IJE TRANSACTIONS C: Aspects Vol. 31, No. 9, (September 2018) 1487-1497

International Journal of Engineering

Journal Homepage: www.ije.ir

A Prioritization Model for HSE Risk Assessment Using Combined Failure Mode and Effect Analysis and Fuzzy Inference System: A Case Study in Iranian Construction Industry

A. Ardeshir, P. Farnood Ahmadi*, H. Bayat

Department of Civil and Environmental Engineering, Amirkabir University of Technology, Tehran, Iran

P A P E R I N F O

Paper history:
Received 27 December 2017
Received in revised form 12 March 2018
Accepted 26 April 2018

Keywords:
Failure Mode and Effect Analysis
Fuzzy Inference System
HSE Risk Assessment
Mamdani Algorithm
Construction Industry

A B S T R A C T

The problem of insufficient data and uncertainty in modeling play a significant role in many engineering and management problems. Therefore, applying some techniques and decision-making processes is essential to attain proper solutions for aforementioned problems under accurate consideration. In this paper, an application of fuzzy inference system for modeling the indeterminacy involved in the problem of HSE risk assessment is presented. For this purpose, Failure Mode and Effect Analysis (FMEA), one of the most practical techniques with high reliability in HSE risk assessment is integrated with fuzzy inference system. The proposed model is executed according to the Mamdani algorithm and fuzzy logic toolbox of MATLAB software. With respect to a case study, a comparison between the proposed model and common FMEA risk assessment approach is made for prioritization of the HSE risks. The selected HSE risk factors which were analyzed are listed in three categories as follows: (a) health risks; (b) safety risks and (c) environmental risks. Based on the proposed model, falling and slipping of workers grouping with safety risks is ranked as the first serious risk with the risk priority number of 0.7938 and skin injury which is classified with health risks is considered as an inconsiderable risk with the lowest risk priority number of 0.0223. Ultimately, by applying the method on a case study, the results indicate that the proposed model by considering economic aspects as an intelligent risk evaluation tool provides more detailed and precise results.

***doi**: 10.5829/ije.2018.31.09c.03*

1. INTRODUCTION

Health, Safety and Environment (HSE) consideration have to be placed above other priorities and nothing is more important than protection of human health, safety and the environment. The construction industry is serviced by a collection of diverse trades and activities, many of which have attendant hazards, a high risk of illness or injury, and involve working in a changing environment [1]. Therefore, With respect to safety aspect, the building industry is known as one of the high-risk work environments in the modern world [2]. Another main reason is combination of the high-risk nature of construction with the low educational level of workers about safety performance. In this regard, workers should be taught safety principles and safety instruments should be provided to workers for added safety performance at construction sites [3]. Preventing accidents and reducing uncertainty could be the best solutions for increasing safety performance in construction industry [4]. Approximately, there are currently more than 70 risk assessment methods in the world which are divided into two quantitative and qualitative groups. Quantitative risk analysis contributes to lessen the likelihood of unexpected and undesirable incidents and to minimize the possible adverse consequences [5]. With correct definition and complete measures during the design and planning stages, 60% of hazardous occupational accidents could be prevented at construction sites in the European Union [6]. Stakeholders such as owners,

*Corresponding Author Email: *Pm.farnood@aut.ac.ir* (P. Farnood Ahmadi)

Please cite this article as: A. Ardeshir, P. Farnood Ahmadi, H. Bayat, A Prioritization Model for HSE Risk Assessment Using Combined Failure Mode and Effect Analysis and Fuzzy Inference System: A Case Study in Iranian Construction Industry, International Journal of Engineering (IJE), IJE TRANSACTIONS C: Aspects Vol. 31, No. 9, (September 2018) 1487-1497

designers and contractors have significant impact on safety performance. The relationship between owner's influence and project safety performance was investigated with focus on project characteristics, contractual safety requirement, the selection of safety contractors, and the owner's participation in safety management during project implementation [7]. Determining a mechanism for measurement of the performance of an organization in the field of health, safety and environment (HSE) is prerequisite for continual improvement attitude which is the spirit of the new HSE management systems. A logical selection-aggregation process is performed to determine the HSE performance status of Iranian drilling industry from key performance indicators (KPIs). This framework is made by combination of quantitative and qualitative techniques and is based on 'award and punishment' policy [8]. A risk assessment model for construction safety has been presented to evaluate risk levels of different work trades. In this assessment predicting high-risk construction activities and avoiding recurrence of past accidents were the objectives of the developed risk assessment model. It is obvious that preventing accidents before their occurrence could be an effective way to improve safety performance. Thus, safety management systems play an important role in analyzing safety risks [3]. Health-safety and environmental risk assessment of Iranian refineries has been done using a multi criteria decision making method. Results indicated that in technological, health-safety, socio economic and biological sections of the refinery, factors influenced by the refinery activities like hearing loss, fire and explosion, power generation, quality of ground water which they are among the most important factor causing risk in the refinery. Groundwater level drop is the most serious natural consequence influenced on refinery activities [5]. An approach for contractors has been studied to estimate safety costs using hazard analysis and risk assessment techniques. Toward this purpose, safety risks and related costs assessed and calculated, and distribution of them were determined to facilitate efficient safety planning. The result of this study showed that safety cost to the total construction cost is about 1.92% [9]. A cross sectional study was done on 14 contracting companies and 483 randomly selected workers of oil, gas and petro-chemistry companies in Iran during 2013. Data collection was performed through interview of workers and managers and two different data collection forms were filled by the workers and managers. Based on a health safety and environment management system (HSEMS) guideline made by the Iranian Ministry of Petroleum, probabilistic data analysis were performed using Statistical Package for Social Science (SPSS) [1].

1. 2. FMEA and Fuzzy Inference System Application for HSE Risk Analysis The U.S. military introduced Failure Mode and Effect Analysis (FMEA) in 1949, and in early 1960, a military standard was established (ML-STD-1629A) for performing FMEA [10]. The method is used to eliminate risks before their occurrences. Risk Priority Number (RPN) is calculated by multiplying the three parameters to rank risks, these parameters are Probability of event (P), risk detection possibility (D) and severity of occurrence (C). This method can be used to evaluate risks in term of the life cycle cost to improve maintainability, reliability of intricate systems [11]. The FMEA technique can be effective in processing information and risky strategic decisions. In recent years, some diverse versions of FMEA were proposed to predict similarities amongst specified types of system failure [12]. Combined FMEA and Fault Tree Analysis (FTA) was used to provide efficient designed safety systems to manage and prevent major potential risks [13].

The construction industry is subject to many uncertainties and intrinsic risks in every section of the project life cycle. Hence, a hybrid framework was introduced to use linguistic phrases to evaluate the expected monetary value of risk events based on the combination of fault trees, event trees, fuzzy logic, and FMEA [14]. The fuzzy RPN method was used for assessing potential failures to ensure lessening of the intensity of ambiguity and uncertainty [15]. A combination of FMEA method and fuzzy theory is used as a semi- quantitative-qualitative method for analyzing failure modes and occupational risks in the construction industry in Iran. The substantial causes of occupational accidents in this field were determined and analyzed. Based on whether the risks have high or low priority rate, modifying actions were suggested to reduce the occupational risks [16]. An integrated model constituted of fuzzy logic, FMEA, fault tree analysis (FTA), and analytical hierarchy process-data envelopment analysis (AHP-DEA) was applied to improve safety risk management system. Two different types of construction projects were considered to validate the framework recommended in this area in the city of Kerman. The results showed that the framework is applicable to all similar construction sites [17].

The objective of a fuzzy expert system creation is to design a dynamic model for performance evaluation of HSE management system. This robust dynamic model can help to control risks and improve the performance of HSE management system. Reduction of human error, interpretation of a large amount of vague data and creation of expert knowledge are the considerable reasons to use fuzzy expert systems [18]. A fuzzy expert system based on the probabilistic terms was developed for assessment of the occupational risks. Factors such as organization, management, human errors, working environment, equipment, and materials were considered. A system of risk evaluation brings about some advantages like better risk management with a proactive vision. It should be noted that this model was validated by four construction case studies in Iran [19]. Adaptive Neuro-Fuzzy Inference System (ANFIS) was adapted for assessment and mitigation of job stress which is considered against the HSE and ergonomic programs. Eventually, operators with a weak stress level were identified [20].

Despite the large number of investigation on the HSE risk management system, HSE risk assessment or safety practices, few studies utilize combination of fuzzy logic principles and FMEA method in the assessment of HSE risks to which medium and large-scale construction projects are exposed. In this study, a risk assessment method with new scenario considering directly two different costs originating from risk and its related events is presented in 3D control surfaces. We claim this systematic model is a practical and efficient tool for the HSE professionals, as it enables them to determine the most important HSE risk factors and reduce the adverse consequences of them. To demonstrate the effectiveness of the model, the outcomes derived from the proposed model were compared with the results obtained by the conventional method.

2. FUZZY LOGIC AND FUZZY INFERENCE SYSTEM

Fuzzy set theory was introduced earlier to deal with the imprecise and uncertainty that is inherent to human arbitration through linguistic terms instead of numerical values in decision-making processes. A normalized fuzzy membership function is between 0 and 1 [21, 22, 23]. Fuzzy Inference System (FIS) is a knowledge-based system that contains a set of membership functions and fuzzy rules [24]. These systems are reliable and practical to use [25]. A common fuzzy inference system is illustrated in Figure 1. As shown in following figure, a FIS includes four main parts (1) fuzzification, (2) knowledge base, (3) fuzzy inference engine, and (4) defuzzification.

2. 1. Fuzzification The process of transforming crisp values into fuzzy If-Then rules is performed by the first part of FIS (Fuzzification phase).

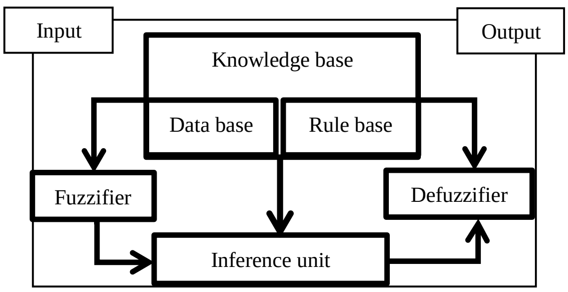

Figure 1. Structure of fuzzy inference system [26]

For linguistic terms of fuzzy sets, input data with the membership functions are converted into fuzzy numbers. It should be noted that membership function selection depends on expert knowledge, modeled problems, and project contexts [27].

2. 2. Knowledge Base A set of fuzzy If-Then rules are developed based on expert's opinion and fuzzy operators in the fuzzy inference system. These rules are described as a connector between input and output fuzzy sets [28].

2. 3. Fuzzy Inference Engine This section of the fuzzy inference system is known as the decision-maker system that has inference capability. In fact, the inference unit engine interprets and analyzes the defined rules in knowledge base. Finally, a logical conclusion is derived from the evaluations. Here the method of Mamdani has been applied. Mamdani fuzzy model uses the concepts of fuzzy logic and fuzzy sets to translate an entirely unconstructed set of linguistic heuristics terms into an algorithm [29].

2. 4. Defuzzification The defuzzification process is used to transfer fuzzy sets into crisp value. In this paper, centroid defuzzification is used to achieve deterministic values due to the fact that this method has continuity and less ambiguity and provides a more accurate output [30]. In order to determine the centroid point ($\bar{x}_0$, $\bar{y}_0$) of an arbitrary fuzzy number A = (a, b, c, d; w) following centroid Equations (1) and (2) were provided by Wang et al [31, 32], where the $g_A^L(y): [0, w] \rightarrow [a, b]$ and $g_A^R(y): [0, w] \rightarrow [c, d]$ are the inverse function of f_A^L and f_A^R, respectively.

$$\bar{x}_0(A) = \frac{\int_a^b x f_A^L(x)dx + \int_b^c (xw)dx + \int_c^d x f_A^R(x)dx}{\int_a^b f_A^L(x)dx + \int_b^c (w)dx + \int_c^d f_A^R(x)dx} \quad (1)$$

$$\bar{y}_0(A) = \frac{\int_0^w y\left(g_A^R(y) - g_A^L(y)\right)dy}{\int_0^w \left(g_A^R(y) - g_A^L(y)\right)dy} \quad (2)$$

For a trapezoidal fuzzy number, the centroid coordinate of A turns out to be as following Equations (3) and (4).

$$\bar{x}_0(A) = \frac{1}{3}[a + b + c + d - \frac{dc - ab}{(d+c)-(a+b)}] \quad (3)$$

$$\bar{y}_0(A) = w\frac{1}{3}[1 + \frac{c - b}{(d+c)-(a-b)}] \quad (4)$$

3. RESEARCH METHODOLOGY

Determination of the critical HSE factors at construction sites is the first step of fuzzy inference system creation to rank the principal HSE risk factors and set a better HSE management system. In this study, the main factors influencing an HSE management at the construction site were investigated according to preliminary questionnaire results to identify some primary factors in the areas of health, safety, and environment. The consulting and analyzing process was done based on the opinions of 10 technical experts (including HSE manager, project manager, engineers, and researches) that were specialists in the field of HSE management and possessed the necessary awareness regarding the raised issues. To achieve logical and solid foundations related to the issue, obtaining feedback from experts is very important. With this perspective, the appointed system can be practical in the construction industry of Iran and other countries in the region. In this regard, several meeting with experts have been held to encourage them to get involved in the research. We selected MATLAB software for the design of our fuzzy inference system.

3. 1. Determining the Risk Factors for Improvement of HSE Management Level As it was mentioned in the previous section, determining the factors was based on experts' opinions. At the first stage, the selection of HSE factors was carried out through a questionnaire. According to their importance, factors were selected and categorized into health, safety, and environment sections. These factors can be seen in Table 1.

3. 2. The Proposed FIS Design In this research, T-norm, supplement, and defuzzification operators along with Mamdani inference engine were used and coding was conducted in the MATLAB coding section.

TABLE 1. The selected HSE factors

Health risks	1. Skin injury
	2. Eye injury
	3. Respiratory illness
	4. Mental disorder
	5. Injuries and amputations
Safety risks	6. Electrocution
	7. Accident with different objects
	8. Being trapped under rubble
	9. Explosion and fire
	10. Workers falling and slipping
	11. Falling objects
	12. inappropriate use of machinery or tools
Environmental risks	13. Emission of CO_2 gas
	14. Improper disposal of construction debris
	15. Improper disposal of workplace's waste water
	16. Making excessive or disturbing noises
	17. Utilization of chemical and harmful substances

At the beginning of construction of a fuzzy expert system, structure identification of rules must be done. It means that the number of rules, input and output variables should be specified. Determination of parameters is commenced after determining the structure. It means that the fuzzy membership functions, the operator type, and related parameters which are used in the expert system should be determined. The final design and coding of the fuzzy inference system can be carried out only after structure identification and determining the parameters for the fuzzy expert system are completed.

3. 3. The Proposed Model for Fuzzy Risk Assessment of HSE Factors The proposed fuzzy risk assessment method in this context contains three phases for risk score evaluation, which these phases are organized based on the fuzzy logic implication. It should be noted that the fuzzy logic is exerted to diminish the ambiguity and uncertainty involved in the modeling procedure. Overall, quantitative, and qualitative techniques are applied in the proposed model. This leads to evaluate risks with high accuracy and certainty.

The first phase of the model concentrates on the probability of risk occurrence. It should be noted that in this study, the probability of risk occurrence with the related costs have been considered as the input of the model. In this section, 27 rules have been defined and the scope of the probability of risk occurrence has been limited to nine modes, very low to very high (VL, VL-L, L, L-M, M, M-H, H, H-VH, and VH). In addition, three fuzzy sets in the form of linguistic weighting variables, which include "low", "medium", and "high", have been utilized to evaluate the importance of the costs arising from the risk. The second phase focuses on the detection possibility of the risk. The costs of identification of risk and related events and detection possibility of risk have been assumed as the input of the inference engine. In this section, there are 15 rules. In order to identify the detection possibility of risk, five modes from very high to very low (VH, H, M, L, and VL) have been assigned, also related costs vary in the range of low up to high in three modes as the previous section. In the third phase, the severity of the HSE risk and associated events in conjunction with the possibility of eliminating risk (PER) have been considered as the inference engine input. Similar to the former section, Linguistic variables of severity of risk occurrence contains five modes from very low to very high and the possibility of eliminating risk (PER) includes three modes from low to high. In this part, 15 rules have been specified. Finally, the fuzzy inference engine computes the final scores for each section to evaluate the level of risk in the form of FMEA formula.

3. 4. Determining the Fuzzy Membership Functions With respect to consultancy with specialists and according to the logic of the HSE management system in medium and large-scale construction projects, the triangular, trapezoidal, and Gaussian fuzzy numbers for linguistic input and output variables were applied. Fuzzy number A = (a, b, c) with a triangular membership function is presented in Equation (5) as follows:

$$\mu_A(x) = \begin{cases} (x-a)/(b-a) & If\ \ a \le x \le b \\ (c-x)/(c-b) & If\ \ b \le x \le c \\ 0 & If\ \ x > c, or\ x < a \end{cases} \tag{5}$$

Similarity, trapezoidal fuzzy number A= (a, b, c, d) with a trapezoidal membership function can be expressed in Equation (6) as follows:

$$\mu_A(x) = \begin{cases} (x-a)/(b-a) & If\ \ a \le x \le b \\ 1 & If\ \ b \le x \le c \\ (d-x)/(d-c) & If\ \ c \le x \le d \\ 0 & If\ \ x > d, or\ x < a \end{cases} \tag{6}$$

The Gaussian function is defined based on two parameters σ and c as follows, whereas σ and c are the width and center of the membership function, respectively. Thus the Gaussian function can be written as Equation (7).

$$f(x;\sigma,c) = e^{\frac{-(x-c)^2}{2\sigma^2}} \tag{7}$$

A combination of triangular and trapezoidal membership functions was used to determine the probability of risk occurrence and its costs. Trapezoidal fuzzy functions were designated to detect the possibility of risk and relevant costs. In addition, trapezoidal functions were used to analyze the severity of risk. Finally, Gaussian functions were set to analyze the possibility of eliminating risk based on logic aspects and the nature of the raised problem. In order to create fuzzy relations, the max-min composition method was selected (and method ='min'; or method ='max'; implementation method ='min' and aggregate method ='max'). The variables are fuzzified based on their fuzzy ratings presented in Tables 2 to 5.

After making the primary structure of the FIS model, the rule base was organized according to the fuzzy ratings and rules which were adjusted on the preference of decision makers to have an appropriate ranking for managers, stakeholders, and suppliers. With respect to the level of importance of the specified parameters, the most significant areas have been identified as absolutely important (AI) areas. Furthermore, not important (NI) areas are corresponded to the least important areas. The importance of an area can be changed according to expert's opinion and project status. The fuzzy If-Then rules containing 57 rules of the model established in MATLAB software package are represented in Table 6.

TABLE 2. Fuzzy ratings definition of probability and its cost

probability of events	**Linguistic term**	**Fuzzy numbers**
More than 80% probability, absolutely the event will happen	VH	(0.9 0.95 1 1)
Probability between 60-80%, occurring of the event is very high	VH-H	(0.75 0.85 0.95)
Probability between 50-60%, occurring of the event is high	H	(0.6 0.7 0.8)
Probability between 40-50%, occurring of the event is slightly high	H-M	(0.45 0.55 0.65)
Probability between 30-40%, occurring of the event is moderate	M	(0.25 0.4 0.5)
Probability between 20-30%, occurring of the event is slightly moderate	M-L	(0.075 0.2 0.3)
Probability between 10-20%, occurring of the event is low	L	(0.05 0.075 0.1)
Probability between 1-10%, occurring of the event is very significantly low	L-VL	(0 0.03 0.06)
Less than 1% probability, The event is very unlikely to happen	VL	(0 0 0.01 0.01)
Costs arising from the risk		
Direct and indirect costs are high	H	(0.45 0.6 1 1)
Direct and indirect costs are moderate	M	(0.2 0.35 0.5)
Direct and indirect costs are low	L	(0.45 0.6 1 1)

TABLE 3. Fuzzy ratings definition of risk eliminating

The possibility of eliminating risk	**Linguistic term**	**Fuzzy numbers**
The possibility of risk elimination is high	H	(0.1198 0.735)
The possibility of risk elimination is moderate	M	(0.0932 0.3809)
The possibility of risk elimination is low	L	(0.0863 0.1747)

TABLE 4. Fuzzy ratings definition of severity of events

Severity of events	**Linguistic term**	**Fuzzy numbers**
The effect of risk on activities is very high	VH	(0.8 1 1 1)
The effect of risk on activities is high	H	(0.5 0.75 0.75 0.9)
The effect of risk on activities is moderate	M	(0.3 0.5 0.5 0.7)
The effect of risk on activities is low	L	(0 0.25 0.25 0.5)
The effect of risk on activities is very low	VL	(0 0 0 0.3)

TABLE 5. Fuzzy ratings definition of detection index and its cost

Detection possibility	Linguistic term	Fuzzy numbers
Certain recognition and control will trace the existence of a failure-quiet clear and certain	VH	(0 0 0.01 0.01)
Have good chance of tracing the existence of a failure-clear and certain	H	(0 0.01 0.05 0.1)
Control may trace the existence of a failure-recognizable	M	(0.05 0.10 0.20 0.30)
Control more likely will not trace the existence of a failure-un recognizable	L	(0.2 0.2 0.40 0.5)
Control absolutely will not trace the existence of a failure-quiet uncertain	VL	(0.40 0.50 1 1)
The cost of risk and related events identification		
Detection cost of risks and ongoing events is high	H	(0.4 0.8 1 1)
Detection cost of risks and ongoing events is moderate	M	(0.07 0.1 0.35 0.5)
Detection cost of risks and ongoing events is low	L	(0 0 0.05 0.1)

TABLE 6. Fuzzy rules

Probability of event			Detection possibility			Severity of consequence		
Input		Output	Input		Output	Input		Output
X_1	X_2	Y_1	X_3	X_4	Y_2	X_5	X_6	Y_3
VL	L	NI	VL	L	I	VL	L	SI
VL	M	NI	VL	M	VI	VL	M	SI
VL	H	SI	VL	H	AI	VL	H	NI
VL-L	L	NI	--	--	--	--	--	--
VL-L	M	NI	--	--	--	--	--	--
VL-L	H	SI	--	--	--	--	--	--
L	L	NI	L	L	I	L	L	SI
L	M	SI	L	M	VI	L	M	SI
L	H	I	L	H	VI	L	H	NI
L-M	L	SI	--	--	--	--	--	--
L-M	M	SI	--	--	--	--	--	--
L-M	H	I	--	--	--	--	--	--
M	L	SI	M	L	SI	M	L	I
M	M	I	M	M	I	M	M	I
M	H	VI	M	H	VI	M	H	SI
M-H	L	SI	--	--	--	--	--	--
M-H	M	I	--	--	--	--	--	--
M-H	H	VI	--	--	--	--	--	--
H	L	I	H	L	SI	H	L	VI
H	M	VI	H	M	I	H	M	VI
H	H	AI	H	H	I	H	H	I
H-VH	L	I	--	--	--	--	--	--
H-VH	M	VI	--	--	--	--	--	--
H-VH	H	AI	--	--	--	--	--	--
VH	L	I	VH	L	NI	VH	L	AI
VH	M	VI	VH	M	SI	VH	M	VI
VH	H	AI	VH	H	I	VH	H	VI

For the fuzzification process, the input fuzzy linguistic variables in the MATLAB environment areillustrated in Figure 2. Furthermore, for output variables, trapezoidal or arbitrary combinations oftriangular and trapezoidal membership functions were considered, which could be unique for each project. The membership functions of output variables are presented in Figure 3.

The interdependency of input and output parameters derived from the rules generated in the FIS model can be indicated by using control surface as represented in Figures 4 to 6. These figures illustrate the influence of input parameters on the output parameter in the fuzzy environment by graphical representation for visual perception. Figure 4 shows the interdependency of P-C on the probability of an event and its related cost. Figure 5 depicts the interdependency of D-C on detection possibility of risk and its related cost and Figure 6 shows the interdependency of C-PER on the severity of consequences and the possibility of eliminating risk.

4. CASE STUDY

To validate the framework recommended in the area of medium and large-scale construction projects, a high-rise residential and commercial building project located in the city of Tehran was selected. The scope of the selected project includes installation of two 23-storey residential towers with an approximate area of 48760 m^2 and a commercial building with an area of 4000 m^2 that is shown in Figure 7.

5. RESULTS AND DISCUSSION

This study focused on economic aspect directly as a parameter in a 3D fuzzy environment to assess the HSE risk factors with high accuracy. Unlike previous studies, fire and explosion was mentioned as a HSE risk factor in the construction building project because of the importance of this risk factor in medium and large-scale construction projects.

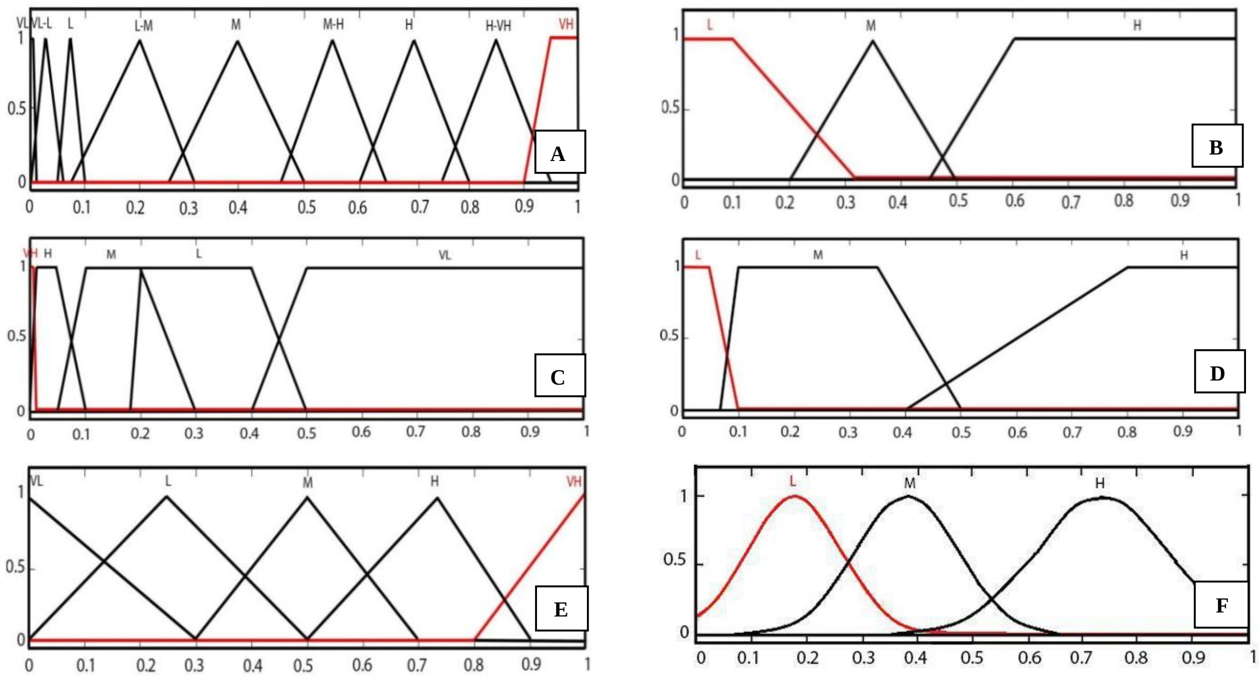

Figure 2. Membership functions of input variables involved in the model (A: probability of events, B: costs arising from the risk, C: detection possibility, D: identification costs, E: Severity of events, F: the possibility of eliminating risk)

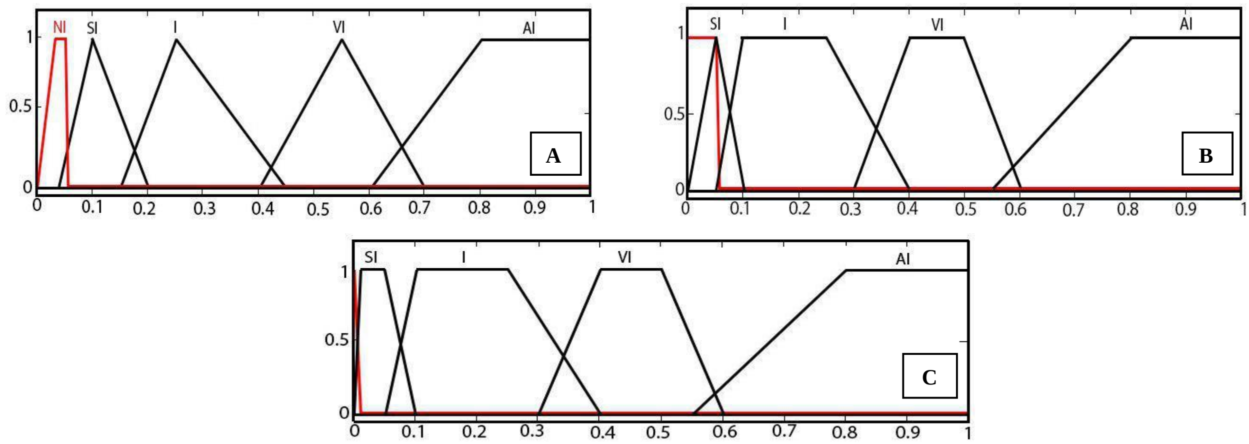

Figure 3. Membership functions of output variables involved in the model (A: probability of events-Cost (P-C), B: Detection possibility-Cost (D-C), C: Severity of events-the possibility of eliminating risk (C-PER))

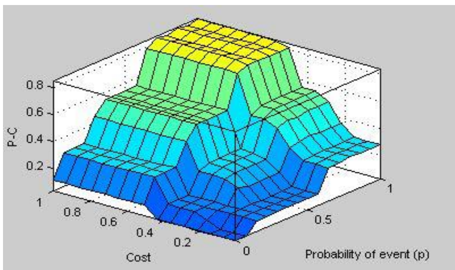

Figure 4. Control surface of P-C on probability of event and cost

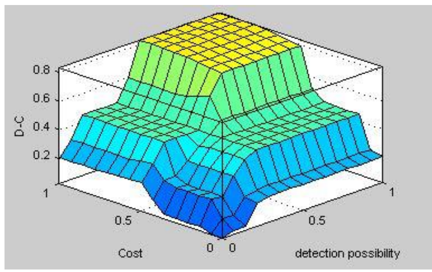

Figure 5. Control surface of D-C on detection possibility and cost

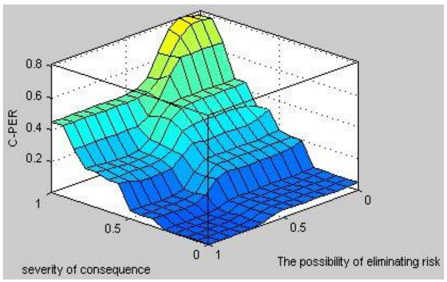

Figure 6. Control surface of C-PER on severity of consequence and the possibility of eliminating risk

Figure 7. Site location map of the case study

In conjunction with considering all parameters of FMEA method to calculate the RPN, the capability of stockholders such as owners, contractors, and suppliers on eliminating potential risks as a new parameter (PER) was considered.

According to the corrective action categories, the results of RPN and risk ranking that can be seen in Tables 7 and 8, the following outcomes were obtained.

Based on the proposed model for ranking the HSE risks, workers falling and slipping, especially workers falling from heights is considered as the most critical risk factor with the risk priority number of 0.7938, and skin injury is known as an inconsequential risk factor with the lowest risk priority number of 0.0223. With respect to the project status and inefficient use of safety devices, risk of falling from heights during welding or work on scaffolds and the risk of falling objects possess high RPNs and these factors are the most serious HSE risks. These findings are in line with the past studies [17, 33].

Injuries/amputations with the risk priority number of 0.668, and explosion and fire with the risk priority number of 0.4605 were ranked as the third and fourth risks, respectively.

TABLE 7. Risk priority number and corrective action categories [17]

Label	Corrective action categories	RPN	Risk's degree
1	Absolutely necessary to take corrective action(s)/ consider avoidance	0.70<RPN	V
2	High priority to take corrective action(s)/ consider avoidance or transfer	0.55<RPN<0.70	IV
3	Moderate priority to take corrective action(s)/ consider mitigation or transfer	0.40<RPN<0.55	III
4	Low priority to take any corrective action(s)	0.20<RPN<0.40	II
5	No corrective actions is required	RPN<0.20	I

TABLE 8. Result of the HSE risks prioritization

No.	Risk factor	RPN 1 (Proposed model)	RPN 2 (Common method)	Risk rating 1	Risk rating 2	Risk's degree 1	Risk's degree 2
1	Skin injury	0.0223	0.0149	17	15	I	I
2	Eye injury	0.2135	0.1642	12	13	II	I
3	Respiratory illness	0.048	0.1343	15	14	I	I
4	Mental disorder	0.2037	0.0119	13	16	II	I
5	Injuries and amputations	0.6685	0.6528	3	3	IV	IV
6	Electrocution	0.4352	0.5851	5	4	III	IV
7	Accident with different objects	0.4073	0.4993	6	5	III	III
8	Being trapped under rubble	0.0451	0.0107	16	17	I	I
9	Explosion and fire	0.4605	0.3479	4	10	III	II
10	Workers falling and slipping	0.7938	0.8812	1	1	V	V
11	Falling objects	0.7841	0.8119	2	2	V	V
12	Inappropriate Use Of Machinery Or Tools	0.3806	0.4836	7	6	II	III
13	Emission of CO_2 gas	0.3736	0.3997	8	7	II	II
14	Improper disposal of construction debris	0.2411	0.3291	11	11	II	II
15	Improper disposal of workplace’s waste water	0.364	0.2612	9	12	II	II
16	Making excessive or disturbing noises	0.0556	0.3631	14	9	I	II
17	Utilization of chemical and harmful substances	0.2972	0.3769	10	8	II	II

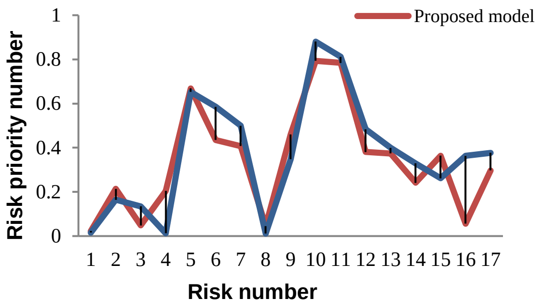

Figure 8. Comparison between the results of the proposed model and common prioritization method (FMEA)

In view of steel structures, HSE engineers' opinion and the project manager's experience in fire accidents in similar projects the risk of fire and explosion is considered more important due to the fact that this factor has high potential to impose remarkable financial damage to the medium and large-scale construction project. In common risk analysis, fire and explosion risk factor is listed as the tenth risk which has low priority to take reformative actions. However, in our proposed model, taking into account the financial and economic aspects, the aforementioned risk has a higher (moderate) priority to take corrective measures. In general, risks related to the safety aspect have higher importance, and thus, require added attention. Environmental risks are realized more than before due to increasing awareness of experts about the negative impact of the construction industry on the environment in Iran. Carbon emission is ranked as one of the most well-known environmental risks (due to the use of diesel engines and consumption of large amounts of concrete for slabs and foundations, etc.). Stricter regulations should be established in the construction sector to observe more environmental issues and related risks. The results show that the health issues are negligible in the construction project in Iran, which may be due to the lack of awareness of the indirect costs arising from health matters and transferring the cost of health risks to insurance companies.

Eventually, for risks with high RPNs, mitigation strategies and operational measures are suggested as possible solutions. To prevent workers falling and slipping or to mitigate the risk of falling objects, certain measures including training of workers, installing safety signs, using personal protective equipment (PPE) and installing proper barriers such as fences, safety nets and separations are practical solutions to minimize unsafe actions and conditions. Raising the knowledge of workers in avoiding dangerous actions is necessary to diminish injuries and amputations. Improvement of fire safety systems and training workers to use fire and life safety equipment such as fire extinguishers in emergencies is recommended to avoid explosion and fire.

A comparison between the results obtained from the model and common method of risk analysis is shown in Figure 8. Ultimately, the difference between values obtained from two methods was measured. The value of root-mean square error (RMSE) is 0.1165. The given RMSE value is justified according to previous investigations with the aim of developing a valid HSE risk assessment model [34]. It should be mentioned that experts confirmed the results of risk prioritization, ranking model, and RMSE value.

6. CONCLUSIONS

Construction projects are complex and have a challenging environment that is subjected to many risks associated with this industry. Therefore, an HSE risk management in the construction industry is essential to improve performance and ensure success of the project. In this article, risks in three main categories of health, safety and the environment have been assessed. The proposed method is based on a new research and field-based case study. The suggested combination of fuzzy logic (fuzzy inference system) and FMEA was applied to assess and rank the HSE risks in a construction (high-rise building) project. Fuzzy logic has been used due to the limitation of common risk method analysis. RMSE value represented the significant but acceptable difference between results acquired from the proposed model and FMEA method, which can be indicative of a more complete model of the new method in comparison to the limited FMEA method in the analysis and ranking of risks. The HSE risks of the case study were analyzed to evaluate the performance of the proposed framework. It should be noted that stakeholders and experts including safety manger, HSE engineers, and project manager have approved the efficiency of this model. Therefore, this model can be helpful for HSE officials to identify risks and provide proper risk management strategies. Ultimately, mitigation strategy and feasible solutions were presented to improve the risk management system. A combination of FMEA and FTA analysis by considering uncertainty through FIS would be a good suggestion for future studies.

7. ACKNOWLEDGEMENTS

During this study, a great deal of support was received from many specialists such as the project manager and HSE engineers within the project. The authors would like to express their appreciation to Mr. Javid Safayi, Mr. Hoobakht Hakimian, Mr. Alireza Jalali, Mr.

Mehran Habibi, Ms. Carroline Anesu Makoni, and Ms. Atefeh Alipourzadeh for the time, effort, and feedback received during this research. This work was financially supported by the environmental research center of Amirkabir University of Technology (Tehran Polytechnic).

8. REFERENCES

1. Gholami, P.S., Nassiri, P., Yarahmadi, R., Hamidi, A., and Mirkazemi, R., "Assessment of Health Safety and Environment Management System function in contracting companies of one of the petro-chemistry industries in Iran, a case study", ***Safety Science***, Vol. 77, No. 77, (2015), 42–47.
2. Liao, C.-W., and Perng, Y.-H., "Data mining for occupational injuries in the Taiwan construction industry", ***Safety Science***, Vol. 46, No. 7, (2008), 1091–1102.
3. Fung, I.W.H., Tam, V.W.Y., Lo, T.Y., and Lu, L.L.H., "Developing a Risk Assessment Model for construction safety", ***International Journal of Project Management***, Vol. 28, No. 6, (2010), 593–600.
4. Roger M. Cooke, "Uncertainty modeling: examples and issues", ***Safety Science***, Vol. 1–2, No. 26, (1997), 49–60.
5. Rezaian, S., and Jozi, S.A., "Health- Safety and Environmental Risk Assessment of Refineries Using of Multi Criteria Decision Making Method", ***APCBEE Procedia***, Vol. 3, No. 3, (2012), 235–238.
6. Dias, L., "Inspecting Occupational safety and health in the construction industry", International Training Center (ITC), International Labor Organization (ILO), Turin, Italy, (2009).
7. Huang, X., and Hinze, J., "Owner's Role in Construction Safety", ***Journal of Construction Engineering and Management***, Vol. 132, No. 2, (2006), 164–173.
8. Amir-Heidari, P., Maknoon, R., Taheri, B., and Bazyari, M., "A new framework for HSE performance measurement and monitoring", ***Safety Science***, Vol. 100, , (2017), 157–167.
9. Gurcanli, G.E., Bilir, S., and Sevim, M., "Activity based risk assessment and safety cost estimation for residential building construction projects", ***Safety Science***, Vol. 80, No. 80, (2015), 1–12.
10. McDonald, M., Musson, R., and Smith, R., Practical Guide to Defect Prevention, Microsoft Press, (2007).
11. Rhee, S.J., and Ishii, K., "Using cost based FMEA to enhance reliability and serviceability", ***Advanced Engineering Informatics***, Vol. 17, No. 3–4, (2003), 179–188.
12. Anand Pillay, J.W., "Modified failure mode and effects analysis using approximate reasoning", ***Reliability Engineering and System Safety***, Vol. 79, No. 1, (2003), 69–85.
13. Liu, C., Hwang, S., and Linو IK, "Safety Analysis of Combined FMEA and FTA with Computer Software Assistance–Take Photovoltaic Plant for Example", ***IFAC Proceedings Volumes,*** Vol. 46, No. 9, (2013), 2151–2155.
14. Abdelgawad, M., and Fayek, A.R., "Comprehensive Hybrid Framework for Risk Analysis in the Construction Industry Using Combined Failure Mode and Effect Analysis, Fault Trees, Event Trees, and Fuzzy Logic", ***Journal of Construction Engineering and Management***, Vol. 138, No. 5, (2012), 642–651.
15. Zhang, Z., and Chu, X., "Risk prioritization in failure mode and effects analysis under uncertainty", ***Expert Systems with Applications***, Vol. 38, No. 1, (2011), 206–214.
16. Seifi Azad Mard, H.R., Estiri, A., Hadadi, P., and Seifi Azad Mard, M., "Occupational risk assessment in the construction industry in Iran", ***International Journal of Occupational Safety and Ergonomics***, Vol. 23, No. 4, (2017), 570–577.
17. Ardeshir, A., Mohajeri, M., and Amiri, M., "Evaluation of safety risks in construction using Fuzzy Failure Mode and EEect Analysis (FFMEA)", ***Scientia Iranica A***, Vol. 23, No. 6, (2016), 2546–2556.
18. Azadeh, A., Fam, I.M., Khoshnoud, M., and Nikafrouz, M., "Design and implementation of a fuzzy expert system for performance assessment of an integrated health, safety, environment (HSE) and ergonomics system: The case of a gas refinery", ***Information Sciences***, Vol. 178, No. 22, (2008), 4280–4300.
19. Amiri, M., Ardeshir, A., and Fazel Zarandi, M.H., "Fuzzy probabilistic expert system for occupational hazard assessment in construction", ***Safety Science***, Vol. 93, No. 93, (2017), 16–28.
20. Azadeh, A., Saberi, M., Rouzbahman, M., and Saberi, Z., "An intelligent algorithm for performance evaluation of job stress and HSE factors in petrochemical plants with noise and uncertainty", ***Journal of Loss Prevention in the Process Industries***, Vol. 26, No. 1, (2013), 140–152.
21. Loftizadeh, A., "Information and control", ***Fuzzy sets***, Vol. 8, No. 3, (1965), 338–353.
22. Mousavi, S.M., Gitinavard, H., and Vahdani, B., "Evaluating Construction Projects by a New Group Decision-Making Model Based on Intuitionistic Fuzzy Logic Concepts", ***International Journal of Engineering - Transactions C: Aspects***, Vol. 28, No. 9, (2015), 1312–1319.
23. Safari, A., Hosseini, R., and Mazinani, M., "A Novel Type-2 Adaptive Neuro Fuzzy Inference System Classifier for Modelling Uncertainty in Prediction of Air Pollution Disaster (RESEARCH NOTE)", ***International Journal of Engineering - Transactions B: Applications***, Vol. 30, No. 11, (2017), 1746–1751.
24. Kandel, A., Fuzzy expert systems, CRC Press, (1992).
25. Rogers, E. and Li, Y., Parallel Processing in a Control Systems Environment, Prentice Hall, (1993).
26. Jamshidi, A., Yazdani-Chamzini, A., Yakhchali, S.H., and Khaleghi, S., "Developing a new fuzzy inference system for pipeline risk assessment", ***Journal of Loss Prevention in the Process Industries***, Vol. 26, No. 1, (2013), 197–208.
27. Alvarez Grima, M., Bruines, P.A., and Verhoef, P.N.W., "Modeling tunnel boring machine performance by neuro-fuzzy methods", ***Tunnelling and Underground Space Technology***, Vol. 15, No. 3, (2000), 259–269.
28. Ghasemi, E., and Ataei, M., "Application of fuzzy logic for predicting roof fall rate in coal mines", ***Neural Computing and Applications***, Vol. 22, No. S1, (2013), 311–321.
29. Amindoust, A., Ahmed, S., Saghafinia, A., and Bahreininejad, A., "Sustainable supplier selection: A ranking model based on fuzzy inference system", ***Applied Soft Computing***, Vol. 12, No. 6, (2012), 1668–1677.
30. Aliakbari Nouri, F., and Shafiei Nikabadi, M., "Providing a fuzzy expert system to assess the maturity level of companies in manufacturing excellence in the food industry of iran", ***International Journal of EngineeringTransaction A: Basics***, Vol. 30, No. 4, (2017), 532–542.
31. Wang, Y.-M., Yang, J.-B., Xu, D.-L., and Chin, K.-S., "On the centroids of fuzzy numbers", ***Fuzzy Sets and Systems***, Vol. 157, No. 7, (2006), 919–926.
32. Wang, Y.-M., "Centroid defuzzification and the maximizing set and minimizing set ranking based on alpha level sets", ***Computers & Industrial Engineering***, Vol. 57, No. 1, (2009), 228–236.
33. Liu, H.-T., and Tsai, Y., "A fuzzy risk assessment approach for

occupational hazards in the construction industry", ***Safety Science***, Vol. 50, No. 4, (2012), 1067–1078.

34. Veerasamy, R., Rajak, H., Jain, A., Sivadasan, S., Varghese, C.P., and Agrawal, R.K., "Ravichandran Veerasamy, et al : Validation of QSAR Models-Strategies and Importance Validation of QSAR Models-Strategies and Importance", ***International Journal of Drug Design and Discovery*** , Vol. 2, No. 3, (2011), 511–519.

A Prioritization Model for HSE Risk Assessment Using Combined Failure Mode and Effect Analysis and Fuzzy Inference System: A Case Study in Iranian Construction Industry

A. Ardeshir, P. Farnood Ahmadi, H. Bayat

Department of Civil and Environmental Engineering, Amirkabir University of Technology, Tehran, Iran

P A P E R I N F O

Paper history:
Received 27 December 2017
Received in revised form 12 March 2018
Accepted 26 April 2018

Keywords:
FMEA
Fuzzy Inference System
HSE Risk Assessment
Mamdani Algorithm
Construction Industry

چکیده

مسئله عدم دسترسی به اطلاعات کافی و عدم قطعیت در مدل‌سازی، نقش قابل توجهی در بروز مشکلات مهندسی و مدیریتی ایفا می‌کند. از این‌رو، بکارگیری تکنیک‌ها و فرآیندهای تصمیم‌گیری به منظور دستیابی به راه‌حل‌های مطمئن برای حل مسائل موجود تحت یک سنجش دقیق ضروری است. در این مقاله، کاربرد یک سیستم خبره فازی (FIS) برای مدل‌سازی عدم قطعیت موجود در بررسی ریسک‌های HSE مورد تحلیل قرار گرفته است. برای رسیدن به این منظور، از ترکیب یک تکنیک کاربردی با قابلیت اطمینان بالا در تحلیل ریسک‌های HSE به نام روش تجزیه و تحلیل عوامل شکست (FMEA) و سیستم خبره فازی (FIS) استفاده شده است. مدل پیشنهادی بر اساس الگوریتم ممدانی و ابزار منطق فازی موجود در نرم‌افزار متلب اجرا می‌شود. با توجه به مطالعه موردی، مقایسه‌ای بین آنالیز ریسک‌های HSE بر اساس مدل پیشنهادی و روش متداول FMEA انجام شده است. ریسک‌های مورد بررسی در سه بخش ایمنی، بهداشت و سلامت، و محیط زیست دسته‌بندی شده‌اند. طبق نتایج بدست آمده از مدل پیشنهادی، لغزش و افتادن کارگران جدی‌ترین ریسک با اهمیت بالا شناخته شده است که نمره اولویت خطرپذیری آن برابر با ۰/۷۹۳۸ می‌باشد. درحالی که جراحت پوستی به عنوان کم‌اهمیت‌ترین ریسک شناسایی شده است که نمره اولویت خطرپذیری آن ۰/۰۲۲۳ بدست آمده است. در نهایت با بکارگیری مدل پیشنهادی در آنالیز ریسک‌های مطالعه موردی، نتایج بدست آمده نشان می‌دهند که مدل پیشنهادی به عنوان یک سیستم هوشمند ارزیاب ریسک با در نظر گرفتن جنبه‌های اقتصادی نتایج دقیق‌تری را ارائه می‌دهد.

***doi**: 10.5829/ije.2018.31.09c.03*