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New Representations for Potential Failure Modes and Corrective Actions in FMEA

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Abstract. Failure modes and effects analysis (FMEA) is a popular reliability tool in petroleum engineering. In FMEA, potential failure modes or corrective actions are evaluated, each assigned a Risk Priority Number (RPN) score, and prioritized for decision making. FMEA is also known as Failure Modes, Effects, and Criticality Analysis (FMECA), while focuses on failure modes prioritization. Despite of the popularity of FMEA and FMECA, it is not clear, how potential failure modes and corrective actions could be represented systematically, for effective decision making. In this paper, two new representations (i.e., a tree representation and a vector representation), for potential failure modes and corrective actions, are proposed. The tree representation for a potential failure mode allows its root cause(s), effect(s) and corrective action(s), together with their severity, occurrence and detection rating(s), to be represented as a three-layer tree model. The tree representation for a corrective action with similar contents is outlined too. The RPN model, together with its score, is represented as a node of the tree model. These tree models can also be represented as their associated equivalence layered-vector representations. In this paper, the usefulness of the proposed approaches is illustrated with benchmark FMEA worksheets pertaining to petroleum engineering.

Keywords. Corrective actions, FMEA, FMECA, Layered-vector representation, Potential failure modes, Risk Priority Number, Tree models.

1. Introduction

Failure modes and effects analysis (FMEA) was first proposed as a formal and systematic design methodology for use in the aerospace industry in 1960s[1]. Since then, FMEA has been proven to be a useful methodology in evaluating potential failure modes and preventing potential failure modes from occurring [1–3]. In general, FMEA is a reliability engineering methodology used to identify and eliminate known and potential failure modes (e.g., problems, or errors) for a design, system, service or process [2]. FMEA is also known as Failure Modes, Effects, and Criticality Analysis (FMECA), while focuses on potential failure modes prioritization [4].

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Today, FMEA has been widely used in a variety of domains, which include automotive [2], electronic [4], chemical [5], aerospace [6], healthcare [7], nuclear [8], manufacturing [9, 10], mechanical [11], agriculture [12] and petroleum engineering [13–16]. Figure 1 illustrates a flow chart of the FMEA methodology (details are presented in Section 2.1). A potential failure mode occurs if a subsystem, part, component, or process fails to meet its intended purpose of functions. A root cause leads to the occurrence of a potential failure mode. The corrective action(s) of a root cause need to be identified too. For each potential failure mode, the effect(s) of the potential failure mode also needs to be determined. The corrective actions or potential failure modes are then prioritized using a Risk Priority Number (RPN) model. The RPN model takes into account three risk factors, i.e., Severity (S), Occurrence (O), and Detection (D). S is an evaluation of the effects of a potential failure mode. O is the evaluation of likelihood that a specific root cause to occur. While D is an evaluation of the effectiveness of the current control mechanism to detect a potential root cause.

Traditionally, an RPN score is obtained by direct multiplication of the S, O, and D ratings. The potential failure modes or corrective actions associated with higher RPN scores are usually given higher priorities. Although FMEA has been widely applied in several domains, it is susceptible to a number of limitations [6, 17]. Indeed, many efforts have been proposed to tackle those limitations [6, 17–24]. Despite of the popularity of research works relating to FMEA and FMECA, it is not clear, how potential failure modes and corrective actions could be represented systematically, for effective decision making.

The aim of this paper is two-folded. Firstly, in this paper, two new representations, i.e., a tree representation and a vector representation, for potential failure modes and corrective actions, are proposed for FMECA and FMEA, respectively. Our proposed tree representation for a potential failure mode allows its root cause(s), effect(s) and corrective action(s), together with their S, O and D rating(s), to be represented as a three-layer tree model. The tree representation for a corrective action, with similar contents, is devised too. In our proposals, the RPN model, together with its score, is represented as a node of the tree models. To ease the handling, these tree representations can also be denoted as their associated equivalence layered-vector representations. Secondly, the usefulness of the proposals for handling potential failure modes with missing risk rating(s) is illustrated too. In this paper, the usefulness of the proposed representations is illustrated with two benchmark FMEA worksheets pertaining to petroleum engineering [13] [14].

2. Preliminaries

2.1. FMEA Procedure

The procedure of FMEA involves several activities, as depicted in Figure 1.

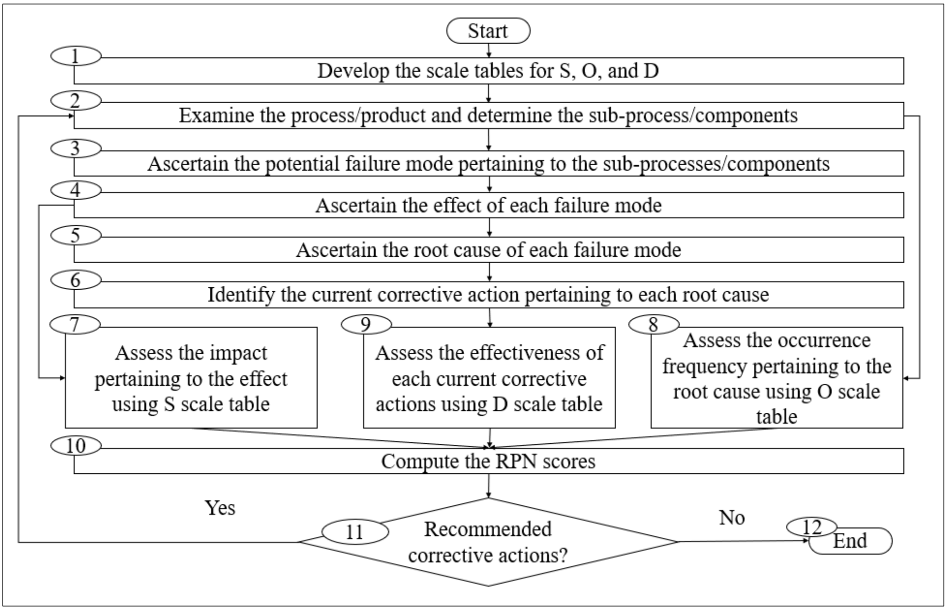

Figure 1. A FMEA Procedure.

A description of the key activities is as follows.

1. Develop the scale tables for S, O, and D risk factors;
2. Examine the process or product and determine the sub-processes or components, respectively;
3. Ascertain the *potential failure mode(s)* of the sub-processes or components;
4. Ascertain the *effect(s)* of each potential failure mode;
5. Ascertain the *root cause(s)* of each potential failure mode;
6. Identify the current *corrective action(s)* pertaining to each *root cause*;
7. Assess the impact pertaining to the *effect* using the S scale table;
8. Assess the occurrence frequency pertaining to the *root cause* using the O scale table;
9. Assess the effectiveness of each current *corrective action* using the D scale table;
10. Compute the RPN scores;
11. Back to (2) if there is any *corrective action*;
12. End.

It is worth noting that a corrective action could be a prevention method, a control action, or a detection method.

2.2. Background

Two definitions from [23] and [24] are considered, as follows.

Definition 1. [23] Three risk factors in an FMEA activity, i.e., S, O, and D, are considered. These risk ratings are represented by $s, o,$ and d, i.e., $s \in \mathrm{S}, o \in \mathrm{O},$ and $d \in \mathrm{D}$, respectively. In addition, the lower and upper bounds of S, O, and D are represented by $\underline{s}$ and $\overline{s}$, $\underline{o}$ and $\overline{o}$, and $\underline{d}$ and $\overline{d}$, respectively.

Definition 2. [24] The RPN space contains all possible RPN scores, i.e., $RPN \in$ RPN space. The lower and upper bounds of the RPN space are denoted by $\underline{RPN}$ and $\overline{RPN}$, respectively, and $\underline{RPN} \leq RPN \leq \overline{RPN}$ is always true.

Note that, a notation, $x \in \{s, o, d\}$ is used, in which x is an element of $\{s, o, d\}$. Besides, x is a natural number, i.e., $x \subset \mathbb{N}$ and $\underline{x} \leq x \leq \overline{x}$ is always true.

3. New Tree and Vector Representations with Benchmark Information

3.1. Notations

An FMEA activity with N failure modes (F_i) or N corrective actions (C_i) to be prioritized, is considered, where $i = 1, 2, \dots, N$. The effect(s), root cause(s), and control(s) or prevention method(s), for F_i or C_i, are denoted by $E_i, RC_i,$ and PM_i, respectively. Each $E_i, RC_i,$ and PM_i is associated with $E_{i,a}, RC_{i,b},$ and $PM_{i,c}$, respectively. The S, O, and D ratings of $E_{i,a}$, $RC_{i,b}$, and $PM_{i,c}$, for F_i or C_i, are denoted by $s_{i,a}$, $o_{i,b}$, and $d_{i,c}$, respectively, such that $a = 1, 2, \dots, u$, $b = 1, 2, \dots, v$, and $c = 1, 2, \dots, w$. Note that $w = 1$ for C_i. The RPN score of F_i or C_i is denoted as RPN_i. To ease the explanation, two benchmark information (i.e., FMEA worksheets) are considered.

3.2. Example [13]

A FMEA worksheet (See Figure 2) for a seal pump from [13] is considered. The focus is on the design of a seal pump, for the oil and gas industry. A total of 7 failure modes need to be prioritized, i.e., $N = 7$. The tree model of F_4 is depicted in Figure 3. The first layer of F_4 consists of its *root node*, also representing the RPN model and together with its RPN score, i.e., $RPN_4 = 168$. There are three nodes in the second layer, also the children for the *root node*, i.e., $E_4, RC_4,$ and PM_4. $E_4, RC_4,$ and PM_4 are associated with $s_4 = 7, o_4 = 8,$ and $d_4 = 3$, respectively. In the third layer, the *children nodes* of E_4, RC_4, and PM_4 are $E_{4,1}, E_{4,2}, E_{4,3}$, $RC_{4,1}, RC_{4,2}, RC_{4,3}$, and $PM_{4,1}, PM_{4,2}, PM_{4,3}$, respectively. $E_{4,1}$, $E_{4,2}$, and $E_{4,3}$ are associated with $s_{4,1} = 7$, $s_{4,2} = 4$, and $s_{4,3} = 6$, respectively. $RC_{4,1}$, $RC_{4,2}$, and $RC_{4,3}$ are associated with $o_{4,1} = 7$, $o_{4,2} = 8$, and $o_{4,3} = 5$, respectively. $PM_{4,1}$, $PM_{4,2}$, and $PM_{4,3}$ are associated with $d_{4,1} = 1$, $d_{4,2} = 3$, and $d_{4,3} = 2$, respectively.

F_i	Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	S	Potential Cause(s) / Mechanism(s) of Failure	O	Current Design Controls	D	RPN	Recommended Action(s)	Responsibility and Target Completion Date
	Seals										
F_1	Sensor mount. seal	Loosen during sensor assembly / service	Leakage	6	Fitting not held in place	1		1	6	New fitting design. Prototype validation	Reliability engineer
F_2		Damaged internal thread	Cannot install sensor	6	Damaged during installation or transportation	1		1	6	Quality control in installation and transportation	Quality supervisor
F_3		Damaged external thread	Cannot install wire nut	3	Damage during shipment to customer	2		1	6	Quality control in shipment	Logistic supervisor
F_4	Hose connection	Crack / break burst. Bad seal poor hose quality	Leak	7	Over pressure	7	Burst, validation pressure cycle	1	49	Test incuded in prototype and production validation testing	Reliability engineer
			Failed mount	4	Vibration	8	Vibration w/road tapes	3	96	Obtain vibration road tape	Quality supervisor
			Hose leak	6	Over pressure	5	Burst, validation pressure cycle with clamps	2	60	Obtain clamps and clamping specification	Quality supervisor
F_5	Heat transfer structure	Stress crack	Leak. Loss of heat transfer	7	Wicking. Material strength	6	Thermal cycle	1	42	Included in product specification	Quality supervisor
F_6		Corrossion	Leak. Loss of heat transfer	7	Coolant quality. Contamination. Environment – int/ext	6	Service simulation coolant evaluation	5	210	Supplier coolant to be evaluated	Reliability engineer
F_7		Steam fail	Leak. Lost of heat transfer	4	Environment – int/ext	1	Service simulation	1	4	Included in product specification	Quality supervisor

Figure 2. Design FMEA for a seal pump from [13] (page 166)

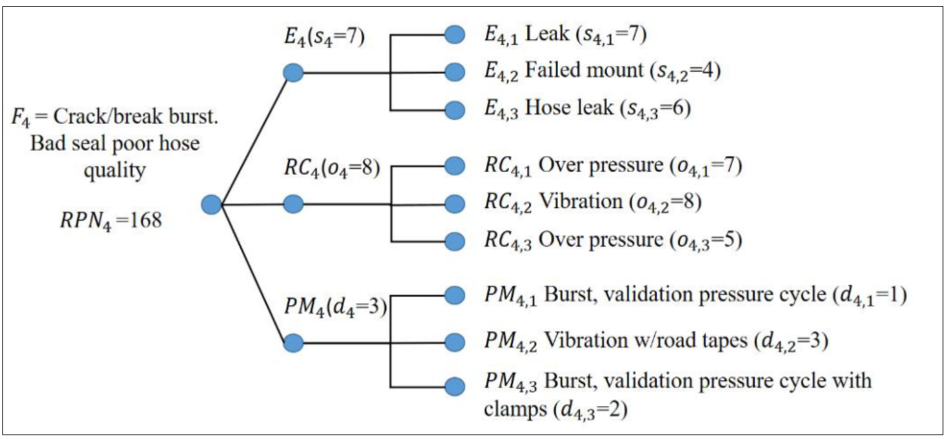

Figure 3. Three-layer rooted tree of F_4

F_i or C_i can also be represented as a nested vector, in the form of Eq. (1). RPN_i can be represented as Eq. (2), which can be further reduced to Eq. (3). All s_i, o_i, and d_i are obtained by aggregating $s_{i,a}$,$o_{i,b}$ and $d_{i,c}$ (i.e., a reduction of the tree), or by manual assignment from the FMEA users.

$$F_i/C_i = [[E_{i,1}, E_{i,2}, \dots, E_{i,u}], [RC_{i,1}, RC_{i,2}, \dots, RC_{i,v}], [PM_{i,1}, PM_{i,2}, \dots, PM_{i,w}]] \quad (1)$$

$$RPN_i = [[s_{i,1}, s_{i,2}, \dots, s_{i,u}], [o_{i,1}, o_{i,2}, \dots, o_{i,v}], [d_{i,1}, d_{i,2}, \dots, d_{i,w}]] \quad (2)$$

$$RPN_i = [s_i, o_i, d_i] \quad (3)$$

F_4 is also represented in Eq. (4). Besides, RPN_4 is represented in Eq. (5), which can be reduced to Eq. (6).

$$F_4 = \left[[E_{4,1}, E_{4,2}, E_{4,3}], [RC_{4,1}, RC_{4,2}, RC_{4,3}], [PM_{4,1}, PM_{4,2}, PM_{4,3}]\right] \quad (4)$$

$$RPN_4 = \begin{bmatrix} [s_{4,1} = 7, s_{4,2} = 4, s_{4,3} = 6], [o_{4,1} = 7, o_{4,2} = 8, o_{4,3} = 5], \\ [d_{4,1} = 1, d_{4,2} = 3, d_{4,3} = 2] \end{bmatrix} \quad (5)$$

$$RPN_4 = [s_4 = 7, o_4 = 8, d_4 = 3] \quad (6)$$

3.3. Example [14]

FMEA for a welding process from [14], is considered (see Figure 4). There is a total of 10 corrective actions to be prioritized, i.e., $N = 10$. Tree models for C_7, C_8 and C_9 are depicted in Figure 5. Note that there is only a prevention method and a D rating for each of C_7, C_8, and C_9. C_7 is used for explanation. The first layer of C_7 consists only the *root node* and it is associated to $RPN_7 = 120$. Again, the *root node* also denotes the RPN model, together with its RPN score. There are three nodes in the second layer, also the children for the *root node*, i.e., E_7, RC_7, and PM_7. E_7, RC_7, and PM_7 are associated with $s_7 = 5, o_7 = 3$, and $d_7 = 8$, respectively. In the third layer, the *children nodes* of E_7, RC_7, and PM_7, are $E_{7,1}$, $RC_{7,1}$, and $PM_{7,1}$, respectively. $E_{7,1}, RC_{7,1}$, and $PM_{7,1}$ are associated with $s_{7,1} = 5$, $o_{7,1} = 3$, and $d_{7,1} = 8$, respectively. The same applies to C_8 and C_9.

Again, C_7 is also represented as Eq. (7). RPN_7 is written as Eq. (8). The same applies to C_8 and C_9, which are represented as Eqs. (9) and (10), respectively. RPN_8 and RPN_9 are represented as Eqs. (11) and (12), respectively too.

$$C_7 = \left[[E_{7,1}], [RC_{7,1}], [PM_{7,1}]\right] \quad (7)$$

$$RPN_7 = [s_7 = 5, o_7 = 3, d_7 = 8] \quad (8)$$

$$C_8 = \left[[E_{8,1}], [RC_{8,1}], [PM_{8,1}]\right] \quad (9)$$

$$C_9 = \left[[E_{9,1}], [RC_{9,1}], [PM_{9,1}]\right] \quad (10)$$

$$RPN_8 = [s_8 = 6, o_8 = 3, d_8 = 4] \quad (11)$$

$$RPN_9 = [s_9 = 6, o_9 = 7, d_9 = 4] \quad (12)$$

C_i	Process type	Type of defects	Cause of defects	Effects of defects	Recommended actions	O	S	D	RPN before intervention	RPN after intervention
C_1	Working on saws	Throwing sparks	Working adjacent flammable materials	Fire	Installation and implementation of the fire safety requirements	9	4	4	144	104
C_2	Argon welding	Exposure to fumes and toxic gas	Fail to use appropriate protective masks	Occupational disease	Using properly designed local exhaust hoods	8	6	5	240	168
C_3	Electric welding	Throwing sparks	The nature of process	Burning	Using personal protective equipment and installing the adsorption sheets	6	5	4	120	62
C_4	Electric welding	Fall from height	Working at height	Injuries	Usage pf belts and safety net	7	9	5	315	206
C_5	Cutting metals	The explosion of cylinder	Lack of training and poor maintenance	Fire and injuris	Safety training programs	3	7	8	168	132
C_6	CO_2 welding	Flash-back flame	Equipment failure	Explosion	Using flashback arrestor	5	6	5	150	142
C_7	Welding	Fire	Fail to separate full and empty cylinders	Fire	Labeling all cylinders	3	5	8	120	96
C_8	Welding	Collision with obstacles	Improper layout	Injuries	Determining passing ways	3	6	4	72	60
C_9	Welding	Collision with forklift trucks	No warning device	Injuries	Audio and visual alarms	7	6	4	168	112
C_{10}	Welding	Hearing loss among workers	High noise levels at workplace	Deafness and hearing loss	Using personal protective equipment	8	6	4	192	148

Figure 4. FMEA for a Welding Process from [14] (page 260)

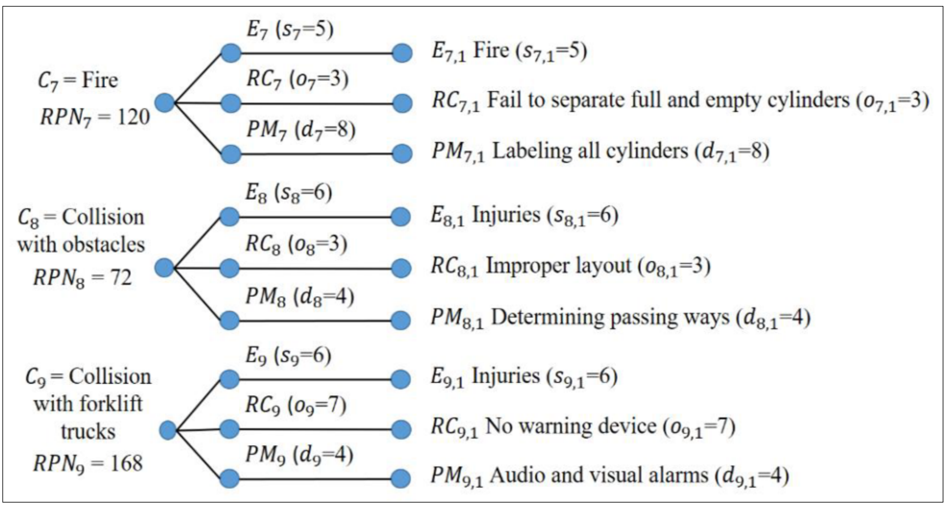

Figure 5. The three-layer rooted trees of C_7, C_8, and C_9.

4. Handling of Missing risk ratings

The proposed approaches in this paper can be extended to the case of FMEA with missing risk ratings. **Example 1** is considered. If $s_{4,2}$ and $s_{4,3}$ are missing, then $s_{4,2} = -$ and $s_{4,3} = -$. The three-layer rooted tree of F_4 with the two missing risk ratings, is depicted in Figure 6. RPN_4 is also denoted in Eq. (13), and it can be reduced to Eq. (14), by considering the worst cases of $s_{4,2}$ and $s_{4,3}$, i.e., $s_{4,2} = s_{4,3} = 10$.

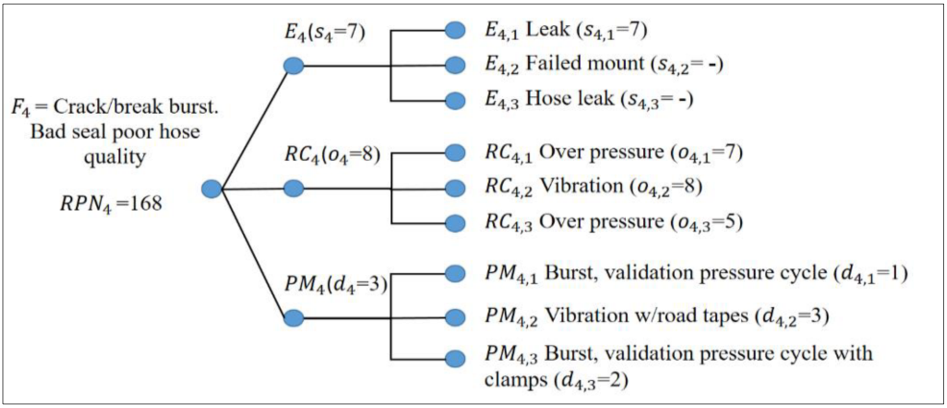

Figure 6. The three-layer rooted tree of F_4 with missing risk ratings.

$$RPN_4 = \begin{bmatrix} [s_{4,1} = 7, s_{4,2} = -, s_{4,3} = -], [o_{4,1} = 7, o_{4,2} = 8, o_{4,3} = 5], \\ [d_{4,1} = 1, d_{4,2} = 3, d_{4,3} = 2] \end{bmatrix} \tag{13}$$

$$RPN_4 = [s_4 = 10, o_4 = 8, d_4 = 3] \tag{14}$$

5. Conclusions

In this paper, two new representations, i.e., a new tree representation and a new vector representation, for potential failure modes and corrective actions were outlined. The usefulness of the proposals was demonstrated with two benchmark information sets. Besides, usefulness of the representations for FMEA with missing risk ratings was demonstrated too. As future works, monotone fuzzy inference based RPN models [18–22] [24] will be included as a part of the representations.

References

[1] Mikulak RJ, McDermott R, Beauregard M. The basics of FMEA; CRC Press; 2008.
[2] Stamatis DH. Failure mode and effect analysis: FMEA from theory to execution; ASQ Quality Press; 2003.
[3] Carlson C. Effective FMEAs: Achieving safe, reliable, and economical products and processes using failure mode and effects analysis; John Wiley & Sons; 2012.
[4] Certa A, Hopps F, Inghilleri R, La Fata CM. A Dempster-Shafer Theory-based approach to the Failure Mode, Effects and Criticality Analysis (FMECA) under epistemic uncertainty: application to the propulsion system of a fishing vessel. Reliab Eng Syst Saf. 2017;159: 69–79.
[5] Garrick BJ. The approach to risk analysis in three industries: nuclear power, space systems, and chemical process. Reliab Eng Syst Saf., 1998; 23(3):195–205.
[6] Bowles JB, Peláez CE. Fuzzy logic prioritization of failures in a system failure mode, effects and criticality analysis. Reliab Eng Syst Saf. 1995; 50(2): 203–213.
[7] Abrahamsen HB, Abrahamsen EB, Høyland S. On the need for revising healthcare failure mode and effect analysis for assessing potential for patient harm in healthcare processes. Reliab Eng Syst Saf. 2016;155: 160–168.
[8] Guimarães ACF, Lapa CMF. Fuzzy FMEA applied to PWR chemical and volume control system. Prog Nucl Energy. 2004; 44(3): 191–213.
[9] Tay KM, Lim C. Fuzzy FMEA with a guided rules reduction system for prioritization of failures. Int J

Qual Reliab Manag. 2006; 23(8), 1047–1066.
[10] Huang J, Li Z, Liu H-C. New approach for failure mode and effect analysis using linguistic distribution assessments and TODIM method. Reliab Eng Syst Saf. 2017;167: 302–309 .
[11] Xu K, Tang LC, Xie M, Ho SL, Zhu ML. Fuzzy assessment of FMEA for engine systems. Reliab Eng Syst Saf. 2002; 75(1): 17–29.
[12] Jong CH, Tay KM, Lim CP. Application of the fuzzy Failure Mode and Effect Analysis methodology to edible bird nest processing. Comput Electron Agric. 2013; 96: 90–108.
[13] Calixto E. Gas and oil reliability engineering: modeling and analysis; Gulf Professional Publishing; 2016.
[14] Kangavari M, Salimi S, Nourian R, Omidi L, Askarian A. Application of Failure Mode and Effect Analysis (FMEA) to assess risks in petrochemical industry in Iran. Iran J Heal Saf Environ. 2015; 2(2), 257–263.
[15] Maniram Kumar A, Rajakarunakaran S, Pitchipoo P, Vimalesan R. Fuzzy based risk prioritisation in an auto LPG dispensing station. Saf Sci. 2018;101: 231–247.
[16] Renjith VR, Jose KM, Kumar PH, Madhavan D. Fuzzy FMECA (failure mode effect and criticality analysis) of LNG storage facility. J Loss Prev Process Ind. 2018; 56: 537-547.
[17] Liu H-C, Liu L, Liu N. Risk evaluation approaches in failure mode and effects analysis: A literature review. Expert Syst Appl. 2013; 40(2), 828–838.
[18] Kerk YW, Tay KM, Lim CP. Monotone interval fuzzy inference systems. IEEE Trans Fuzzy Syst. 2019; 27(11): 2255 - 2264.
[19] Jee TL, Tay KM, Lim CP. A new two-stage fuzzy inference system-based approach to prioritize failures in failure mode and effect analysis. IEEE Trans Reliab. 2015; 64(3): 869–877.
[20] Pang LM, Tay KM, Lim CP. Monotone fuzzy rule relabeling for the zero-order TSK fuzzy inference system, IEEE Trans Fuzzy Syst. 2016; 24(6): 1455 - 1463.
[21] Kerk YW, Teh CY,Tay KM, Lim CP. Parametric conditions for a monotone TSK fuzzy inference system to be an *n*-ary Aggregation Function, IEEE Trans Fuzzy Syst. 2021; 29(7): 1864 - 1873.
[22] Kerk YW, Tay KM, Lim CP. Monotone Fuzzy rule interpolation for practical modelling of the zero-order TSK fuzzy inference system, IEEE Trans Fuzzy Syst. 2022; 30(5): 1248 - 1259.
[23] Chang WL, Pang LM, Tay KM. Application of self-organizing map to failure modes and effects analysis methodology. Neurocomputing. 2017; 249: 314–320.
[24] Kerk YW, Tay KM, Lim CP. An analytical interval fuzzy inference system for risk evaluation and prioritization in failure mode and effect analysis. IEEE Syst J. 2017; 11(3): 1589 - 1600.