APPLICATION OF FUZZY FMEA TO PERFORM AN EXTENSIVE RISK ANALYSIS IN MARITIME TRANSPORTATION ENGINEERING

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SUMMARY

The nature of maritime transportation involves numerous hazards, which can lead to serious consequences for human life, marine environment and ship. Therefore, achieving a high level of safety is recognised as paramount in maritime industry (Akyuz, 2016). In order to achieve this purpose, this paper prompts a fuzzy based Failure Mode and Effects analysis (FMEA) to perform an extensive risk analysis in the maritime transportation industry. The method has capable of identifying potential failures and calculating risk priority number (RPN) by capturing nonlinear casual relationships between the failures. The proposed method is applied to hatch cover failures in operational aspects in bulk carrier ships since potential failures of hydraulic hatch covers have serious concerns for ship owners. Besides its theoretical insight, the paper has practical benefits to ship owners, superintendents as well as safety professionals by identifying potential failure and offering early corrective actions.

1. INTRODUCTION

Maritime safety has one of the critical issues in maritime industry. Particular care should be taken to enhance safety and minimize risk since the consequences of failures are extremely damaging for crew, marine environment and the commodities on-board the ship. There are a large number of failures/hazards that may occur due to the nature of operations carried out on-board ships (Akyuz & Celik, 2016; Ugurlu et al., 2015; Liwang et al., 2012). In order to prevent potential failures and minimize risks, the maritime authorities have been adopting a set of regulations and circulars. Despite the growing concerns, statistics have shown that there are still fatal incidents on-board ships (Weng & Yang, 2015; Akyuz, 2015a). Therefore, safety and risk researchers have increasing their attention by focusing on proactive solutions to retain a high level of safety in the maritime transportation industry. In the literature, there have been a wide range of studies undertaken with regards to risk analysis in the past decade (Langard et al., 2015; Akyuz, 2015b; Lavasani et al. 2015; Njumo, 2013; Pillary & Wang, 2003). The primary aim of those studies is to mitigate risk level since risk combines likelihood of hazardous event and severity of consequences.

While FMEA is one of the best tools to carry out risk analysis, there have been limited studies undertaken in maritime industry. There are a few research papers conducted using the method, which provides useful information for the risk management process. For instance, Pam et al. (2013) applied fuzzy FMEA to perform a comprehensive risk analysis with regards to discharged ballast water and invasive species. Likewise, a study adopting fuzzy based FMEA was presented to perform risk analysis for yacht system design (Helvacioglu & Ozen, 2014). In the paper, the authors support their research with Multi-Attribute Group Decision Making approaches to solve the selection of failure modes on the process of yacht design. Furthermore, Yang & Wang (2015) introduced a hybrid approach including FMEA and fuzzy evidential reasoning to perform risk assessment in offshore engineering systems. To demonstrate the hybrid approach, failure criticality analysis is carried out by the collision of a FPSO system with a shuttle tanker during tandem offloading operation. A different framework integrating FMEA with ordered weighted geometric averaging (OWGA) and generalized mixture operators (GMOs) presented as a novel approach to perform a sophisticated risk analysis in marine engineering (Mentes & Ozen, 2015). The paper is demonstrated with a case study which evaluates critical causes of a motor yacht fuel system faults. A similar study was introduced to overcome limitation of conventional FMEA (Emovon et al., 2015). In the paper, the author developed two model based approach including VIKOR and CP in order to prioritise the risk of failure modes.

On the other hand, FMEA is a powerful risk analysing approach applied in maritime industry. The method has extended with both grey theory and fuzzy theory to calculate the fuzzy risk priority numbers (Zhou & Thai, 2016) in recent months. The authors have demonstrated the proposed model through a case study in which tanker equipment failures are analysed. Akyuz et al. (2016) have recently presented a technical research which integrates fuzzy logic theory into FMEA technique to evaluate CIC database of Black Sea MOU. In the paper, the fire-safety system CIC database of MOUs is evaluated and relevant risks are determined.

As the risk assessment is very critical issue to prevent crew injury, loss of life and environmental pollution, analysing of potential failures can pose a major challenge from the point of maritime safety analysis. In this context, the purpose of this paper is to perform comprehensive risk analysis by adopting fuzzy FMEA approach. The proposed approach is demonstrated with critical hatch cover failures in in bulk carrier ships. Accordingly, potential failures can be analysed and evaluated by addressing the risk priority number. In the view of above, the paper consists of following outline. This section gives brief description of the aim, scope and literature review of paper. Section 2 expresses the methodology. Section 3 provides application. Section 4 gives conclusion and contribution of the research into maritime industry.

2. METHODOLOGY

This paper takes benefit of fuzzy sets based FMEA to conduct risk analysis.

2.1 FMEA

There are a large numbers of risk analysis methods utilised in literature. One of the robust one is FMEA which enables to evaluate potential failures through the RPN. The method allows user to identify the failure modes of each component and the effects of failure on the other components (Pam et al., 2013). The effects of the relevant failure is assessed and the result of examination provides useful information for risk assessment. The method is quite simple and user friendly since it uses RPN for ranking. The RPN addresses the most critical failure modes that need to be considered. The method adopts linguistic priority terms to rank the failures of likelihood (O), severity (S) and detectability (D) by using numeric scale from 1 to 10. The RPN can be found with following equation (1).

$$RPN = O \: x \: S \: x \: D \qquad (1)$$

Hence, the highest risk level factor can be found within the system. The process of method basically compose of six main steps; i) Identify potential failures in the system, ii) Determine potential effects of each failure, iii) Determine score of likelihood, iv) Assign score of severity, v) Determine score of detectability vi) Calculate the RPN.

2.2 LIMITATION of FMEA

Although traditional FMEA has been still applying in numerus disciplines, it has some fundamental limitations (Akyuz et al., 2016; Ben-Daya & Raouf, 1993). For instance, different sets of O, S and D numeric ratings may produce same RPN value since the corresponding risk may be totally different. Another critical weakness of the method is that small deviations in one rating may lead to different effects on the RPN. The last one is difficulty of quantification of those factors. It means that the proper numeric scales are not clearly expressed (Akyuz et al. 2016). Due to the aforementioned limitation, the conventional FMEA approach needs to be modified. In order to achieve this purpose, FMEA factors should be aggregated in a nonlinear manner rather than linear. Fuzzy sets approach, for instance, can be adopted to cope with aforementioned problems.

2.3 FUZZY FMEA

Fuzzy set theory was introduced to deal with uncertain of systems (Zadeh, 1965; Akyuz & Celik, 2015; Demirel et al., 2015; Celik & Gumus, 2015). The method employs linguistic variables to address risks and model uncertainty inherent in natural language (Zadeh, 1965). Fuzzy set theory was successfully applied to FMEA by addressing two common types; a rule-based expert system and a fuzzy aggregation approaches (Wang et al., 2009). To overcome aforementioned weaknesses of traditional FMEA, rule-based expert system is used since it has capable of capturing nonlinear causal relations between failures. The rule-based system consists of two fundamental components. They are rule-base which is constituted of some rules including specific type of knowledge base and inference engine which is adopting actions on the basis of the input interaction.

A rule-based system on the basis of fuzzy FMEA is adopted to perform a comprehended risk analysis. Thus, aggregation process of O, S and D can be performed in nonlinear manner. Figure 1 shows process of fuzzy FMEA which is having 3 inputs and 1 output variables.

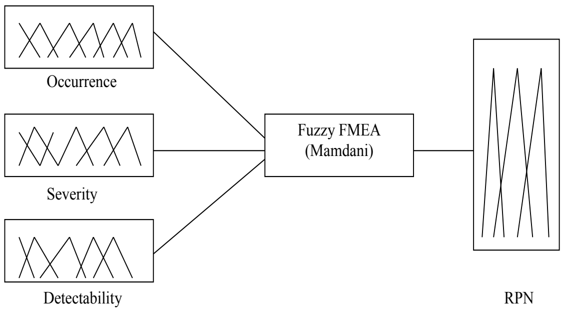

Figure 1. Process of fuzzy FMEA.

The rule-based fuzzy FMEA approach utilises Mamdani method as an inference engine. The Mamdani method is one of the most practical inference techniques since it is applied with a set of fuzzy rules (Mamdani & Assilian, 1975). The main purpose of the Mamdani method is to eliminate the problems of using multiplicative aggregation. Hence, it is able to transform a large number of data sets into useful outcomes. As soon as input parameters are inserted in system, the rule-based system takes benefits of inference engine and produce an output. The rule-based system adopts human judgements and domain knowledge on the basis of if-then rules. In this context, the process of rule-based fuzzy FMEA consists of following steps.

Step 1 – Construct a detailed FMEA worksheet: In order to perform comprehensive risk analysis, a worksheet including potential failures, potential effects of failures and potential consequences are prepared. While the primary aim of the method is to identify all aspects of failures, a detailed FMEA worksheet is required to comply with the method application principles.

Step 2 – Fuzzification process: In this step, crisp input values are converted into fuzzy values on the basis of linguistic variables and membership functions (Chanamool & Naenna, 2016). To accomplish this, a scale of score in each variables (O, S, D) are defined to derive membership function for inputs. Figure 2 and 3 depicts input and output variables' membership function for RPN (Kumru & Kumru, 2013). The membership functions of input variables (O, S, D) are having five different level addressing the scores: almost none, low, medium, high and very high.

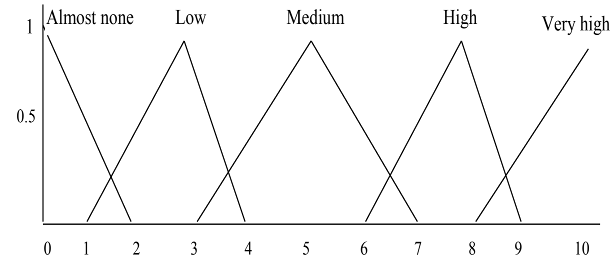

Figure 2. Membership function for input variables.

On the other hand, the output variables (RPN) are having ten different levels: none, very-low, low, high-low, low-medium, medium, high-medium, low-high, high and very high.

Step 3 – Construct and evaluate rule-base: In this step, if-then rules from the human experts based on domain knowledge are constructed. Accordingly, a knowledge base and inference engine are set up to present useful outcomes from the rules. The basic form of linguistic fuzzy if-then rules can be illustrated as follows (Akyuz et al., 2016).

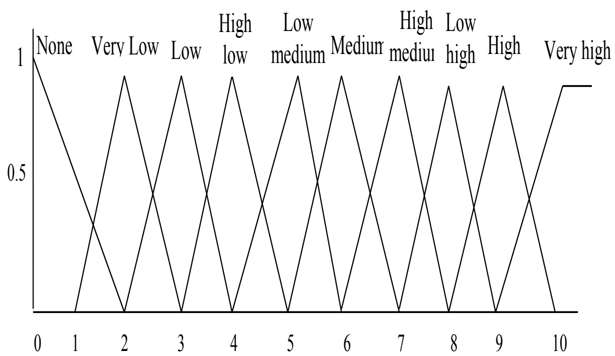

Figure 3. Membership function for output variable.

$$Rule_i = IF\ o\ is\ O_i\ and\ s\ is\ S_i\ and\ d\ is\ D_i\ THEN\ RPN\ is\ R_i \quad (2)$$

$$where\ i = 1, 2, 3, \dots, n$$

There are 125 rule database defined in the view of experts assistance since the input variables have fifteen different statements and output has ten. The fuzzy input variables are evaluated by adopting aforementioned rule-base and fuzzy logic operation to determine risk priority number along with degree of membership in risk category (Chanamool & Naenna, 2016). The Mamdani method is used in the inference engine.

Step 4 – Defuzzification process: After constructing rule database and evaluating the rules, crisp values of RPN are needed to perform the risk analysis. At this point, centre of area defuzzification process is carried out to transform the fuzzy output into crisp output. The following equation is used to convert fuzzy values into crisp numbers (Akyuz & Celik, 2015; Gumus et al., 2013).

$$z^* = \frac{\int \mu_{\tilde{\delta}}(z) z dz}{\int \mu_{\tilde{\delta}}(z) dz} \quad (3)$$

3. APPLICATION

The fuzzy FMEA method is applied to perform a comprehensive risk analysis for hydraulic hatch cover failures in bulk carrier ships as the potential failures of hydraulic hatch covers have serious concerns for ship owners.

3.1 PROBLEM STATEMENT

Hatch cover is very important for the safety of the vessel, ship crew and particularly for commodity. The studies show that most of causalities related to the cargo due to the failure of hatch cover since the primary aim of the hatch cover is to prevent cargo inside the cargo holds. Almost third of all P&I club claims are due to cargo problem and most of those are caused by water leakage (Gard, 2014). The leakage may cause serious consequences such as major cargo claim, environment pollution or crew injury. Therefore, the hatch cover should be fully watertight to prevent any leakage into the cargo holds. Specifically, hydraulic operated hatch cover is very common among the dry bulk cargo ships as they account for about forty percent of the global merchant fleet (UNCTAD, 2015). The nature of operation carried out by hydraulic hatch cover is very onerous even if it represents flexible solution during operation. In this context, the potential failures of hydraulic hatch cover in operational aspects are significant for ship owners, superintendents and safety professionals to enhance safety, prevent cargo and environment pollution.

3.2 ANALYSIS OF RESPONDENTS

In order to conduct risk analysis for hydraulic hatch cover in operational aspect, assessment of marine experts are used. The experts' judgements provides a quick evaluation of the state of knowledge about a particular aspect. To achieve this purpose, it was connected with one of the world's leading P&I Club corresponding office. The marine surveyors/experts who are working for P&I Clubs regularly attend on-board dry-bulk cargo ships to conduct hatch cover survey or inspect hatch cover related cargo claims. Therefore, they have utmost experiences and knowledge about the potential failures and effects of hydraulic hatch cover. The details of marine surveyors/experts are provided in Table 1 respectively.

Table 1. Marine experts' profile details.

Marine expert	Title	Educational level	Years in marine and shore-based experienced	Age
1	Claim handler	BSc.	15	42
2	P&I surveyor	MSc.	10	36
3	P&I surveyor	BSc.	13	38

3.3 APPLICATION OF FUZZY FMEA TO ANALYSE POTENTIAL RISKS

In order to apply fuzzy FMEA approach through potential failures of hydraulic hatch cover in bulk carrier ship to analyse potential risks, an extensive survey was performed with marine surveys. In the survey, the marine experts were asked to advise potential failure modes, their effects and potential consequences in case of hydraulic hatch cover defect. With the aim of marine experts and brainstorming techniques, a detailed FMEA worksheet, which is illustrated in Table 2, is created. As depicted, there are 16 operational failure modes and their effects ascertained by gathering feedbacks and guidance from the marine experts, P&I Club circulars and Classification survey reports. Relevant consequences are also identified in a same manner. Accordingly, the detailed worksheet enables a practical contribution to identify and eliminate failures from the system. Thereafter, quantification process of each failure mode is achieved via a Matlab software programming. The fuzzy logic toolbox is created by having 3 inputs and 1 output variables. While 5-level triangular membership functions are used for input variables, 10-level are used for output variables. After that, the complicated FMEA worksheet is presented to marine experts for evaluation of each potential failure. Table 3 shows evaluation scores of three marine experts for each potential failure. Since there are 3 marine experts evaluated the each potential failures, arithmetic means of score is obtained.

After getting evaluation score, rule-based inference engine is constructed in Matlab software. As the input variables have 15 different statements and output variable has 10, 125 rule-based are defined with the assistance of marine experts. All possible conditions are assessed in course of 125 rules (Akyuz et al., 2016; Chanamool & Naenna, 2016; Kumru & Kumru, 2013). For instance, IF occurrence is *almost none*, severity is *almost none* and detectability is *almost none*, THEN risk (RPN) is *none* (rule-1). Another example is IF the occurrence is *very high*, severity is *hig*h and detectability is *very high*, THEN risk (RPN) can be found *high* (rule-120*)*. According to the 125 rule databased, Table 4 illustrated crisp RPN values which are calculated on the basis of Mamdani method for each failure modes. In order to reflect differences, the RPN values based on traditional FMEA is also calculated.

Table 2. Detailed FMEA worksheet.

	Failure mode	Failure effect	Potential consequences
FM_1	Deformation of hatch cover panel	Not to close hatch cover properly	Heavy damage to cargo (wetting, impairment, etc.)
FM_2	Steel surface coaming connection fault	Space among the surface	Leakage
FM_3	Cross-joint cleating fault	Insufficient pressure on gasket	Leakage
FM_4	Internal cracking at joints	Reducing load carrying capacity	Damage to cargo or ship crew
FM_5	Distortion or cracking in compression bar	Rubber gasket do not fit permanently	Leakage (damage to cargo or environment)
FM_6	Gasket deformation	Watertigtness will not be achieved	Leakage (heavy damage to cargo)
FM_7	Unclear coaming plate	Hatch cover panels not to close properly	Commercial damage
FM_8	Deformation of landing pads	Wearing on pads	Leakage (heavy damage to cargo)
FM_9	Cracking at drainage channel	Water will be ingress inside the hold	Heavy damage to cargo (wetting, impairment, etc.)
FM_{10}	Blocked drain valves	Water not to be drained	Leakage (heavy damage to cargo)
FM_{11}	Damage to non-return drain valve	Drainage of channel not to be achieved.	Leakage
FM_{12}	Malfunction of quick acting cleat	Compression of the gasket will not be achieved	Leakage (damage to cargo or environment)
FM_{13}	Inoperable hydraulic jacks	Inoperable hatch cover panel	Operation suspended
FM_{14}	Hydraulic line leakage	Insufficient hydraulic pressure	Hatch cover will not open
FM_{15}	Hydraulic line bursting	Hatch cover will not be operated	Commercial damage / heavy damage to environment and crew
FM_{16}	Malfunction of hydraulic pump	Inoperable hatch cover panel	Damage to cargo, crew or environment

Table 3. Marine experts' evaluation.

	M. Expert 1			**M. Expert 2**			**M. Expert 3**		
	O	*S*	*D*	*O*	*S*	*D*	*O*	*S*	*D*
FM_1	6	8	3	7	7	2	8	7	5
FM_2	5	5	6	7	6	7	4	5	7
FM_3	6	6	4	5	5	6	5	7	5
FM_4	5	7	7	4	6	8	3	6	9
FM_5	4	6	3	3	5	2	4	5	2
FM_6	9	8	4	8	6	2	9	9	1
FM_7	5	5	3	7	6	4	8	4	3
FM_8	7	6	4	6	7	5	5	5	5
FM_9	5	7	6	6	8	8	4	8	5
FM_{10}	4	5	6	5	7	3	3	5	4
FM_{11}	3	6	4	4	3	6	6	4	5
FM_{12}	6	5	3	7	6	4	7	7	2
FM_{13}	4	6	4	5	4	5	3	4	3
FM_{14}	5	4	4	3	7	2	6	5	2
FM_{15}	6	6	2	7	8	3	8	8	3
FM_{16}	4	5	4	5	7	5	6	7	4

3.4 FINDINGS AND DISCUSSION

In the view of findings, the average fuzzy RPN can be found 6.31 which is quite higher. This implies that most of potential failures represent high risk which is beyond acceptable level. In light of the Table 4, FM_1 (Deformation of hatch cover panel) has the highest risk as the fuzzy RPN value ranks on the top. Any deformation on the hatch cover panel causes serious internal damages such as wear and tear of the plates, in particular during opening or closing of hatch covers. The deformation may affect water-tightness of hatch cover and cause serious damage to cargo inside hold. Attention is directed to proactive measures such as effective maintenance of plates. Corrosion should be prevented by complying with the manufacturer recommendation. Also proper inspection of panels is regularly carried out to ensure that panels will be adequate at all times. Furthermore, FM_3 (Cross-joint cleating fault) has also high fuzzy RPN as it ranks on the second place among the all failure modes. In the event of cross-joint cleating failure, hatch cover panels are not adequately linked together. Hence, it may not provide sufficient pressure on the gasket and may cause serious water leakage. A regular inspection and maintenance including lubricating of moving parts should be carried out as preventive measure. Also, some additional cleats should be inserted in appropriate place to provide sufficient pressure on the gasket.

FM_{16} (Malfunction of hydraulic pump) is another critical failure mode which is having the third highest fuzzy RPN.

Table 4. Fuzzy RPN values.

	Fuzzy FMEA		Classical FMEA	
Failure mode	Fuzzy RPN	Prioritization	RPN	Prioritization
FM_1	7.67	1	171.11	4
FM_3	7.33	2	160.00	6
FM_{16}	7.00	3	137.22	8
FM_4	6.67	4	202.67	2
FM_9	6.67	5	242.78	1
FM_{12}	6.67	6	120.00	10
FM_2	6.33	7	189.63	3
FM_6	6.33	8	155.04	7
FM_7	6.33	9	111.11	11
FM_{13}	6.33	10	74.67	14
FM_{11}	6.00	11	93.89	13
FM_{14}	6.00	12	66.37	15
FM_8	5..67	13	168.00	5
FM_{15}	5.67	14	136.89	9
FM_{10}	5.33	15	98.22	12
FM_5	5.00	16	45.63	16

In case of malfunction of hydraulic pump, sufficient hydraulic oil pressure cannot be produced. Therefore, hatch cover panels cannot be opened or closed during the operation. Serious consequences can result if the hatch cover panels are inoperable. Specifically, the nature of operation can pose potential dangers for cargo (hydraulic oil contamination), ship crew (injury or loss of life) or environmental pollution (hydraulic oil pollution). To prevent aforementioned risk, proper cleaning and maintenance should be carried by ship crew. The regular maintenance takes place once a mount as per ship's PMS (Planned maintenance system). Hydraulic oil lines connected to pump should also be kept clean and cool.

Another critical failure modes which rank on the fourth place with 6.67 fuzzy RPN value are FM_4 (Internal cracking at joints), FM_9 (Cracking at drainage channel) and FM_{12} (Malfunction of quick acting cleat) respectively. Internal cracking at joints may induce substantial in-plate stresses on the panels. Since this failure affect structure of panels, it may cause to reduce load carrying capacity. In order to prevent it, regular monitoring should be performed. Necessary maintenance should be done by consulting manufacturer as well as classification society. Likewise, cracking at drainage channel is another structural problem since drainage channel provides to drain the water away. In case of cracking at drainage channel, rain or sea water accumulated at coaming will penetrate into the cargo hold. If the cracking is found, it must be renewed with approved materials immediately and painted to prevent corrosion. The malfunction of quick acting cleat poses a threat since it may produce inadequate gasket compression. Thus, insufficient tension is produced to achieve tightness of hatch cover. Physical damage and age hardening are key attributes of malfunction of cleats (Lloyd's, 2002[19]). To remedy this problem, regular monitoring should be carried out. Greasing of moving parts should be performed to increase elasticity of rubber inside the cleat. A special type of protective tape can be used to avoid external damages.

In general, hatch covers and their components are handled with utmost care to prevent potential risks affecting cargo, human life and marine environment (Lloyd's, 2002). Hatch covers, panels and their equipment should be inspected and monitored at the end of each cargo operation to prevent potential hazards or failures.

4. CONCLUSIONS

The prevention of risks in maritime transportation engineering is of paramount significant. Although maritime regulatory bodies are trying to mitigate risks by adopting a set of rules and regulations, safety level has not reached the desired level yet. Therefore, risk assessment approaches are widely welcomed in the industry. One of the most powerful risk analysis techniques is FMEA which provides an effective way to evaluate the risk level of component failures. However, the method is criticized due to some shortfalls. Fuzzy set is one way to overcome aforementioned shortfall of traditional FMEA. This paper takes benefit of fuzzy FMEA approach to perform a comprehensive risk assessment in maritime transportation industry. The method enables a fuzzy rule-based to identify and rank the potential failures of systems. The strength of the method is to have identical fuzzy RPN values but different risk levels. The fuzzy FMEA approach is applied to hatch cover system in operational aspect as the failures of hatch cover can lead to major cargo damage due to insufficient watertightness. A detailed FMEA worksheet covering potential failures, their effects and potential consequences is prepared and quantification of each failure mode is achieved via Matlab software. In the view of the findings, it appears that the most of potential failures represent high risk. Accordingly, necessary preventive measures are recommended.

In conclusion, this paper provides a practical contribution into maritime industry since it provides on-going efforts towards improvement of safety related operation in dry bulk cargo ships, particularly deck operations such as hatch covers opening and closing, hold cleaning, cargo securing, lashing, trimming, etc. where high risk involved. Thus, potential failures of each operation can be revealed and necessary preventive measures can be taken in advance to minimize risk level. Moreover, ship owners, ship superintendents, P&I clubs or Classification societies can utilize the outcomes of risk analysis to mitigate human error occurrences and consequences. Furthermore, a practical software tool can be designed on the basis of theoretical framework of this paper to transform potential failure modes and effects in risk analysis into meaningful information in safety management. The further study may be extended with interval type-2 fuzzy sets instead of fuzzy sets to cope with more uncertainty in decision-making problem.

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