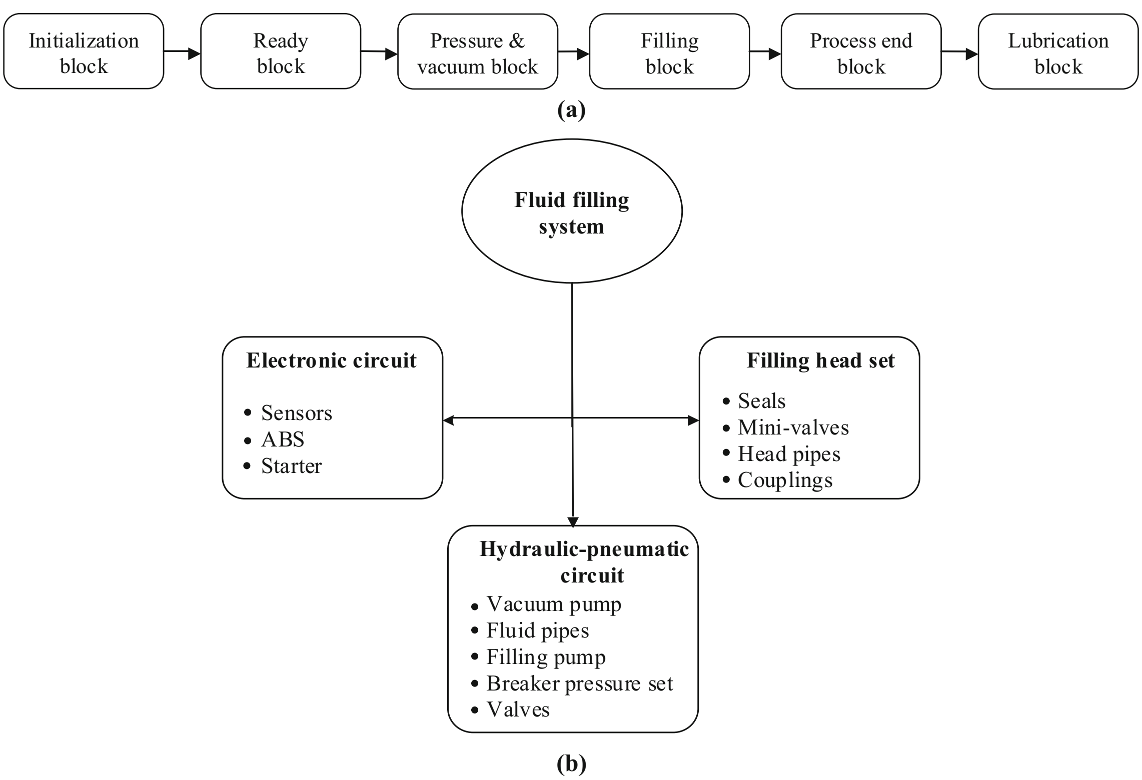

Fig. 2 Process description (**a**) and structural diagram (**b**) of the fluid filling system

Table 6 Functional failures, failure modes and effects in the fluid filling system

Sub-system	Component	Functional failure	Serial number of failure mode	Failure modes	Failure effects description
Hydraulic–pneumatic circuit	Filling pump	Fluid filling failed	Fm $_1$	Bearing failure affected by corrosive cause	Breakdown of filling pump and equipment
			Fm $_2$	Electromotor failure affected by circuit faults	
			Fm $_3$	Goring the wears	
			Fm $_4$	Seals fail affected by more function	
	Vacuum pump	Vacuum supply failed	Fm $_5$	Filter fail affected by more function	Breakdown of vacuum pump and equipment
			Fm $_6$	Rotor fail affected by more function	
			Fm $_7$	Fatigue and strain of spring affected by more pressure	
			Fm $_8$	Electromotor failure affected by circuit faults	
			Fm $_9$	Blade fail affected by more function	
	Fluid pipes	Failure in air and fluid transfer	Fm $_{10}$	Leakage and corrosion of pipes	Lead to leakage increase and fault in filling process
	Breaker pressure set	The actual pressure is not shown	Fm $_{11}$	Excessive system pressure	Do not display the exact pressure. This issue leads to damage the pipes and valves
		Pressure supply failed	Fm $_{12}$	Spring fails of pressure control valve	Incorrect adjustment of circuit lead to pressure instability
			Fm $_{13}$	Failure and abrasion of activator	Incorrect adjustment of circuit pressure that leads to pressure instability
	Valves	Improper close and open	Fm $_{14}$	Failure and abrasion of spool valve	In addition to displaying the values, it can disrupt the process
			Fm $_{15}$	Valves failure effected by more function	
		Improper adjustment	Fm $_{16}$	Failure and abrasion of activator	In addition to displaying the values, it can disrupt the process
Filling head set	Couplings	Fluid filling failure	Fm $_{17}$	Failure and leakage of couplings	Leaks in filling head interfere the process of filling and testing of fluid
	Mini-valves		Fm $_{18}$	Failure or leakage of mini-valves	
	Seals		Fm $_{19}$	Failure of O-rings and seals affected by more function	
	Head pipes		Fm $_{20}$	Leakage of head pipes	
Electronic circuit	Sensors	Detection of fluid, pressure failed	Fm $_{21}$	Sensors failure affected by more function and circuit confusion	Resulting in equipment fault and ultimately leading to disruption of production operations
	ABS	Failure in test brake paths	Fm $_{22}$	Failure of conductor, cables and main units such as bobbin and cores	There is no electronic connection to open the electric valves and hydraulic valves
	Starter	Fluid filling failed	Fm $_{23}$	Starter failure affected by circuit confusion	There is no possibility of filling through the head set

3.2 Rating expert judgment

As mentioned earlier, in order to implement the FMEA method, a group of experts are required. Table 2 clearly indicates that the weights (scores) of experts are not the same. Hence, Table 7 shows the experts' weights related to the fluid filling system in an automotive production line and their characteristic to accomplish the process judgments in the FMEA approach.

3.3 Traditional FMEA results

The result of traditional FMEA to estimate the S, O, and D as well as RPNs for each failure mode of fluid filling system based on experts' judgment are given in Table 8. As it can be seen, however some RPNs are different from each other, but they have a same judgment. For instance, the RPN of O-rings and seals as 19th failure mode has first priority rank from the all expert opinion provided their RPNs are 504, 700, 720 and 630, respectively. Further, most of priority ranking of failure modes are different from each other. It is noteworthy that experts are not to be able to cluster the 23 failures within 23 risk group. Hence, the

Table 7 Expert weighting of group decision-making for the present case study

Expert	Education	Age	Profession position	Job tenure	Weighting score (w)
Expert 1:	Bachelor (3)	35 (2)	Engineer (3)	15 (3)	0.244
Expert 2:	Master (4)	38 (3)	Low-ranking academic (4)	10 (3)	0.311
Expert 3:	Associate (2)	30 (2)	Technician (2)	16 (4)	0.222
Expert 4:	Associate (2)	34 (2)	Technician (2)	16 (4)	0.222
Total	11	9	11	14	45/45 = 1

Table 8 Traditional RPN value for different failure modes based on four expert's opinion

Fm	Expert 1				Rank	Expert 2				Rank	Expert 3				Rank	Expert 4				Rank
	S	O	D	RPN		S	O	D	RPN		S	O	D	RPN		S	O	D	RPN	
1	10	2	7	140	16	10	3	8	**240**	12	9	2	6	108	19	10	3	8	**240**	12
2	9	2	7	126	17	8	2	6	96	18	9	3	6	162	18	8	3	8	192	15
3	8	3	6	144	15	7	3	6	126	17	8	2	5	80	20	7	3	8	168	16
4	7	5	6	210	12	6	5	6	180	16	7	6	5	210	16	6	4	6	144	17
5	9	6	6	**324**	8	8	6	5	**240**	12	9	6	5	270	11	8	5	6	**240**	12
6	9	9	5	405	4	9	9	6	486	2	9	9	4	**324**	7	9	9	5	405	2
7	9	8	6	**432**	3	7	6	6	252	10	8	6	7	336	6	9	7	5	**315**	7
8	9	7	6	378	5	7	5	7	245	11	8	8	7	448	3	9	7	5	**315**	7
9	10	5	10	500	2	9	4	10	**360**	5	10	5	9	450	2	8	4	8	256	11
10	6	3	2	36	18	4	2	4	32	20	5	3	4	60	21	6	3	3	54	20
11	9	8	5	**360**	6	8	7	5	**280**	9	9	7	4	252	12	9	6	6	324	5
12	10	9	2	180	14	10	10	1	100	19	10	8	3	240	13	9	7	3	189	19
13	10	10	2	200	13	10	10	2	200	14	10	10	2	200	17	10	10	2	**200**	14
14	8	10	3	240	11	7	9	3	189	15	8	10	4	320	8	7	9	2	126	18
15	8	10	4	320	9	7	9	5	315	7	8	10	5	400	5	9	10	4	360	3
16	7	10	4	**280**	10	8	10	5	**400**	3	8	9	4	**288**	9	7	10	5	350	4
17	10	7	5	350	7	9	8	5	**360**	5	10	7	6	420	4	9	5	6	270	10
18	9	9	4	**324**	8	8	7	5	**280**	9	9	8	4	**288**	9	8	7	4	224	13
19	8	9	7	504	1	10	10	7	700	1	9	10	8	720	1	10	9	7	630	1
20	10	7	4	**280**	10	10	7	3	210	13	9	6	4	216	15	10	6	5	300	8
21	10	7	4	**280**	10	10	8	5	**400**	3	10	7	4	280	10	10	8	4	320	6
22	9	8	5	**360**	6	8	8	5	320	6	8	7	4	224	14	9	8	4	288	9
23	9	8	6	**432**	3	8	7	5	**280**	9	9	6	6	**324**	7	10	5	4	**200**	14

Bold values with same RPN value have same rank in each column

Table 9 The results of using 3-scale fuzzy method for different membership functions

Fm	Trapmf				Trimf				Gauss2mf				Pimf				Average	Rank
	S	O	D	FRPN	S	O	D	FRPN	S	O	D	FRPN	S	O	D	FRPN		
1	8	2	7	37	8	2	7	**35**	6	1	6	**41**	8	1	7	35	37	16
2	8	2	6	31	8	2	6	**35**	6	1	6	**41**	8	1	6	30	34	17
3	7	2	6	25	7	2	6	25	6	1	6	**41**	7	1	6	23	29	18
4	5	5	5	123	5	5	5	123	6	6	6	200	5	5	5	123	142	12
5	8	5	5	218	8	5	5	218	6	6	6	193	8	5	5	209	210	8
6	8	8	5	**351**	8	8	5	351	6	6	6	187	8	8	5	354	**310**	2
7	8	6	5	**214**	8	6	5	**212**	6	6	6	**192**	8	6	5	**215**	**208**	**9**
8	8	6	5	**214**	8	6	5	**212**	6	6	6	**192**	8	6	5	**215**	**208**	**9**
9	8	5	8	**351**	8	5	8	346	6	6	6	187	8	5	8	354	**310**	2
11	5	2	3	10	5	2	3	14	6	1	5	35	5	1	3	9	17	19
11	8	6	5	**239**	8	6	5	235	6	6	6	191	8	6	5	**245**	**228**	**7**
12	8	8	2	**46**	8	8	2	40	6	6	1	**40**	8	8	1	40	42	15
13	8	8	2	**46**	8	8	2	46	6	6	1	**40**	8	8	1	44	44	14
14	7	8	2	86	7	8	2	86	6	6	3	87	7	8	2	85	86	13
15	8	8	5	314	8	8	5	314	6	6	6	**188**	8	8	5	316	283	4
16	7	8	5	**281**	7	8	5	75	6	6	6	**188**	7	8	5	283	207	10
17	8	6	5	244	8	6	5	244	6	6	6	191	8	6	5	**245**	231	6
18	8	7	5	276	8	7	5	276	6	6	6	189	8	7	5	278	**258**	**5**
19	8	8	6	411	8	8	6	411	6	6	6	185	8	8	6	405	353	1
20	8	5	4	164	8	5	4	164	6	6	5	182	8	5	4	164	169	11
21	8	7	5	**281**	8	7	5	281	6	6	6	**188**	8	7	5	283	**258**	**5**
22	8	8	5	322	8	8	5	322	6	6	6	**188**	8	8	5	323	289	3
23	8	6	5	**239**	8	6	5	241	6	6	6	191	8	6	5	240	**228**	**7**

Bold values with same RPN value have same rank in each column

Table 10 The results of using 5-scale fuzzy method for different membership functions

Fm	Trapmf				Trimf				Gauss2mf				Pimf				Average	Rank
	S	O	D	FRPN	S	O	D	FRPN	S	O	D	FRPN	S	O	D	FRPN		
1	9	3	7	158	9	3	7	155	9	3	7	159	9	3	7	158	37	18
2	8	3	6	127	8	3	6	124	8	3	6	128	8	3	6	127	34	19
3	8	3	6	102	8	3	6	105	8	3	6	103	8	3	6	102	29	20
4	6	5	5	153	6	5	5	153	6	5	5	153	6	5	5	153	142	14
5	8	5	5	205	8	5	5	205	8	5	5	206	8	5	5	205	210	10
6	9	9	5	419	9	9	5	421	9	9	5	426	9	9	5	421	311	2
7	8	6	6	282	8	6	6	282	8	6	6	285	8	6	6	283	**208**	**11**
8	8	7	6	353	8	7	6	353	8	7	6	354	8	7	6	354	**208**	**11**
9	9	5	9	385	9	5	9	385	9	5	9	390	9	5	9	386	310	3
10	5	3	4	47	5	3	4	47	5	3	4	47	5	3	4	47	17	21
11	9	7	5	300	9	7	5	300	9	7	5	301	9	7	5	300	**228**	**9**
12	9	8	2	156	9	8	2	156	9	8	2	156	9	8	2	156	42	17
13	9	9	3	**210**	9	9	3	**210**	9	9	3	**213**	9	9	3	**210**	44	16
14	8	9	3	**210**	8	9	3	**210**	8	9	3	**213**	8	9	3	**210**	86	15
15	8	9	5	358	8	9	5	358	8	9	5	362	8	9	5	359	283	5
16	8	9	5	**341**	8	9	5	**341**	8	9	5	**343**	8	9	5	**341**	207	12
17	9	7	5	316	9	7	5	316	9	7	5	317	9	7	5	317	231	8
18	8	8	5	324	8	8	5	319	8	8	5	327	8	8	5	325	255	7
19	9	9	8	601	9	9	8	600	9	9	8	610	9	9	8	603	353	1
20	9	6	4	249	9	6	4	249	9	6	4	250	9	6	4	250	169	13
21	9	8	5	**341**	9	8	5	**341**	9	8	5	**343**	9	8	5	**341**	258	6
22	8	8	5	308	8	8	5	308	8	8	5	309	8	8	5	308	289	4
23	9	6	5	273	9	6	5	273	9	6	5	274	9	6	5	273	**228**	**9**

Bold values with same RPN value have same rank in each column failures have been classified into 18, 20, 21 and 20 risk group. It means that some of failure modes have the same priority ranking. For example, 11th, 18th, 23rd failure modes in second expert's opinion have same priority ranking of 9th. This problem is considered as a withdrawn in traditional FMEA method. Hence, to solve such problems, in this study, a developed fuzzy theory based FMEA technique for risk analysis performed.

3.4 Fuzzy-FMEA results

The results of Fuzzy-FMEA model for three indices of S, O, and D as well as FRPNs under 3-scale, 5-scale and 10-scale considering four membership function and five defuzzification algorithms are provided in Tables 9, 10 and 11. The results obtained from statistical comparison by employing the four membership function subjected to the different scales revealed that there has not been any significant difference between FRPNs. It means that the type of membership functions had not influenced on FRPN estimation. While the comparison between the FRPNs average obtained from the three scales for each type of membership function showed that they have a significant difference. The average FRPNs obtained from 5-scale and 10-scale modes was not significantly differ (291 and 274), but their difference with 3-scale was meaningful (163). Therefore, it can be mentioned that the number of scale in the definition of S, O, and D indices has a significant effect on FRPNs. The results of Fuzzy-FMEA model based on 3-scale show that it has not success to classify the 23 failures into 23 risk groups. In this context, the traditional FMEA result may be reliable to FRPN estimation. For example, in this case, the FRPN values for failure modes 7 and 8 are same into different membership functions. The result of the 5-scale implementation showed that the performance of the Fuzzy-FMEA method has mostly improved. However, 23 failure modes are classified into 21 clusters. Further, the results of the 10-scale implementation showed that the Fuzzy-FMEA method could successfully classify the 23 failure modes into 23 clusters. Therefore, the number of scale is a primary ingredient in the performance of the Fuzzy-FMEA method.

Given that the high performance with 10-scale, various defuzzification algorithms were evaluated. As seen in Table 12, most of the failure modes have the same ranking and even the difference in their RPN values are not statistically significant with different algorithms. Therefore, it can be concluded that defuzzification algorithms have no significant effects on FRPN and Rank values.

Table 11 The results of using 10-scale fuzzy method for different membership functions

Fm	Trapmf				Trimf				Gauss2mf				Pimf				Average	Rank
	S	O	D	FRPN	S	O	D	FRPN	S	O	D	FRPN	S	O	D	FRPN		
1	10	3	7	172	10	3	7	172	10	3	7	174	10	3	7	173	173	20
2	8	3	7	139	8	3	7	139	8	3	7	139	8	3	7	139	139	21
3	7	3	6	127	7	3	6	127	7	3	6	127	7	3	6	127	127	22
4	7	5	6	184	7	5	6	184	7	5	6	184	7	5	6	184	184	18
5	8	6	6	264	8	6	6	264	8	6	6	264	8	6	6	264	264	14
6	9	9	5	403	9	9	5	403	9	9	5	403	9	9	5	403	403	2
7	8	7	6	326	8	7	6	326	8	7	6	326	8	7	6	326	326	7
8	8	7	6	341	8	7	6	341	8	7	6	340	8	7	6	341	341	5
9	9	5	9	368	9	5	9	368	9	5	9	371	9	5	9	369	369	3
10	5	3	3	46	5	3	3	46	5	3	3	46	5	3	3	46	46	23
11	9	7	5	301	9	7	5	301	9	7	5	301	9	7	5	301	301	10
12	10	8	2	176	10	8	2	176	10	9	2	177	10	9	2	176	176	19
13	10	10	2	185	10	10	2	185	10	10	2	188	10	10	2	186	186	17
14	7	9	3	206	7	9	3	206	7	9	3	208	7	9	3	207	207	16
15	8	10	5	337	8	10	5	337	8	10	5	339	8	10	5	337	337	6
16	8	10	6	319	8	10	5	319	8	10	5	321	8	10	5	320	320	8
17	9	7	5	344	9	7	6	344	9	7	5	345	9	7	5	344	344	4
18	8	8	4	276	8	8	4	276	8	8	4	276	8	8	4	276	276	13
19	9	9	7	608	9	9	7	608	9	9	7	615	9	9	7	610	610	1
20	10	7	4	243	10	7	4	243	10	7	4	244	10	7	4	243	243	15
21	10	8	4	307	10	8	4	307	10	8	4	310	10	8	4	308	308	9
22	8	8	5	294	8	8	5	294	8	8	5	294	8	8	5	294	294	12
23	9	7	5	300	9	7	5	300	9	7	5	301	9	7	5	300	300	11

Table 12 The results of using different defuzzification algorithms

Fm	Centroid		Bisector		MOM		LOM		SOM	
	FRPN	Rank	FRPN	Rank	FRPN	Rank	FRPN	Rank	FRPN	Rank
1	172	20	173	19	175	19	172	20	173	20
2	139	21	141	21	133	21	139	21	141	21
3	127	22	128	22	122	22	127	22	128	22
4	184	18	182	18	179	18	184	18	182	18
5	264	14	263	14	259	14	264	14	263	14
6	403	2	405	2	396	2	403	2	405	2
7	326	7	330	7	315	7	326	7	330	7
8	341	5	346	6	331	6	341	5	346	4
9	368	3	373	3	372	3	368	3	373	3
10	46	23	46	23	44	23	46	23	46	23
11	301	10	305	12	291	12	301	10	305	10
12	176	19	178	20	173	20	176	19	178	19
13	185	17	188	17	186	17	185	17	188	17
14	206	16	206	16	202	16	206	16	206	16
15	337	6	338	5	334	5	337	6	338	6
16	319	8	321	8	316	8	319	8	321	8
17	344	4	341	4	340	4	344	4	341	5
18	276	13	278	13	268	13	276	13	278	13
19	608	1	609	1	614	1	608	1	609	1
20	242	15	241	15	242	15	242	15	241	15
21	307	9	313	9	308	9	307	9	313	9
22	294	12	291	11	291	11	294	12	291	12
23	301	11	301	10	301	10	301	11	301	11

3.5 Sensitivity analysis

A sensitivity analysis was performed to assess the effect of risk factors on FRPN. This is beneficial to prevent unexpected failures and hence, increase the safety and availability of fluid filling system through suitable maintenance decision making process. The results of the sensitivity analysis, indicating the impact of three plus and minus variations in S, O, and D indices on FRPN value are shown in Figs. 3, 4 and 5. It can be seen, the increasing and decreasing the S index has no effective impact on FRPN values and their prioritization. However, the S variation for

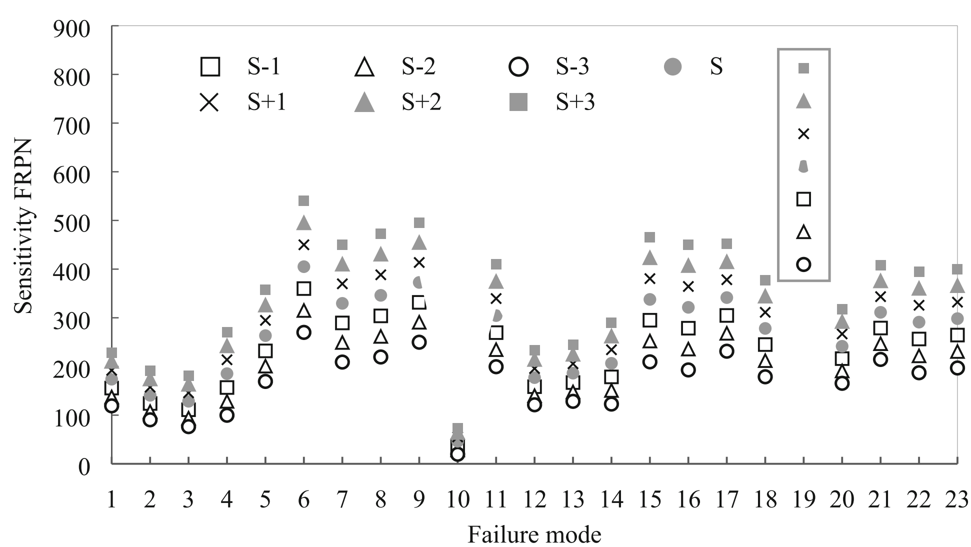

Fig. 3 Sensitivity analysis of severity on FRPN

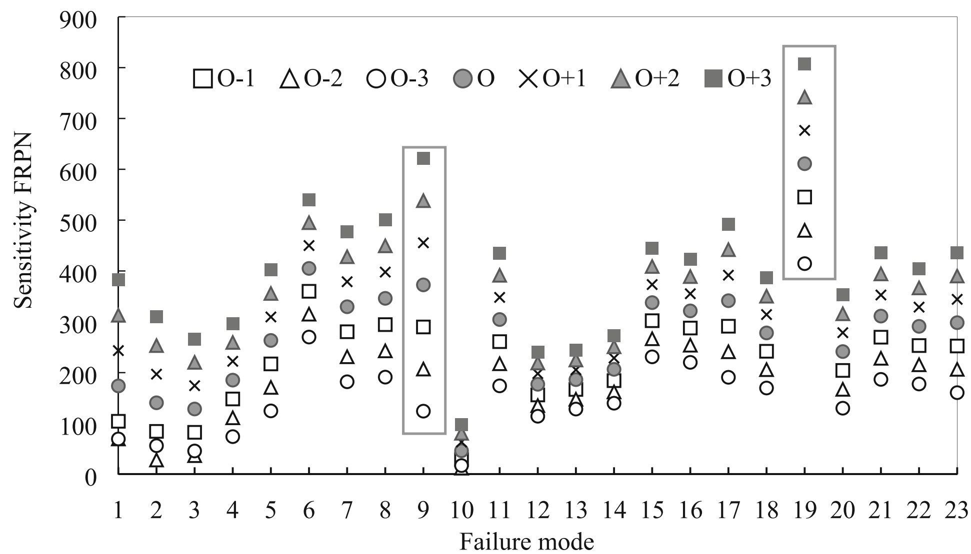

Fig. 4 Sensitivity analysis of occurrence on FRPN

19th (seals) failure mode has the greatest impact on FRPN (Fig. 3). As seen in Fig. 4, the impact of O variation on FRPN value and risk priority is more effective than S indices. As seen, the O variation for the 9th (blade failure of the vacuum pump) and the 19th (the seals) failure modes have the greatest impact on FRPN. The sensitivity result of D indices on RPN value are given in Fig. 5. It can be seen, increasing the D indices in the most failure modes have the major positive impact on FRPN and their priority clustering compared with other risk parameters. Hence, considering the above results, the D, O, and S indices respectively, have the most effective on the FRPN variation and it's ranking on failure modes, as well. Further, the sensitivity analysis was applied to find out the beta effect on the FRPNs. Beta values are selected as a set of 0.1, 0.3, 0.5, 0.7 and 0.9 which are presented in Fig. 6. The result represents the beta coefficient is not sensitive on FRPN value. It means that in this study, the expert's traits has not sensible impact on FRPN estimation.

3.6 Maintenance decision making

In this section, the risk classification of failure modes related to fluid filling system in an automotive assembly lines and their application to maintenance decision making to help engineering managers were discussed. After prioritizing the failure modes into 23 risk levels under 10-scale mode, a risk classification to suggest the suitable maintenance actions includes low (0–104), medium (104–208), high (208–312), very high (312–415) and critical (415–623) that are presented in Table 13. Based on the results, the 19th failure mode (O-rings and seals) due to the

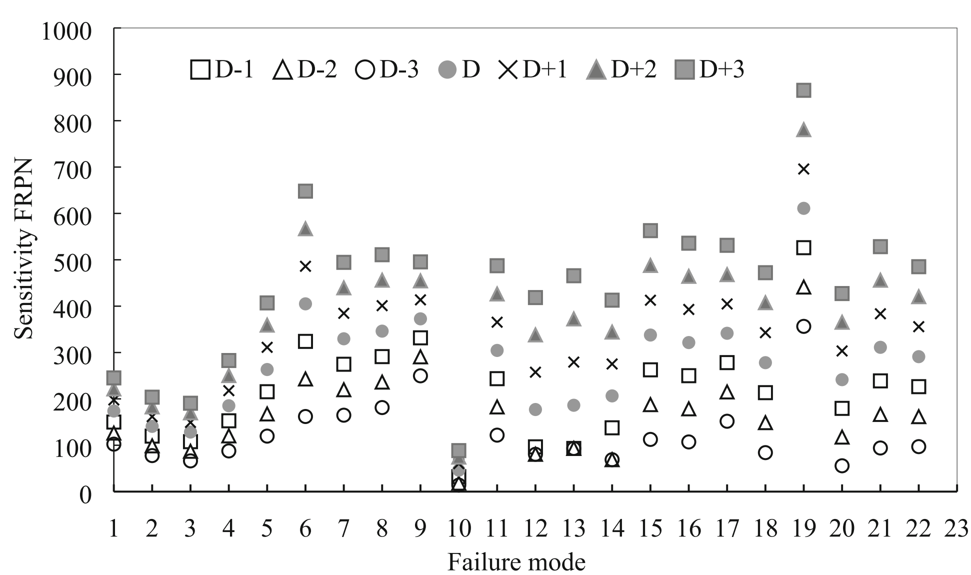

Fig. 5 Sensitivity analysis of detectability on FRPN

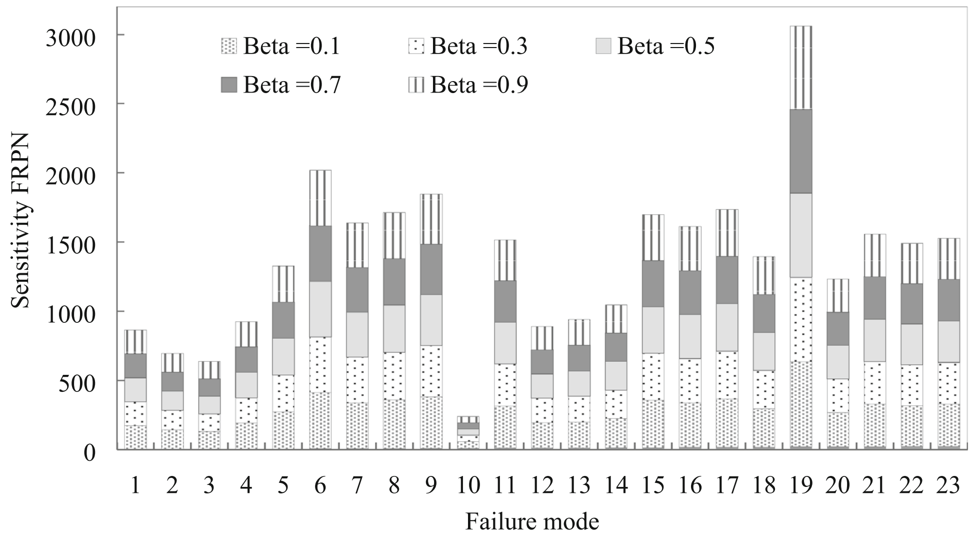

Fig. 6 Sensitivity analysis of the expert's traits on FRPN estimation

Table 13 The result of risk classification of failure modes

Subsystem	Component	No. failure	FRPN	Rank	Sensitivity
Hydraulic–pneumatic circuit	Filling pump	1	177	15	Medium
		2	138	20	Medium
		3	127	17	Medium
		4	183	16	Medium
	Vacuum pump	5	264	18	High
		6	404	10	Very high
		7	325	6	Very high
		8	341	8	Very high
		9	375	2	Very high
	Fluid pipes	10	46	23	Low
	Pressure control valve	11	300	4	Medium
		12	178	21	Medium
		13	189	22	Medium
	Hydro-valves	14	207	19	Medium
		15	340	12	Very high
		16	321	9	Very high
Filling head set	Couplings	17	345	3	Very high
	Mini-valves	18	276	13	High
	O-rings and seals	19	616	1	Critical
	Head pipes	20	245	14	High
Electronic circuit	Sensors	21	312	5	High
	ABS	22	296	11	High
	Starter	23	304	7	High

more function in filling head set has allocated the first class with the highest FRPN value. Followed by, 6th (rotor failure), 7th (fatigue and strain of spring affected), 8th (electromotor failure) and 9th (blade failure) for vacuum pumps, 15th and 16th for hydraulic–pneumatic valves, and also 17th (couplings in filling head set) failure modes have allocated the second group with the highest RPN values. It can be mentioned that the majority of failures with the highest FRPN value are related to filling head set and hydraulic–pneumatic circuit. From the filling head set, the operator's error might be due to weakness of maintenance staff in servicing and daily inspections, and neglecting suitable training of operators. Therefore, some training courses for maintenance staff and operators of the fluid filling system with the aim of improving their performance and increasing the experiences and skills should be considered. In addition to, improving the technical aspects of filing head set such as using light weight head could affect personal faults reduction and the ergonomic aspect would be prohibited form muscle and joint pressures. In order to reduce personal faults, a filling head set known as G^3 Blue that consider ergonomic evolution and weight reduction up to 20% has been designed. From the hydraulic-pneumatic circuit, especially for vacuum pumps due to high operation, the main actions such as well-timed inspection and servicing are very important.

4 Conclusion

This paper aimed to study the risk analysis through a developed Fuzzy-FMEA model and its application to the automotive industry. The main functional failures, failure modes and their effects for a fluid filling system were determined. As a novelty to reliable estimation of RPN, the effect of expert's traits, different type of scales, various membership functions and defuzzification algorithms were evaluated as main effective decision attributes. The results revealed that the Fuzzy-FMEA model with 10-scale could be used as a reliable attitude and credible alternative to risk analysis. The sensitivity analysis showed that expert's traits had no sensible impact on FRPN estimation and the detectability index is more effective on FRPN variation. In addition, based on risk classification results, the maintenance decision making can be employed for the failures with the highest RPN value as a priority. These results could be useful to help the engineering manages to improve availability and safety of fluid filling systems in automotive assembly lines. In addition, due to the lack of operative risk analysis in maintenance decision making process, further enhancements and investigations are recommended as combination of the existing decision making methods.

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