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AN EXTENSION OF THE FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS WITH FUZZY ANALYTICAL HIERARCHY PROCESS METHOD TO ASSESS THE EMERGENCY SAFETY BARRIERS

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The emergency safety barrier is one of the reactive technical safety barriers in industrial facilities. Degrade of emergency safety barriers can lead to a major accident with serious consequences for people, property and the environment. In this context, the purpose of this article is to present a proposed methodology to identify these deficiencies, thus ensuring the effectiveness of the emergency safety barriers. This paper presents an integrated approach that uses fuzzy set theory, extension of failure modes, effects and criticality analysis and the fuzzy analytic hierarchy process method to deal with uncertainty in decision-making related to the prioritization of risk factors. These risk factors are the prioritization of corrective actions associated with the most critical disturbance modes to improve the reliability of emergency safety barriers. In addition, a Liquefied Petroleum Gas production facility was selected as a case study to assess the emergency safety barriers. The results show that the proposed methodology provides the possibility to evaluate the fire-fighting systems. In addition, the fuzzy analytical approach method is the most reliable and accurate. Therefore, some corrective actions are suggested to reduce the failure criticality of the emergency safety barriers and help practitioners prioritize the improvement of the emergency safety barriers of the Liquefied Petroleum Gas storage facility. This paper has an important role in the dysfunctional analysis of the emergency safety barriers related to the others effects of the release of LPG, such as the effects of domino scenarios.

Keywords: Emergency Safety Barriers; Disturbance Modes, Effects and Criticality Analysis; Fuzzy Set Theory; Analytic Hierarchy Process; Corrective Actions.

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1. INTRODUCTION

LPG Storage tank accidents are rare but can result in serious consequences, including death, injury (Gomez *et al*., 2008; Al-Shanini *et al*., 2014), supply chain disruption, significant financial loss and environmental impact. A large tank fire is very complex and requires large amounts of fluids, such as foam and water, as well as equipment and emergency response teams to fight the fire. Looking at past events, we understand that the cost of this accident is very high. Moreover, reducing the number of major accidents based on Hazard and Operability (HAZOP analysis for unsafe installation is necessary. However, traditional HAZOP analysis has limitations in quantifying deviations (Wang *et al*., 2022). This study introduces Artificial Neural Networks (ANN) and Aspen HYSYS to explore the possibility of quantifying HAZOP deviations. The results show that the predicted severity of deviations can be close to the actual severity of deviations, and the prediction accuracy can reach almost high. Thus, the method reduces the possibility of ignition, rupture and liquid leakage. To this end, each major industrial accident is a reminder of the importance of preparedness to respond effectively in the event of an emergency by installing an effective emergency safety barrier (Hamzi *et al*., 2013; Innal *et al*., 2014; Girard *et al*., 2016). QRA is a systematic tool for assessing the hazards and methods to prevent and mitigate potential accidents. Quantitative chemical process risk analysis provides a quantitative or qualitative method for assessing industrial risks and identifying safety barriers for cost-effective risk reduction.

For this reason, the implementation of safety assessment and risk management of storage tanks is an important barrier measure to reduce risk occurrence and severity based on impact analysis. It also assesses their safety status and increases the

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level of safety management (Sarvestani *et al*., 2021). To ensure better prevention, there are several types of safety barriers in the chemical industry, such as technical barriers and human and organizational barriers. Emergency response actions are one of the safety barriers implemented in the industry.

Several articles were interested in the modeling and evaluation of emergency response plan (Zhou *et al*., 2017; Hou *et al*., 2021; Kazemian Talkhooncheh *et al*., 2021; Bai *et al*., 2022). Consequently, emergency response actions consist of several types of barriers. This study is based on barriers to prevent fire emergencies. Any industrial chemical activity involves unexpected events that are tied to the behavior of workers, the organization of work and the facility design. We can locate multiple preventive or protective safety barriers in actual work environments (Sunindijo, 2015). These barriers contain components to protect, mitigate and prevent hazardous sequences of events. We can build adequate safety barriers by analyzing functions and thus reduce risks. Explaining how the safety barrier system fails and the causes of its failure will help reduce the potential accidents and their consequences (Kang *et al*., 2016).

The occurrence of high-risk accidents in petrochemical industries is not uncommon. In recent years, a number of major accidents have occurred in petrochemical areas throughout Algeria (Chettouh *et al*., 2016), the most disastrous of which that claimed lives and caused great material damage is perhaps the one that took place in the Skikda industrial pole in October 2005 (Ait Ouffroukh *et al*., 2018). In fact, preventing and reducing fire hazards of this sort in the industrial sector can be attributed to the implementation of proper safety measures. Thus, one of the most common methods used as a measure against hazardous risks is found in firefighting systems. Previous research has focused on the barriers to reducing gas explosions in the petrochemical industry by using fire-fighting systems, fire-fighting pump systems, and water deluge systems (Wingerden, 2000; Davies *et al*., 2004; Guetarni *et al*., 2019).

Several methods have been developed in the chemical industry to ensure maximum safety and reliability. Hence, a new fuzzy bow tie (BT) method and Bayesian networks are used for risk assessment to overcome the lack of prior probability problems in aviation operations. Finally, the results of the analysis are confirmed by the values of the safety indicators (Pouyakian *et al*., 2021). Therefore, (Wu *et al*., 2021) proposed an integrated quantitative risk assessment model for port-liquefied natural gas (LNG) bunkering and storage based on the Bayesian Catastrophe- EPE (Energy Transfer Theory, Preliminary Hazard Analysis and Evolution Tree) method. The results of the scenario analysis were implemented to determine the critical hazards and quantitative correlation between each element considered in LNG accidents.

Additionally, (Sarvestani *et al*., 2021) developed a predictive accident model for dynamic risk assessment of refinery propane storage tanks. Hazards and safety barriers were identified using the methodology of the identification of major accident hazards (MIMAH) approach. Bow tie diagrams were constructed, and barriers on the diagrams were identified and verified by refinery experts. According to the System hazard identification, prediction and prevention (SHIPP) model (Rostamabadi *et al*., 2020), safety barriers have been categorized into seven main barriers. The failure rate of the basic events of the fault tree was extracted from reliable sources, and the prior probability of the barriers was calculated. Using the prior probability of barrier failure, the probability of occurrence of each consequence severity level was calculated using an event tree analysis. Finally, the posterior probability of the consequences was calculated using the posterior probability of barrier failure.

Several researchers have successfully applied the Failure Mode and Effects Analysis (FMEA) in various fields. FMEA is a useful technique for identifying hazards in complex systems. FMEA is used to prioritize failure modes, called failure mode and effects criticality analysis (FMECA). Traditionally, a metric called the Risk Priority Number (RPN) is commonly used in FMEA to obtain an order of priority of possible failure modes. RPN is often considered the product of detection (O), severity (S), and non-detection (D) of the failure mode (Certa *et al.*, 2017).

As mentioned earlier, the FMECA team members they often have difficulty articulating their ratings with precise numbers. We observed that there is a significant amount of literature based on multi-criteria techniques that have focused exclusively on improving the risk assessment process in FMEA by overcoming the shortcomings of the traditional FMEA technique (Tian *et al*., 2018). Indeed, as a strategy to deal with the inevitable imprecise estimation of failure probability in diverse real-world applications, many studies have considered uncertain situations. To this end, the fuzzy set theory has been proposed as an alternative to risk estimation of failure modes in which the available information is uncertain, incomplete, and imprecise (Balaraju *et al*., 2019). Due to the difficulty and complexity for FMECA, team members need to determine the risk of potential failure modes, for which multiple risk factors should be considered. The risk of failure modes can be prioritized and treated as a multi-criteria problem.

The next popular method for FMEA consists of multi-attribute decision-making (Salabum *et al*., 2020) such as Fuzzy Set Theory (Kabir *et al*., 2018), FAHP (Hu *et al*., 2009), ANP (Wang *et al*., 2016) and TOPSIS (Liu *et al*., 2018). As a result, a recent study (Kumari *et al*., 2023) proposed an FMEA of conventional sewage treatment plants in humid subtropical regions using multi-criteria based on fuzzy set theory, i.e., fuzzy analytical hierarchy process (FAHP) method and a fuzzy technique for ordering preferences by similarity to the ideal solution (FTOPSIS) to obtain the failure mode (FM) rate (Alarcin *et al*., 2014). FAHP is used to calculate the weight of three risk factors (RF), i.e., occurrence (O), which refers to the possibility of occurrence of the cause of failure; severity (S), which measures the degree to which the cause of the failure affects the system, and detection (D), which is the ability to detect the cause of the failure before it actually fails. FTOPSIS is then used to determine the order of FMs that indicates their criticality. In addition, an integrated approach for fuzzy failure modes and effects analysis using fuzzy AHP and improved Fuzzy Multi-Attribute Ideal Real Comparative Analysis (modified FMAIRCA) (Boral *et al*., 2020). First, we calculate the fuzzy relative importance among risk factors using the FAHP method and then use these important values in our proposed modified FMAIRCA to rank the failure modes according to their risk level. Our modified FMAIRCA method is computationally light and able to provide more solutions that are viable. We review a reference case in the field of FMEA to test the capabilities of our integrated approach and highlight its utility. In addition, we compare the estimation result with other MCDM methods, and a sensitivity analysis is performed to highlight the robustness of the proposed approach.

In this context, this study aims to provide an additional framework for assessing the ambiguity and imprecision of an extension of failure modes and effects criticality analysis by prioritizing the risk factors associated with breaching emergency safety barriers. Therefore, the purpose of this paper is to assess the risks of breaching the emergency safety barriers and to prioritize the risk factors associated with the proposed corrective actions. This paper presents an integrated approach that uses fuzzy set theory, failure mode expansion, effect and importance analysis, and the fuzzy analytic hierarchy process method to deal with uncertainty in risk factor prioritization decisions. For this, a new technique was developed, which contains two main stages. First, it is necessary to estimate the value of the risk priority number for the disturbance modes of all components of the emergency safety barriers using the method of analyzing the modes, effects and criticality of the disturbance based on the provided feedback. Second, corrective actions are suggested based on the values obtained from the risk priority numbers of the disturbance modes. In addition, risk factors such as personal, environmental, societal, and production factors are prioritized using the fuzzy AHP method (Bahmed *et al*., 2016). To illustrate the effectiveness of the proposed methodology, a real case study of LPG storage tanks for an LPG complex in Algeria is presented. In addition, this study allows us to assess the risk of emergency safety barriers by prioritizing the risk factors and suggest the best improvement measures to ensure complete safety in LPG storage tanks. In addition, this study aims to provide an additional basis for prioritizing corrective actions suggested by risk factors identified in emergency safety barriers.

After this introduction in Section 1, the rest of the paper is structured as follows. Section 2 provides a detailed description of the proposed methodology. Section 3 presents a case study of a fire-fighting system in an Algerian LPG complex. Section 4 presents the results of that discussion. Section 5 deals with the results of this work and future research.

2. METHODOLOGY

The proposed methodology consists of two steps, as shown in Figure 1.

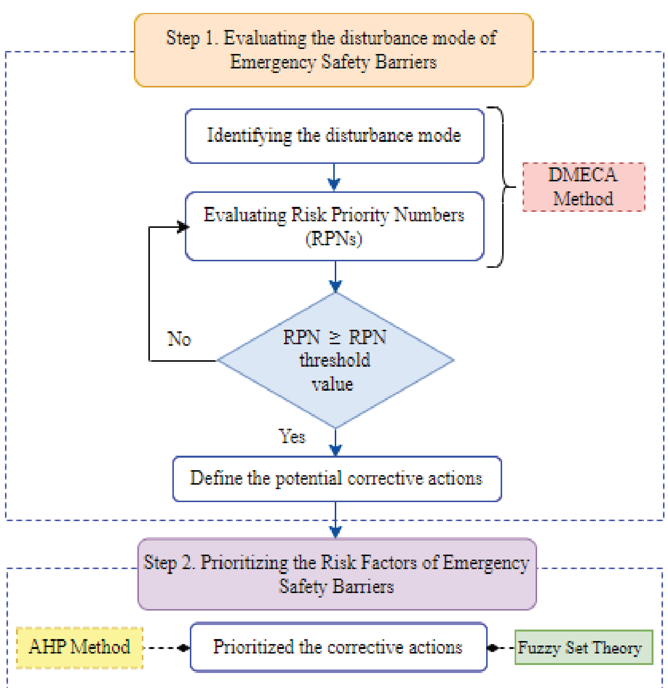

Figure 1. The proposed methodology.

The first step aims to evaluate the disturbance mode of emergency safety barriers. This step requires information on each disturbance mode in terms of frequency, probability of non-detection and impact of possible consequences. Here, this step consists of three steps. (1). Identification of disturbance modes using disturbance mode, effects and criticality analysis. (2). Estimate the risk priority number for each disturbance mode. (3). Determination of possible corrective actions of critical disturbance modes. Once the risk priority number is calculated, the second step is to use the Fuzzy Analytical Hierarchy Process (FAHP) method to select risk factors to control the impact of disturbance modes whose risk priority numbers exceed a given threshold limit, requiring an action plan to be triggered. This selection is made by prioritizing the effectiveness of each corrective action with respect to the impact of the breach of emergency safety barriers on the four risk factors: personnel, environment, population, and production. A detailed description of these stages is provided in the following paragraphs.

2.1. Evaluating the disturbance mode of emergency safety barriers

Failure Mode and Effects Analysis (FMEA) is a management technique for the product development and operations process. It defines the probability and severity of possible system failures. An effective FMEA study allows failure modes to be identified based on past experience with similar products or processes. It ensures the removal of these failure modes from the system with minimal resource usage and effort. FMEA is implemented using BS EN 60812:2006 (ICE 60812), which provides guidance on how FMEA can be implemented to achieve various reliability objectives.

FMEA aims to define, identify and eliminate potential failures before they reach the customer. FMEA, which is a proactive approach, is used as a risk assessment approach to identify and address potential breakdowns in service and production systems and processes. The other methods of risk assessment represent poor failure modes (FM) after accidents. This position provides an opportunity to regulate current programs, use suggested activities to reduce the likelihood failure modes and prevent dangerous accidents. This is defined as a failure mode in which they could not meet the system design requirements. I failure mode can cause other failure modes to occur (Efe *et al*., 2017).

Equation (1) represents the risk priority number (RPN) using the multiplication criteria of occurrence (O), severity (S), and detection (D). The terms O, S, and D are the probability, severity, and detectability of failure (Liu *et al*., 2014).

$$RPN = f(F, I, D) = F \cdot D \cdot I \tag{1}$$

Aitouche (2011) proposes an extension of the Failure Modes, Effects and Criticality Analysis. Disturbance Mode, Effects and Criticality Analysis method is adopted in this work in order to accurately handle potential obstacles (rather than failures suitable for technical systems) that may occur during the execution of emergency safety barriers that has a predominant organizational aspect. The main steps of the disturbance modes, effects and criticality analysis approach are outlined below.

(1) Identification of the possible disturbance modes, their respective causes and effects.
(2) Evaluation of the risk priority number of each disturbance mode of the system components based on the disturbance frequency "F", its impacts "I" and its non-detection probability "D".

The "F" parameter is expressed as the number of considered disturbance modes over time or under solicitation (for example, once per year). In many cases, it is more appropriate to classify "F" in quality classes. The frequency classes used in our case are illustrated in Table 1. The "I" parameter characterizes the estimation of the effects (consequences) of the disturbance mode on the function of the studied system. The classification categories shown in Table 2 are often used. It is worth noting that the "F" and "I" class parameters should be defined and calibrated to be in accordance with international and national standards and relevant to company policies. Non-detection "D" of an identified disturbance mode is the probability that warning signals (if any) that are proactive information will not be detected. They make it possible to clarify the possible occurrence of triggering events associated with potential consequences. In most cases, these warning signs require a quick response. Different detection options can include different alarms, test actions and human perception. Note that when estimating the "D" parameter, existing measures that are likely to reduce the frequency of the disturbance mode must be taken into account. In addition, some disturbance modes can be detected immediately when they occur (e.g., "false closing" of a valve installed on a water main), while some others are only detected during test operations, simulations or real situations (e.g., "failure to start" standby fire pump; emulsifier is obsolete). The accepted classification of the "D" parameter is shown in Table 3. The classification of the risk priority number adopted is shown in Table 4.

Table 1. Disturbance mode frequency classification.

Level	Qualitative description
1	Very unlikely disturbance
2	Unlikely disturbance
3	Likely disturbance
4	Very likely disturbance

Table 2. Disturbance mode impact classification

Level	Qualitative description
1	Minor impact
2	Medium impact
3	Critical impact
4	Catastrophic impact

Table 3. Disturbance mode non-detection classification.

Level	Qualitative description
1	Obvious Detection: strong sign before detection of a disturbance and automatic detection device (alarm).
2	Possible Detection: an event easy to detect but requires a special reaction.
3	Unlikely Detection: an event hard to detect and requires reaction or complex means (disassembly, etc.)
4	Impossible Detection: very weak signals before the occurrence of an event.

Table 4. Risk Priority Number ranking.

RPN class	Qualitative description
$01 \leq RPN \leq 12$	Negligible
$12 < RPN \leq 16$	Medium
$16 < RPN \leq 20$	High
$20 < RPN \leq 80$	Very high

2.2. Prioritizing the risk factors of emergency safety barriers

After setting the potential corrective actions to cope with the disturbance mode identified as unacceptable, it remains to prioritize them and select the most suitable ones. Several studies show that the calculation of a single Risk Priority Number, which is the case in DMECA approaches, to characterize the impacts on different targets is not effective for a reliable decision-making process regarding the actions to be implemented for controlling risks and optimizing costs (Kutlu *et al.*, 2012; Liu *et al.*, 2012). In order to overcome this limitation, a new approach suggesting an integration of the DMECA method with the multi-criteria decision support methods has been developed (Braglia, 2000). In our work, the Fuzzy Analytic Hierarchy Process method is used where the corrective actions selection relies on prioritizing the risk factors of emergency safety barriers on four identified targets: the personal, the environment, the public and the production. These risk factors are respectively designated as $\mathrm{RF_{Per}}$, $\mathrm{RF_{Env}}$, $\mathrm{RF_{Pub}}$ and $\mathrm{RF_{Pro}}$.

The analytic Hierarchy Process (AHP) method is a structured multi-criteria decision approach, which was first introduced by Saaty (Saaty, 1990; 1998), an American operational research expert. Designed to reflect the way people actually think, the Analytic Hierarchy Process method is one of the most popular analytical techniques for solving complex decision-making problems (Aminbakhsh *et al.*, 2013; He *et al.*, 2015). Although there are many methods implemented in Fuzzy AHP (Chang, 1996), Buckley's method (Buckley, 1985; Tzeng *et al.*, 2011) is widely used in research because of its simplicity. The steps of the Fuzzy AHP procedure are as follows:

Step 1: Hierarchy construction. The decision-making hierarchy is constructed by decomposing the decision-making problem into its basic part: a hierarchy of mutually related decision-making elements (hierarchy of sub-problems). Analytic Hierarchy Process methods generally consist of a top-level (target layer), several intermediate levels (criterion layers), and lower levels (alternative layers) (Zhang *et al.*, 2016). In the decision-making process, there is one objective and a finite set of alternatives from which the decision-maker is usually asked to select the best one based on consideration of a set of criteria. Criteria are characteristics that make one alternative preferable to another with respect to a given goal (Brunelli, 2015). Figure 2 shows an example of a security system selection hierarchy.

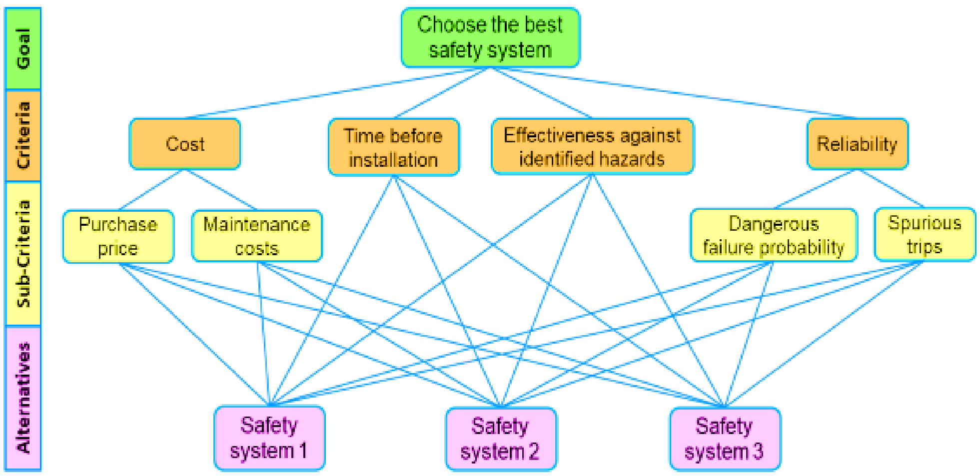

Figure 2. Hierarchy example for the selection of a safety system.

Step 2: Pairwise comparison matrices between criteria. Fuzzy triangle scale is used to prioritize criteria in the hierarchy, indicating their relative importance among other criteria. These criteria or alternatives are compared using linguistic terms, as shown in Table 5 below.

Table 5. Linguistic terms and the corresponding triangular fuzzy scale.

Linguistic scales	Scale of fuzzy number
(1,1,1)	Just equal (Je)
(1,1,3)	Equally important (Eq)
(1,3,5)	Weakly important (Wk)
(3,5,7)	Essentially important (Es)
(5,7,9)	Very strongly important (Vs)
(7,9,9)	Absolutely important (Ab)

In this study, Buckley's FAHP is used to find the fuzzy weights since it is easy to implement. The procedure can be summarized by the given "Equation (2)":

$$\tilde{A}=\begin{bmatrix} 1 & \tilde{a}_{12} & \dots\dots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \dots\dots & \tilde{a}_{2n} \\ \dots. & \dots. & & \dots. \\ \tilde{a}_{m1} & \tilde{a}_{m2} & \dots\dots & 1 \end{bmatrix}, \tag{2}$$

where $\tilde{A}$ pairwise comparison matrix and:

$$\tilde{A}=\begin{cases} i > j, (1,1,3), (1,3,5), (3,5,7), (7,9,9) \\ i = j,\ (1,1,1) \\ i < j, (1,1,3)^{-1},\ (1,3,5)^{-1}, (3,5,7)^{-1}, (5,7,9)^{-1}, (7,9,9)^{-1} \end{cases}. \tag{3}$$

Step 3: Normalized relative weights of criteria. In this step, the geometric means of fuzzy comparison value $\tilde{r}_i$ and fuzzy weight $\widetilde{W}_i$ were calculated as shown in Equations (3) and (4).

$$\tilde{r}_i = (\tilde{a}_{11} \otimes \tilde{a}_{12} \otimes \ldots \otimes \tilde{a}_{in})^{1/n} \quad (3)$$

$$\widetilde{W}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \oplus \ldots . \oplus \tilde{r}_n)^{-1} , \quad (4)$$

where $\tilde{a}_{in}$ is the fuzzy comparison value of criterion i to criterion n, $\tilde{r}_i$ is the geometric mean of the fuzzy comparison value of criterion i to each criterion, $\widetilde{W}_i$is the fuzzy weight of the ith criterion, which can be indicated by Triangular Fuzzy Numbers (TFNs), $\widetilde{W}_i = (l_{w_i}, M_{w_i}, u_{w_i})$. Here l_{w_i}, M_{w_i} and u_{w_i} stand for the lower, middle and upper values of the fuzzy weight of the *i*th criterion.

Step 4: The procedure of defuzzification is to locate the Best Non- fuzzy Performance value (BNP). To utilize the COA (Center Of Area) method to find out the BNP is a simple and practical method, and there is no need to bring in the preferences of any evaluators, so it is used in this study. The BNP value of the fuzzy number $\tilde{R}_i$ can be found by the following Equation (5):

$$BNP_i = {[(uR_i - lR_i) + (MR_i - lR_i)]}/{3} + lR_i \, . \quad (5)$$

The proposed methodology for the selection of corrective actions related to a given emergency response action is illustrated in the following section.

3. CASE STUDY: FIRE-FIGHTING SYSTEMS OF A LPG UNIT

In order to implement the approach described in Section 2, this section proposes to evaluate the risk of a fire-fighting system installed in the liquefied petroleum gas (LPG) storage area. The choice of this site is due to its availability in an area close to other oil and gas industries and its sensitivity to our country's economy. For these reasons, the installed fire-fighting systems must be reliable to protect the site in the event of a disaster.

The fire-fighting systems would, at the request of the voting system of 2-of-3 detectors that can be used to control pressure in the LPG storage area to reduce the heat load from the fire. Therefore, it is clear that the reliability of the fire-fighting systems must be high in order to obtain sufficient power to reduce the heat load. Figure 3 shows, schematically, the flow diagram of the main function within this fire-fighting systems, which is to provide storage space for the LPG unit.

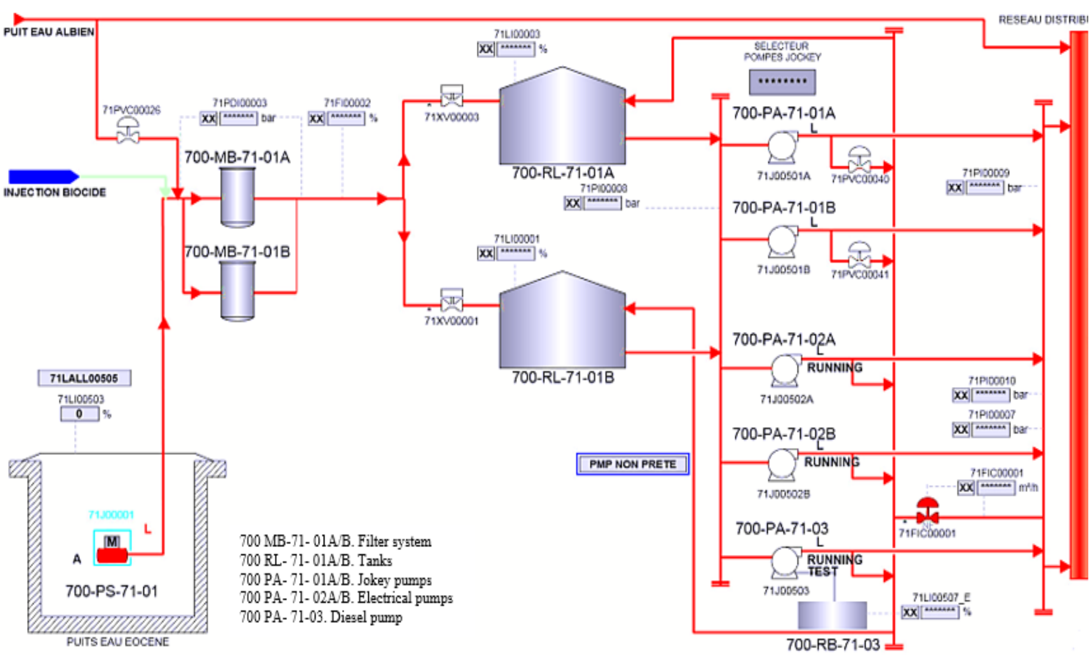

Figure 3. Simplified flow diagram of the fire-fighting systems of the liquefied petroleum gas storage.

The fire-fighting systems in the liquefied petroleum gas storage facility include a water deluge system, a water tank system, a pump system and a logical system. The water deluge system is activated automatically or manually. Via the water tank system, the liquid from the well and outside the site is stored in two tanks with a capacity of 15000 m3 each. In case of a fire hazard, the signal also goes from the central panel to the valve of the water system, opening it and establishing a water channel in the tank caused by water pressure. This water network is integrated with the filter system to prevent corrosion problems in the water pipes. Multi-functional pump systems included with two jockey pumps (2 × 100%), 30 m3 / h at 9 barg, two electric pumps (2 × 50), 550 m3 / h at 10 barg and diesel pumps (1x100), 1100 m3 / h in 10 barg in standby mode and supply water to the ring on demand. In order to distribute the firewater to all fire-fighting systems on-site, the ring-main is constantly pressed at 9 barg by a jockey pump. In the event of gas or fire, fire and gas logics send a signal to the electric pumps and flood valve to start. When the overflow valve slides into the fireplace it opens, and water flows through the overflow channels. To maintain the pressure level in the ring-main, pressure devices are installed in the ring-main.

A study of fire-fighting systems related to the LPG unit by using the proposed methodology combining the DMECA and FAHP methods will be detailed next. We remind you that the purpose of the study is to determine the consequences of this regime of violation of fire-fighting systems and to determine the appropriate corrective actions.

3.1. Evaluating the disturbance mode of the fire-fighting systems

The DMECA method is used to identify the critical disturbance modes of the fire-fighting systems through the evaluation of Risk Priority Number. Table 6 illustrates an extract from the DMECA method study of fire-fighting systems related to the LPG storage complex. The information needed to characterize the different disturbances is obtained by feedback and by means of questionnaires.

Table 6. Extract from the DMECA study of fire-fighting systems relating to the LPG complex.

Component	Disturbance mode	Causes of failure	Failure effect	Detection	Criticality			
					F	I	D	RPN
Deluge valve	• Fail to open on demand.	• Blocked closed. • Electromechanical system does not work.	• Not passing water.	• Gas detector system.	3	4	3	36
	• Large leakage.	• Corrosion. • Damage	• Reduced water passage.	• Inspection.	2	3	2	12
Nozzle spray	• Clogged	• Limestone.	• The water curtain does not protect all the equipment.	• Inspection. • Use wide spray diameters to avoid clogging.	2	3	3	18

In this study, determining the threshold value of the risk priority number that triggers an action plan (corrective actions) required the development of a questionnaire, which was answered by fifteen employees in the LPG complex.

The results of this questionnaire are shown in Figure 4, which indicates that a significant number of the participating persons (53 %) judged that the RPN threshold is in the range of ($20 < RPN \leq 80$). Thus, we define RPN = 20 as the minimal value triggering an action plan.

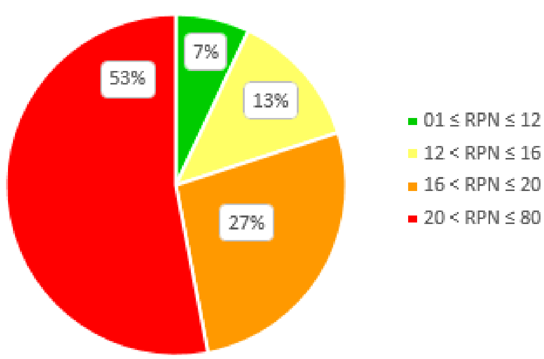

Figure 4. Questionnaire results for the RPN threshold value determination.

Based on the results of Table 6, the disturbance mode "fail to open on demand" of the component "deluge valve" has an RPN value is 36, which pertains to the "Very high" class (20 < RPN ≤ 80). Note that this disturbance mode implies necessary preventive maintenance and regular testing, which the flame detection system in position open. As the Risk Priority Number threshold value (20) is exceeded, the above disturbance mode "fail to open on demand" has, therefore, to be controlled through the triggering of corrective actions plan. The next step is to prioritize the different possible corrective actions to be taken with respect to their effectiveness in controlling the disturbance mode "internal emergency plan procedures not updated" using the Analytic Hierarchy Process method.

According to the results obtained following the evaluation of the risk of the fire-fighting system, the most critical disturbance mode is "fail to open on demand". To this end, corrective actions are proposed in order to make the critical disturbance mode reliable. The following Table 7 represents a list of corrective actions.

Table 7. The only 10 corrective actions.

Corrective actions	Description
CA.1	Clean regularly the nozzle spray
CA.2	Treat pipe corrosion
CA.3	Improving observation process
CA.4	Applying cyclic maintenance tests
CA.5	Change of defective material
CA.6	Updating failure analysis procedure
CA.7	Increasing number of site visits
CA.8	Increasing inspection analysis
CA.9	Implementing Risk-Based Maintenance
CA.10	Revising and improving work procedures and instructions

3.2. Prioritizing the risk factors of fire-fighting systems

The following study is based on interviews and group discussions conducted at the LPG complex with the participation of ten experts. Thus, the hierarchical structure of the study is constructed, as shown in Figure 5. It contains the decision objective "Prioritize risk factors of the fire-fighting system", the alternatives to achieve it (10 corrective actions (CA)), and the criteria for evaluating the alternatives (personal of risk factor (Pers._RF), environment (Envi._RF), public (Pub._RF) and production (Prod._RF)). It is worth noting that the frequency (F) and non-detection (D) parameters are not taken into account, as they still do not change regardless of the risk factor (i.e., personal, public, environmental and production).

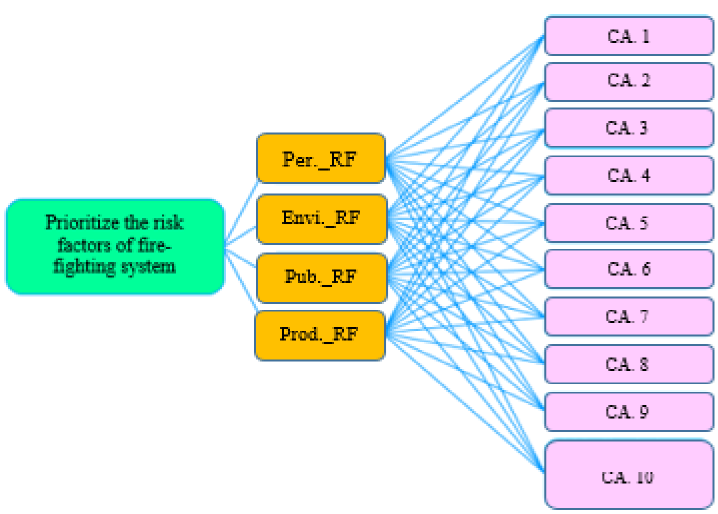

Figure 5. The hierarchy for prioritizing risk factors for the disturbance mode "fail to open on demand".

The pairwise comparisons between all risk factors were made by using data from sets of questionnaires participated by three workers who are dealing with the setup process. The collected data were averaged to compile the opinion from all of three decision-makers in Table 8. The pairwise comparison data of each risk factor towards each other in triangular fuzzy numbers from Table 5 were then synthesized into matrices contribution form as in Table 9.

Table 8. Pairwise comparison among all the criteria involved in the hierarchy.

Q	(7,9,9)	(5,7,9)	(3,5,7)	(1,3,5)	(1,1,3)	Criteria	(1,1,1)	Criteria	(1,1,3)	(1,3,5)	(3,5,7)	(5,7,9)	(7,9,9)
1						C1		C2			x		
2						C1		C3		x			
3						C1		C4		x			
4					x	C2		C3					
5						C2		C4		x			
6					x	C3		C4					

Table 9. Pairwise contribution matrices for all risk factor

	Pers._RF			Envi._RF			Pub._RF			Prod._RF		
Pers._RF	1.000	1.000	1.000	3.000	5.000	7.000	1.000	3.000	5.000	1.000	3.000	5.000
Envi._RF	0.140	0.200	0.330	1.000	1.000	1.000	0.330	1.000	1.000	1.000	3.000	5.000
Pub._RF	0.330	1.000	1.000	1.000	3.000	5.000	1.000	1.000	1.000	1.000	3.000	5.000
Prod._RF	0.330	1.000	1.000	0.330	1.000	1.000	0.330	1.000	1.000	1.000	1.000	1.000

Using "Equation (3)", the geometric means of fuzzy comparison value $\tilde{r}_1$ were calculated as shown in Table 10 and the example calculation for all risk factors.

Table 10. Geometric means of fuzzy comparison values.

Criteria	$\tilde{r}_i$		
Pers._RF	1.316	2.590	3.637
Envi._RF	0.464	0.880	1.133
Pub._RF	0.758	1.732	2.236
Prod._RF	0.435	1.000	1.000
Total	2.973	6.202	8.007
Reverse (power of -1)	0.336	0.161	0.125
Increasing order	0.125	0.161	0.336

Using "Equation (4)", the geometric means of fuzzy values were then converted to relative fuzzy of weight, as shown in Table 11, by multiplying them with the total of reverse fuzzy geometric means in increasing order. Finally, the procedure of defuzzification is to locate the Best Non- fuzzy Performance value (BNP) is calculated by using "Equation (5)". Hence, the weight of the criteria is this shown in Table 11.

Table 11. Relative fuzzy weight and best non-fuzzy performance of each criteria.

Criteria	$\widetilde{W}_i$			BNP	Rank
Pers._RF	0.165	0.417	1.222	0.444	1
Envi._RF	0.058	0.142	0.381	0.143	3
Pub._RF	0.095	0.279	0.751	0.277	2
Prod._RF	0.054	0.161	0.336	0.136	4

Using the same step as before, the pairwise comparison step was repeated, but this time all ten alternatives were compared on each risk factor. However, it would be difficult to describe all the calculations because they follow the same steps as the pairwise comparison of each risk factor against the other risk factors. The final total score for each alternative is shown in Table 12 below.

Table 12. Aggregation results for each alternative according to each risk factor.

Criteria	Scores of alternatives with respect to related of the risk factors										
	Weights	CA1	CA2	CA3	CA4	CA5	CA6	CA7	CA8	CA9	CA10
Pers._RF	0.444	0.128	0.051	0.040	0.155	0.076	0.108	0.092	0.049	0.129	0.172
Envi._RF	0.143	0.119	0.053	0.068	0.151	0.065	0.137	0.094	0.053	0.128	0.130
Pub._RF	0.277	0.118	0.049	0.071	0.161	0.065	0.116	0.093	0.056	0.127	0.143
Prod._RF	0.136	0.122	0.057	0.065	0.155	0.058	0.122	0.091	0.057	0.138	0.133
Total (score Alt * weight of risk factors)		0.123	0.052	0.056	0.156	0.069	0.116	0.092	0.053	0.130	0.153

4. RESULTS AND DISCUSSIONS

The above-mentioned methodology is used here to the dysfunctional analysis of the fire-fighting system related to LPG safety by using the extension of the FMECA and FAHP methods. This methodology is proposed of a liquefied petroleum gas installation in Algeria. In this study, a method based on the Disturbance Modes, Effects and Criticality Analysis (DMECA) is proposed to analyze the disturbance mode of emergency safety barrier "fire-fighting system". Based on the fuzzy Analytic Hierarchy Process method, the risk factors related to the disturbance of the "fire-fighting system" were prioritized. In addition, the corrective actions related of each risk factor is selected. The fuzzy AHP method produces more reliable results than the classical AHP method because the uncertainties associated with expert judgments are minimized, and the results are more accurate and reliable.

Figure 6 shows the score values for all risk factors using the conventional AHP and the fuzzy AHP method. Therefore, the risk factor of the personal has a 44.4% effect on the disturbance of the "fire-fighting system" to an LPG accident. According to the obtained results, the weight values are most reliable and accurate when using the fuzzy AHP method. Summary results of the prioritization of corrective actions by the risk factor are presented in Table 13.

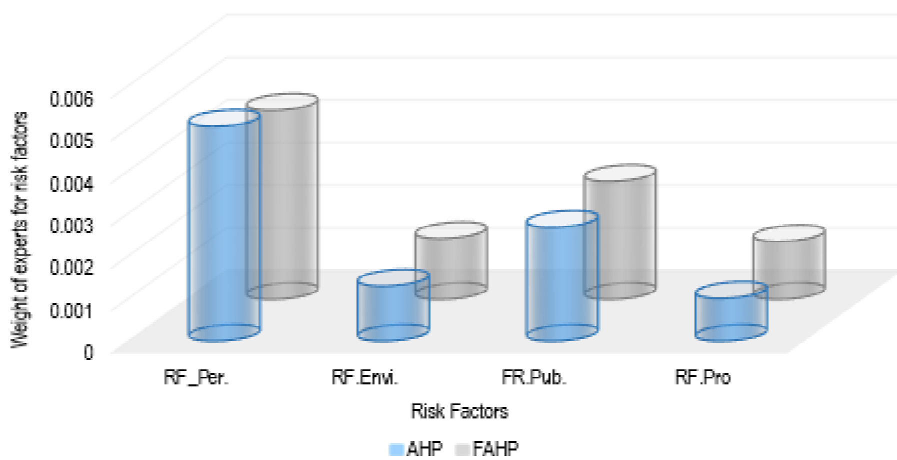

Figure 6. Comparison of the weight values of the risk factors by using the AHP and FAHP methods.

Table 13. Summary results of the prioritization of corrective actions by the risk factors.

Corrective actions	Risk factor of personal		Risk factor of Environment		Risk factor of Public		Risk factor of Production	
	AHP	FAHP	AHP	FAHP	AHP	FAHP	AHP	FAHP
CA1	0.133	0.128	0.121	0.119	0.127	0.118	0.12	0.122
CA2	0.038	0.051	0.044	0.053	0.04	0.049	0.043	0.057
CA3	0.051	0.040	0.058	0.068	0.054	0.071	0.057	0.065
CA4	0.168	0.155	0.158	0.151	0.166	0.161	0.162	0.155
CA5	0.061	0.076	0.062	0.065	0.068	0.065	0.07	0.058
CA6	0.107	0.108	0.118	0.137	0.107	0.116	0.116	0.122

Corrective actions	Risk factor of personal		Risk factor of Environment		Risk factor of Public		Risk factor of Production	
	AHP	FAHP	AHP	FAHP	AHP	FAHP	AHP	FAHP
CA7	0.096	0.092	0.099	0.094	0.102	0.093	0.098	0.091
CA8	0.034	0.049	0.041	0.053	0.043	0.056	0.042	0.057
CA9	0.125	0.129	0.127	0.128	0.124	0.127	0.128	0.138
CA10	0.186	0.172	0.173	0.130	0.17	0.143	0.163	0.133

Figure 7 shows the score values for the corrective actions associated with the personal risk factor using the conventional AHP and the fuzzy AHP method. Thus, corrective action 10 (Revising and improving work procedures and instructions) has a 17.2% on the personal risk factor of disturbance of the emergency safety barrier "fire-fighting system". According to the obtained results, the weight values are most reliable and accurate when using the fuzzy AHP method.

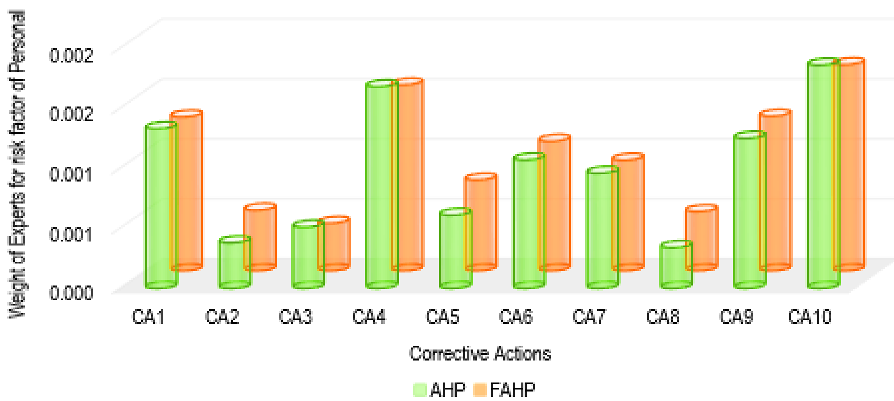

Figure 7. Comparison of the weight values of the personal risk factor by using the AHP and FAHP methods.

Figure 8 shows the score values for all the corrective actions related to the environmental risk factor using the conventional AHP and the fuzzy AHP method. Therefore, corrective action 4 (applying cyclic maintenance tests) affects the environmental risk factor and effectiveness of the fire-fighting system by 15.1%. According to the obtained results, the weight values are most reliable and accurate when using the fuzzy AHP method.

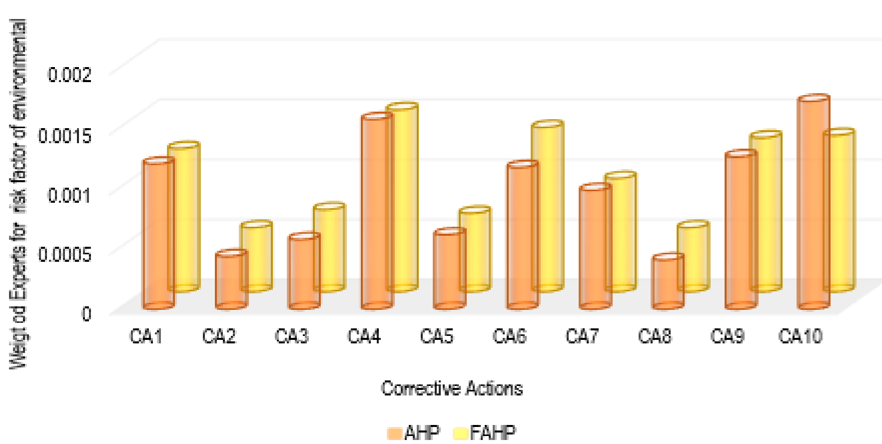

Figure 8. Comparison of environmental risk factor weights by AHP and FAHP methods.

Figure 9 shows the score values for all corrective actions related to the public risk factor using the conventional AHP and the fuzzy AHP method. Therefore, corrective action 4 (application of cyclic maintenance testing) has a 16.1% effect on the public risk factor and effectiveness of the fire-fighting system. According to the obtained results, the weight values are most reliable and accurate when using the fuzzy AHP method.

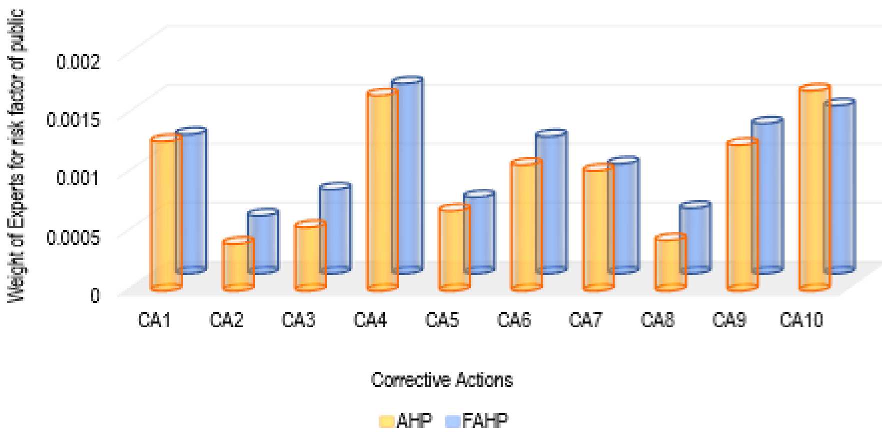

Figure 9. Comparison of the weight values of the risk factor of the public by using AHP and FAHP methods.

Figure 10 shows the score values for all the corrective actions related to the production risk factor using the conventional AHP and the fuzzy AHP method. Therefore, corrective action 4 (application of cyclic maintenance testing) affects the production risk factor and effectiveness of the fire-fighting system by 15.5%. According to the obtained results, the weight values are most reliable and accurate when using the fuzzy AHP method.

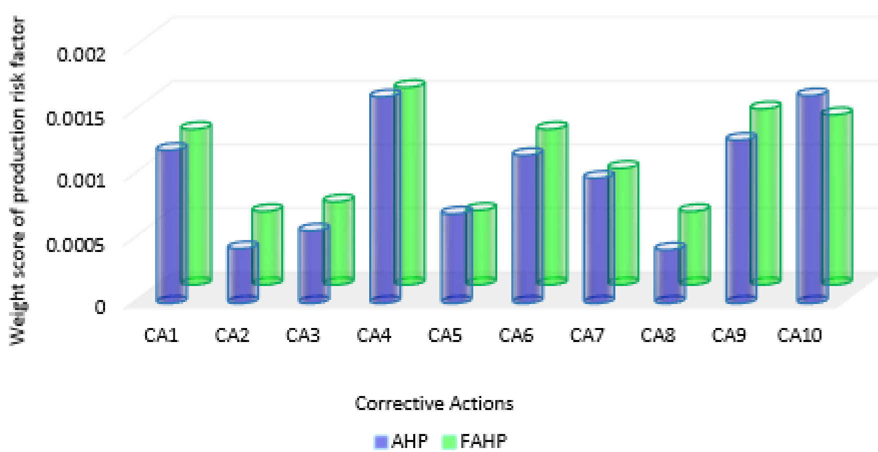

Figure 10. Comparison of the weight values of production risk factor by using AHP and FAHP methods.

From Table 14 and Figure 11, it is clear that corrective action 4, which applies cyclic maintenance testing for an improved LPG emergency barrier "fire-fighting system", is the best choice among other alternatives according to the highest points (15.6%). However, corrective action 10 can be selected as the second-best alternative since it acquired the second-highest score (15.3%).

Table 14. Corrective actions final ranking.

Corrective actions	Percentages	Rank	Corrective actions	Percentages	Rank
CA1	12.3	4	CA6	11.6	5
CA2	5.2	9	CA7	9.2	6
CA3	5.6	8	CA8	5.3	8
CA4	15.6	1	CA9	13	3
CA5	6.9	7	CA10	15.3	2

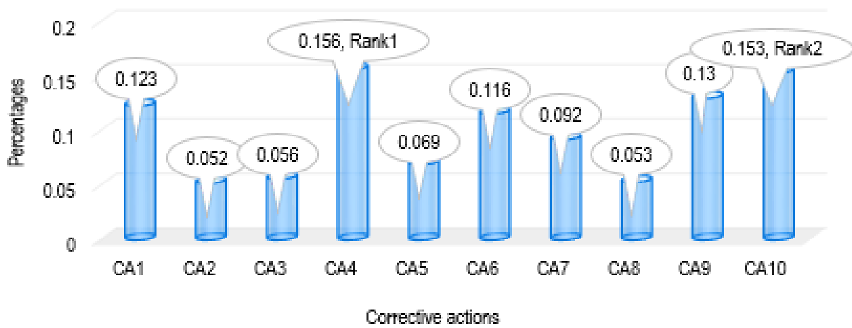

Figure 11. Ranking of the corrective actions.

5. CONCLUSION

Industrial facilities exposed to serious hazards require the installation of emergency safety barriers that must meet the specifications of the regulatory authorities. Emergency safety barriers are aimed at minimizing the consequences of an accident both inside and outside the facility and require the timely execution of specified procedures by people with appropriate training and resources. The purpose of this document is to prioritize the risk factors of each corrective action with respect to the impact of the emergency safety barrier. For this, a new methodology was developed, consisting of two main steps. First, it is required to estimate the risk priority number of emergency safety barriers using a feedback-based Disturbance Modes, Effects and Criticality Analysis method. In the second step, based on the obtained risk priority Number, the corrective actions to be selected first are determined by the Fuzzy Analytical Hierarchy Process (FAHP) method according to their effectiveness in relation to the impact of the disturbances on the four risk factors: personal, environmental, public and production.

The proposed approach was illustrated on the fire-fighting system of an LPG installation located in Algeria. After identifying the relevant failure modes and estimating the associated risk priority numbers. The Fuzzy Analytical Hierarchy Process method was used to prioritize several risk factors based on corrective actions according to their effectiveness against the risk factors (personal risk factor, environmental risk factor, public risk factor, and production risk factor) of a particular disturbances mode: "fails to open on demand." Several pairwise comparisons were conducted before reaching a final ranking of corrective actions based on the well-formed mathematical foundations associated with the FAHP method. The fuzzy AHP method produces more reliable results than the classical AHP method because the uncertainties associated with expert judgments are minimized, and the results are more accurate and reliable. The resulting ranking can be very practical in prioritizing corrective actions within budget constraints. The results show that the effectiveness of emergency safety barriers are formulated around the application of cyclic maintenance tests so that the impact of an LPG accident is less of a human risk factor.

The proposed methodology is participatory, creating synergy and interaction between people with different backgrounds and backgrounds. However, these interactions can lead to large discrepancies between the opinions of team members, resulting in a large amount of inconsistency.

For future work, our research activities continue to deal with the uncertainty and inaccuracy of subjective expert judgments by exploring different variants of the analytic hierarchy process, such as the fuzzy analytic hierarchy process type 2 method (FT2AHP). In addition, the proposed methodology will be tested using multi-emergency safety barriers and other types of accident scenarios.

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