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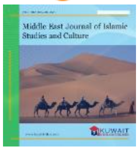

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Identifying and Prioritizing of Indicators Affecting Resilience in the Event of Fire-Induced Emergencies in a Combined Cycle Power Plant Using Fuzzy Analytic Hierarchy Process (FAHP)

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Abstract: ***Background***: Increasing the level of resilience is one of the approaches to reduce the consequences of fire. Emergency resilience is one of the most important and practical concepts in crisis management that has been considered in recent years. ***Objectives***: The current study was aim to identify and prioritize of indicators affecting resilience in the event of fire-induced emergencies in a combined cycle power plant using fuzzy analytic hierarchy process (FAHP). ***Methods***: By reviewing the texts and semi-structured interviews with 15 experts, 20 effective indicators in fire resilience in the combined cycle power plant were identified and classified into three main groups based on the McManomen model. In the next step, the weights of the indices of each group were determined using the FAHP method. Finally, the first three indicators of each group were selected for final prioritization and pairwise comparisons were performed between them again. ***Results***: The results showed that three indicators of structural stability (w=0.168), senior management awareness of roles and responsibilities (W = 0.145), risk perception and acceptance (W = 0.138) play the most important role. And logistics support index (0.069) is the least important in determining the level of resilience. ***Conclusion***: By recognizing the effective indicators in determining the level of resilience against fire in emergency situations, decision makers could define and implement corrective and preventive measures to improve safety and increase resilience based on priority.

Keywords: Prioritization, Fire, Emergency, FAHP, Combined Cycle Power Plant.

Research Paper

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INTRODUCTION

The electricity industry is one of the most important economic and industrial infrastructures of any country. The growing need for electricity in the world, especially in under developing countries, demands the development of power plants, which has been very rapid in Iran in recent years [1].

Advances in technology have increased the complexity of process systems, which in turn has led to major accidents on a large scale in recent years [2].

Accidents such as fires in combined cycle power plants are inevitable. Shirali *et al.*, (2014) showed the high risk of turbine explosion or fire in a combined cycle power plant using the fuzzy reliability approach and the occurrence of this accident will have severe consequences as well [3].

Occurrence of fires in these power plants could lead to death, injury, reduction of production, equipment failure and severe financial losses [4]. Sadeghi *et al.*, (2020) estimated the financial cost of a combined cycle fire at approximately $ 4.12 million using the DOW index [5].

However, in order to prevent the occurrence of human and financial losses due to fire in these power plants, measures such as fire risk assessment, monitoring of fire alarm system and increasing the level of resilience in case of fire is recommended [6-8].

The concept of resilience was firstly introduced by Hauling in the field of ecology; however, different definitions of resilience have been proposed in the field of accidents [9].

Following is one of the common and practical definitions in the field of safety: an inherent ability of a system is to regulate its performance before, during and after changes or disturbances in the system to maintain the required performance in both predictable and unpredictable conditions [10].

Resilient organizations are the ones which might overcome crises and emergencies caused by accidents at low costs, due to their high level of preparedness and planning [11].

In this regard, relatively much attention has recently been paid to organizations resilient to crisis and emergency situations. Researchers have tried to identify the characteristics of resilient organizations or societies and introduce the indicators needed to create these societies and organizations [12].

The use of multi-criteria decision making techniques (MCDM) has been considered by researchers to identify and prioritize resilience indicators in recent years [13].

The resilience engineering indicators were ranked in a refinery complex using fuzzy TOPSIS method and the weight and rank of indicators were determined and analyzed in the study of Jafari *et al.,* (2017) [14)].

Shirali *et al.,* (2019) conducted a study to evaluate the resilience indices using the ANP network analysis process method in a metal company to determine the weights of the indices and their effect on each other [15].

Therefore, the application of multi-criteria decision making methods in different fields of science might be important. As mentioned, due to the increasing use of combined cycle power plants to generate electricity, the construction and operation of these power plants has also increased. Due to the fact that the risk of accidents such as fires in this power plant is high, increasing the resilience of dealing with fire accidents might lead to a reduction in human and financial losses in these power plants. It is very important to identify the effective indicators and prioritize them so as to better improve in the level of fire resilience; thus, using multi-criteria decision making methods could be useful.

OBJECTIVES

The aim of the current study was to identify and prioritize of indicators affecting resilience in the event of fire-induced emergencies in a combined cycle power plant using fuzzy analytic hierarchy process (FAHP).

METHOD

Sample Size and Data Collection

The present study is a descriptive and analytical research conducted at the early 2021. In this study, 20 personnel with at least 10 years of experience in a combined cycle power plant were randomly selected and interviewed semi-structured. Due to the prevalence of the corona epidemic and in order to comply with health protocols, all interviews were conducted through social networks. In a semi-structured interview, instead of having a limited number of questions, the researcher has a framework of different topics to explore and uses these topics to gather the necessary information. At the end of the interview, 20 indicators were presented based on McManomen's model classified into three groups: situational awareness indicators, key vulnerability indicators, and adaptability capacity indicators [16]. Firstly, the indices of each group were weighed using fuzzy hierarchical analysis. Then, in order to identify the most important priorities, three important indicators from each group were selected and pairwise comparisons were performed between these criteria again.

Fuzzy Analytic Hierarchy Process

Fuzzy Analytic Hierarchy Process (FAHP) is one of the multi-criteria decision making techniques used in various sciences to weigh and prioritize indicators. This method can calculate and prioritize the final weight of each index by performing pairwise comparisons between indicators. In this study, the fuzzy hierarchical analysis method presented by Chang was used, the steps of which were as follows [17].

Creating a Hierarchical Structure

The first step in making a decision is to determine the hierarchical structure. In this method, the target and the indicators are set in a hierarchical structure.

Table 1: Indicators and sub-indices of fire resistance in emergency situations

Group	Adaptability	Vulnerability	Situational awareness
Criteria	Literacy level of staff and managers	Operating machines and equipment	Roles and responsibilities
	Lessons learned from events	Number of hydrant valves in the power plant	Perception of danger
	Organizational Chart	Emergency water supply station	Awareness of intra-organizational communication

Group	Adaptability	Vulnerability	Situational awareness
	Motivational actions	Correct location of stations	Insurance awareness
	Logistic support	Ability of human forces	Equipment recognition
		Operational facilities	Awareness of the number of fireboxes
		Equipment efficiency	Identifying the risk points
	Structural stability of stations		

Defining Fuzzy Numbers and Performing Even Comparisons

In this step, even comparison is done using fuzzy triangular numbers. An anonymous questionnaire was sent to the experts via social media and they were asked to compare the effective indicators of fire resilience in an emergency using the verbal expressions in Table 2, pair by pair.

Formation of Pairwise Comparison Matrix using Fuzzy Numbers

In this stage, the agreement matrices are formed according to the decision tree and using the opinions of experts, and then the incompatibility rate is calculated according to the Gogus and Butcher method. The pairwise comparison matrix will be as follows:

$$\widetilde{A} = \begin{bmatrix} 1 & \widetilde{a}_{12} & \cdots & \widetilde{a}_{1n} \\ \widetilde{a}_{21} & 1 & \cdots & \widetilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \widetilde{a}_{n1} & \widetilde{a}_{n2} & \cdots & 1 \end{bmatrix}$$

Calculating S_i for each row of pairwise comparisons

S_i, which is itself a triangular fuzzy number obtained from Equation (1)

$$S_i = \sum_{j=1}^{m} M_{gi}^{j} \otimes \left[\sum_{i=l}^{n}\sum_{j=l}^{m} M_{gi}^{j}\right]^{-1}$$

In this equation, i represents the row number j represents the column number. M_{gi}^{j}j indicates the fuzzy numbers of even matrices.

Amounts of $\left[\sum_{i=l}^{n}\sum_{j=l}^{m} M_{gi}^{j}\right]^{-1}$ and $\sum_{i=l}^{n}\sum_{j=l}^{m} M_{gi}^{j}$ and $\sum_{j=1}^{m} M_{gi}^{j}$ could be calculated as following **equations**.

Equation 2: $\sum_{j=1}^{m} M_{gi}^{j} = \left(\sum_{j=1}^{m} l_j \,.\, \sum_{j=1}^{m} m_j \,.\, \sum_{j=1}^{m} u_j\right)$

Equation 3: $\sum_{i=l}^{n}\sum_{j=l}^{m} M_{gi}^{j} = \left(\sum_{j=1}^{n} l_j \,.\, \sum_{j=1}^{n} m_j \,.\, \sum_{j=1}^{n} u_j\right)$

Equation 4: $\left[\sum_{i=l}^{n}\sum_{j=l}^{m} M_{gi}^{j}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i} \,.\, \frac{1}{\sum_{i=1}^{n} m_i} \,.\, \frac{1}{\sum_{i=1}^{n} l_i}\right)$

Calculating the magnitude of S_is to (compared to) each other

In general, if M1= (l_1, m_1, u_1) and M2=(l_2, m_2, u_2) are two fuzzy triangular numbers, the magnitude of M1 than M2 is defined as follows (Fig. 2).

Equation 5: V ($M_2 \geq M_1$)=hgt ($M_1 \cap M_2$) = $\mu_{M_2}(d) = \begin{cases} \begin{matrix} 1 \\ 0 \end{matrix} & if\ m2 \geq m1 \\ \frac{l1-u2}{(M_2-u2)-(m1-l1)} & if\ l1 \geq u2 \\ & other\ wise \end{cases}$

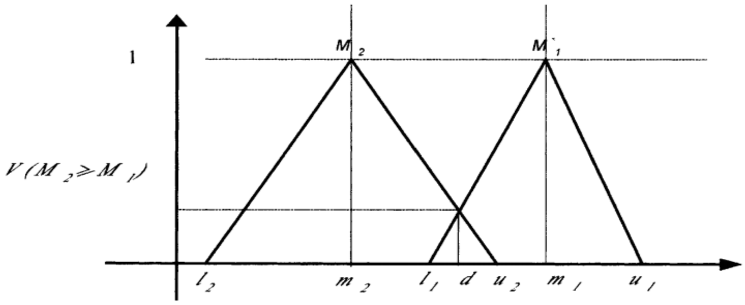

Figure 2: The degree of magnitude of two fuzzy numbers than each other

On the other hand, the magnitude of a triangular fuzzy number is obtained from K of another triangular fuzzy number from Equation 6:

V (M≥M1, M2, ….M_k) = V[$(M \geq M1) and\ (M \geq M2) and \ldots \ldots and\ (M \geq M_k)$]

= Min V (M≥M_i),i=1,2,3,….,k

Table 2: Linguistic scale and its synonymous triangular fuzzy numbers

Fuzzy number	Linguistic scale	Fuzzy number scale
(1,1,1)	Equal importance	1
(1,2,3)	Equal importance to slightly more	2
(2,3,4)	Slightly more important	3
(3,4,5)	A little more important to more important	4
(4,5,6)	More important	5
(5,6,7)	More important to much more important	6
(6,7,8)	Much more important	7
(7,8,9)	Much more important than absolute important	8
(8,9,10)	Absolute important	9

Calculating the weight of criteria and options in paired comparison matrices

Equation 7 is used for this purpose:

$\acute{d}(A_i)$=Min V ($S_{i\geq} S_{k)}$ k= 1, 2,…., n , k≠i

Therefore, the non-normalized weight vector will be as follows

Equation 8: $w \acute{=} (\acute{d}(A_l).\acute{d}(A_l) \ldots.\acute{d}(A_n))^T\ A_l$ =(i= 1,2,….,n)

Calculating the final weight vector

To calculate the final weight vector, the weight vector calculated in the previous step must be normalized, so the final weight is calculated from Equation [9].

Equation 9: $w = d(A_l).d(A_l) \ldots.d(A_n))^T$

Calculating the Incompatibility Rate

In order to ensure the accuracy of comparisons and the reliability of decision matrices, the incompatibility rate was calculated using the proposed Gagos and Butcher method. If the obtained incompatibility rate is less than 0.1, it indicates the acceptability of the comparisons made [18].

RESULTS

The results of the first stage of pairwise comparisons in the group of situational awareness indices showed that the index of three indicators of management awareness of roles and tasks with a final weight of 0.219, risk perception and acceptance with a final weight of 0.171 and safety awareness index with a final weight of 0.165, play the most important roles, respectively.

Table 3: Normal and abnormal weights of situational awareness group indicators

Priority	Normal weight	Abnormal weight	Fuzzy product			Indicator
			L	M	U	
1	0.219	1.000	0.083	0.032	1.351	Management awareness of roles and tasks
2	0.171	0.777	0.039	0.163	0.662	Understanding and accepting risk
3	0.165	0.751	0.035	0.154	0.609	Awareness of available safe points
4	0.157	0.714	0.029	0.139	0.556	Awareness of intra-organizational communication
5	0.150	0.682	0.023	0.133	0.503	Knowledge of how equipment works
6	0.090	0.410	0.018	0.055	0.273	Awareness of the number of fire stations
7	0.046	0.210	0.012	0.026	0.164	Insurance awareness

Moreover, the results of pairwise comparisons in the vulnerability group showed that the three indicators of structural stability, manpower capability and operational facilities with weights of 0.217, 0.180, and 0.135 are the three important indicators of this group, respectively.

Table 4: Normal and abnormal weight of vulnerability group indicators

Priority	Normal weight	Abnormal weight	Fuzzy product			Indicator
			L	M	U	
1	0.217	1.000	0.063	0.051	1.552	Structural stability
2	0.180	0.832	0.043	0.141	0.753	Ability of manpower
3	0.135	0.623	0.042	0.136	0.708	Operational facilities
4	0.108	0.501	0.032	0.124	0.675	Number of hydrant valves in the power plant
5	0.093	0.429	0.031	0.114	0.581	Emergency water supply station
6	0.090	0.418	0.031	0.113	0.432	Proper location of fire stations

Priority	Normal weight	Abnormal weight	Fuzzy product			Indicator
			L	M	U	
7	0.088	0.409	0.030	0.109	0.351	Equipment efficiency
8	0.085	0.394	0.021	0.108	0.253	Operating machines and equipment

Furthermore, based on the results obtained from pairwise comparisons, three important indicators of the adaptability group include the level of literacy of staff and managers (w = 0.299), lessons learned from accidents (w = 0.223) and logistical support (w = 0.211).

Table 5: Normal and abnormal weight of adaptability group indicators

Priority	Normal weight	Abnormal weight	Fuzzy product			Indicator
			L	M	U	
1	0.299	1.000	0.070	0.457	1.712	Literacy level of staff and managers
2	0.223	0.761	0.059	0.202	0.886	Lessons learned from events
3	0.211	0.718	0.049	0.185	0.767	Logistic support
4	0.166	0.567	0.035	0.106	0.531	Motivational actions
5	0.104	0.354	0.024	0.048	0.295	Organizational Chart

The results of the second stage and final pairwise comparisons with fuzzy hierarchical analysis showed three indicators of structural stability (w = 0.168), senior management awareness of roles and responsibilities (W = 0.145), risk perception and acceptance (W = 0.138) play the most important role. And the three indicators of learning from past accidents (w = 0.082), awareness of safe points (0.077) and logistical support (w = 0.069) play the least role in increasing the level of resilience in emergency situations caused by fire.

Table 6: Final prioritization of indicators affecting resilience

Priority	Normal weight	Abnormal weight	Fuzzy product			Indicator
			L	M	U	
1	0.168	1	0.085	0.912	1.324	Structural stability
2	0.145	0.863	0.067	0.156	0.821	Senior management awareness of roles and responsibilities
3	0.138	0.823	0.075	0.142	0.813	Understanding and accepting risk
4	0.123	0.732	0.059	0.136	0.789	Ability of manpower
5	0.106	0.632	0.046	0.135	0.783	Operational facilities
6	0.088	0.528	0.041	0.129	0.768	Literacy level of employees and managers
7	0.082	0.490	0.039	0.127	0.767	Lessons learned from past events
8	0.077	0.459	0.037	0.116	0.753	Awareness of safe places
9	0.069	0.413	0.029	0.105	0.749	Logistic support

DISCUSSION

Complex socio-technical systems are very vague and unpredictable. The number of combined cycle power plants, as a critical socio-technical system, is being increased. Thus, the numbers of people working in these industries and the surrounding populations who are at risk are being increased as well. These new procedures and tools are needed to deal with emergencies and unpredictable events such as fires. One of these tools could be resilience engineering. Nowadays, resilience has become a fundamental and important issue for managers of organizations, because it could be used to better manage the risks in emergencies [19].

In recent years, the issue of increasing resilience to accidents has become an important and vital area as the simultaneous and reciprocal movement of sustainable development and disaster management to increase the level of resilience is currently being discussed. Therefore, the present study was designed and implemented with the aim of identifying and prioritizing the most important indicators and sub-indicators of increasing the level of resilience against fire accidents in combined cycle power plants using fuzzy hierarchical analysis. Norris (2011) studied strategies to improve the level of resilience in organizations. The results showed that resilience in organizations requires accurate and continuous evaluation of three important indicators of situational awareness, sensitivity management and adaptive capacity which is consistent with the results of the present study [20].

The results of the current study showed that the structural stability index against fire with a final weight of 0.168 is the most important index in the level of resilience against fire accidents in a combined cycle power plant. The non-flammability of materials used in fire-resistant structures immediately after exposure to the flame could help prevent the fire from spreading rapidly and also withstand the flames until rescue workers arrive. Durable materials should not immediately lose their strength. This feature causes the structure to remain stable against fire and maintain its resistance [21].

Obinna UkeniAkaa *et al.,* (2016) used the AHP method to prioritize the fire-fighting solutions in steel structures, which was selected as the most appropriate fire-fighting strategy in strengthening and protecting the structure [22].

Askaripoor *et al.,* (2015) using fuzzy logic and hierarchical analysis method, determined that fire in turbines of combined cycle power plants is the most important hazard in this industry. And the most important solution to reduce the damage caused by fire is to increase the stability of the structure and the use of fire-resistant materials, which is consistent with the results of the present study [23].

The current study findings showed that the senior management awareness index of roles and responsibilities with a final weight of 0.145 after the structural strength index is the most important in the resilience level of power plants in the face of fire emergencies. In Omidvar *et al.,* study, fuzzy hierarchical analysis method was used to evaluate the level of resilience performance of a petrochemical industry. The results showed that commitment, management and risk perception indicators are very important in determining the level of resilience.

Petrochemical industry is one of the process industries. In these industries, due to the high volume of storage and production of highly flammable materials, there is a risk of fire and explosion accidents. Therefore, one of the most important indicators to improve the level of resilience in these industries is management commitment and risk perception (management commitment in various areas such as financing, commitment to safety, safety of production, audit and inspection) is manifested which is consistent with the results of the present study [24].

Pinion *et al.,* also noted in their study that management's commitment to safety increases staff self-reporting control over their jobs. This indicates that in order to improve the level of resilience, the greatest effort should be made to change the thinking of senior management, in order to value safety issues and accept it as a value in the organization [25].

Also, Jafari Nodooshan *et al.,* (2017) identified and prioritized organizational resilience indicators in a refinery complex using the fuzzy TOPSIS method. The results showed that the senior management commitment index with a final weight of 0.035 has a higher priority than other indices. The difference between industry and also the lack of structural stability index in the study of Nodoshan *et al.,* might be the reason for the difference between the two studies [14].

According to the results, the third important indicator in increasing the level of resilience against fire is the risk perception and acceptance index with a final weight of 0.138. The risk acceptance and recognition index was reported as the important and effective indicator in organizational resilience in the study of Benoît and Caroline study (2020), which is consistent with the results of the present study [9].

Acceptance and risk recognition is possible using fire risk assessment [26]. Fire risk assessment is a useful tool for identifying potential fire hazards and the factors influencing its occurrence, determining the safety situation and developing emergency planning [27].

It is possible to identify fire-prone points in combined cycle power plants using risk assessment, and to define and create control measures to prevent fires and increase resilience against them [28].

Another important indicator according to the results is the ability of human resources weighing 0.123. Human resources industries are the heart of the activities of organizations. According to experts view, proper management of human resources, which includes such things as job satisfaction, reducing job stress, reducing work-family conflict will increase employee commitment and engagement, and ultimately the safety and resilience of the organization [29].

The next indicators in determining the level of resilience against fire are operational facilities, the level of literacy of personnel and managers, learning from accidents, awareness of safe points and logistical support, respectively. Operational facilities are another important indicator in determining the level of resilience that regardless of the type and factors of fire, operational facilities such as fire alarm and extinguishing systems are the main and important equipment which must be considered in the design. Meanwhile, pumping stations are the main part of the fire extinguishing systems [30].

One of the most important actions of managers and supervisors demonstrating their practical support for safety is to provide safety training. In a study conducted in an oil refinery, it was reported that training has the greatest impact on managerial and organizational factors [31].

In the present study, the internal relationships between indicators have not been investigated, which could be referred to as limitations. This study was also conducted under the influence of the prevalence of Covid 19 disease, which caused the interview process to be done in absentia. Also, it was not possible to access more experts. Therefore, it is suggested to perform studies with a larger number of involving experts in future to evaluate the effects of internal communication between criteria using ANP network analysis.

Conclusion

Given the importance of fire resilience in emergency situations in combined cycle power plants, appropriate dimensions and indicators should be defined to measure the degree of fire resilience in industry. Then, by determining the weight and prioritizing the indicators, useful information should be provided to managers and decision makers, which should be used in planning to reduce the risk of fire in combined cycle power plants, as well as modeling and defining emergency response plans. In other words, in sensitive and important industries such as combined cycle power plants where the risk of fire is high, it is necessary to identify the important and effective indicators in order to improve the safety and increase the resilience and focus on them on a priority basis. Based on the findings of the current study, structural stability and senior management awareness of roles and responsibilities and acceptance and perception of risk are more effective than other indicators in determining the level of resilience of combined cycle power plants in the face of emergencies caused by fire. Therefore, it is necessary to think of measures to make senior management more familiar with safety issues based on increasing resilience in order to make decisions in emergency situations so as to reduce the damage caused by fire.

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