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Evaluation of Chemical Organizations According to The Root Causes of Industrial Accidents with Analytical Hierarchy Process

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Abstract

In this study, it was aimed to evaluate the accident risk of chemical organizations according to the root causes of industrial accidents with the Analytical Hierarchy Process(AHP). First of all, the data of occupational accidents with death and loss of limb in the chemical industry between 2015 and 2020 were evaluated with Pareto analysis by using the statistics of the Social Security Institution (SSI). As a result of the analysis, the main criteria that make up 80% of the accidents in the sector were obtained. Then, the final main and sub-criteria that could be the root cause of industrial accident were determined, and these criteria were weighted over the opinions of the relevant experts using AHP method. Human errors, one of the main criteria, were determined as the most important criterion with 35%. By applying AHP for the second time, three sample high-level organizations were evaluated according to the root causes of industrial accidents. Organizations showed a distinctive ranking in terms of industrial accident risk (Organization B= 0.420> Organization A= 0.354 >Organization C= 0.226). With the proposed methodology, quantitative and qualitative evaluation criteria were included in the model simultaneously, and an objective result was obtained through expert opinions.

Cite

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1. INTRODUCTION

Today, in addition to making life easier, products containing risks against the environment and human health are produced by industrial establishments. As a result of the difficulties experienced in controlling these emerging risks, major industrial accidents occur where negative effects can be seen in the short, medium and long term. Prevention of industrial accidents, minimizing their effects and measures to intervene in the accident are extremely important and the root causes of the accidents should be analyzed. There is no generally accepted definition of what root cause analysis is in the literature. The possible definition can be made as “structured research aimed at determining the actual cause of a problem and the actions necessary to eliminate it”. Root cause analysis cannot be performed using a single tool or strategy. Root cause analyzes can be grouped into 7 subgroups according to their purposes (Andersan and Fagerhaug, 2006):

1. Understanding the problem

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GU J Sci, Part A 12(2) 332-357 (2025) 10.54287/gujsa.1621519

2. Identifying ideas about the cause of the problem

3. Data collection

4. Data analysis

5. Root cause identification

6. Eliminate/remove root causes

7. Implement a solution

Accidents should be treated as a problem to be solved, as a state of difficulty. When attempting to solve a problem, one must identify the cause (or causes) of the problem and find ways to eliminate those causes and prevent it from recurring. Once you have identified the causes, eliminating them often becomes a much easier task. Zhang et al. (2020) developed a methodology for the detection of root causes of accidents in coal mines, using the characteristics of safety culture deficiencies based on accident statistics. Emphasis was placed on the role of departments and the audit environment in developing a safety culture to reduce industrial accidents. Botti et al. (2020) analyzed 118 occupational accidents that occurred in Italy between 2002 and 2015 on the root causes of accidents in the manufacturing sector. The apparent cause was shown to be voluntary adoption of an inappropriate procedure. Alekseeva et al. (2020) statistically examined the accidents in pipeline gas transport establishments in order to determine the root causes of the accidents. A functional relationship was established between the pipe manufacturer's faults and the number of corrosion-related accidents and latent defects, including defects in construction and installation work. Ghatorha et al. (2020) applied root cause analysis to increase productivity in the press manufacturing industry. Flange fixture was developed with the fishbone method and machining time was reduced by approximately 9.5 hours. Wang et al. (2018) developed a symbolic transfer entropy method with binary encoding and decimal decoding to increase resistance to noise and reduce data loss while creating a data model for complex electromechanical systems. Li et al. (2016) proposed a root cause framework, including both fixed errors and non-stationary errors, for the data-driven identification of root causes of errors in process industries. A case study on the Tennessee Eastman process was applied and the proposed framework was shown to be valid. In the study carried out by Yilmaz et al. (2016), it was emphasized that occupational health and safety was a system at both the industrial and public level, and the inadequacy of any stage of this system would reduce the level of prevention of the problem by other measures.

The root causes of industrial accidents, such as occupational accidents, can be very diverse. In addition to human errors, process, equipment, environmental effects, etc. factors must be taken into account. The problems of choosing the most suitable one among the alternatives or ranking the alternatives by considering more than one criterion are called multi-criteria problems. MCDM methods are used to choose the best decision problems according to a wide range of concrete and intangible criteria or qualities and to ensure that decisions are made in cases where there is more than one criterion. There are a limited number of studies in the literature on the analysis of root causes with MCDM methods. Ozdemir et al. (2018) used MCDM methods regarding occupational accidents on board and indicated the priority order of the causes of occupational accidents: human factors, lack of management, ship-related problems, cargo problems and environmental factors. Wang et al. (2013) emphasized the importance of understanding the root causes in order to take effective preventive measures after the accident in their accident analysis model studies using MCDM methods. Human Factors Analysis and Classification System (HFACS) and Evidence-Based Reasoning (ER) MCDM methods were proposed in order to investigate the root causes of the accident and to rank the related prevention measures. It was seen that MCDM methods are widely used in risk assessment studies of various occupational accidents. By Yucesan and Gul (2021), probability and severity parameters of hazards in an aluminum plate manufacturing establishment were weighted using the Fuzzy Analytic Hierarchy Process (FAHP), and then the priority order of 23 different hazard groups was determined using Fuzzy TOPSIS (Technique for Order Preference by Similarity). It was shown that the three most important hazard groups for the organization were suffocation from gases, electric shock and falling objects, respectively. In another study by Gul (2020), Pythagorean fuzzy AHP and fuzzy VIKOR analyzes were applied in the gun and rifle barrel outer surface oxidation and coloring unit in occupational health and safety risk assessment. The proposed approach produced reliable results that better represent the uncertainty of the decision-making process. It was stated by Dabous et al. (2021) that electronics manufacturing was the most common application area for the integration between MCDM and FMEA, and the TOPSIS method was the most applied MCDM approach in the manufacturing industry. Fata et al. (2021) applied the VIKOR method by ranking the occupational health and safety risks including human factors. The proposed method was applied in a company that sells furniture and produces wooden products in Sicily, and a high success was achieved in distinguishing the risks. Bragatto et al. (2021) investigated the impact of the COVID-19 pandemic on the Italian chemical and process industries to which the Seveso III Directive applies. Using the AHP method, an innovative organizational "resilience" model was proposed, aiming to develop a higher capacity to face similar new crises in the future. A risk analysis model was developed with Analytical Network Process(ANP) and TOPSIS methods by Ciftci et al.(2020). The model was applied in the metal industry, providing a sequencing and interrelationships between risk factors to identify significant risks. In addition, not only traditional risk factors, but also psycho-social factors were discussed in the study. Viegas et al. (2020) performed a multi-criteria hazard and operability analysis for process safety. In practice, 40 hazards were defined; resource savings, greater focus, objectivity and a more realistic perception of danger were achieved. Oz et al. (2019) applied an extended TOPSIS model with Pythagorean fuzzy sets to prioritize hazards in a natural gas pipeline. A sensitivity analysis was also performed on the parameter weights to validate the model. Turskis et al. (2019) used the MCDM method to identify the most effective people in preventing accidents in construction Small and Medium Enterprises(SME)s. It was determined that key

GU J Sci, Part A 12(2) 332-357 (2025) 10.54287/gujsa.1621519

stakeholders, including the developer, project leader, OHS specialist, OHS coordinator, contractor and subcontractor, were the most effective people to prevent occupational accidents at SME construction sites. Koulinas et al. (2019) stated that it would be beneficial to use a popular multi-criteria decision-making method and a quantitative risk analysis technique together to rank and prioritize risks, as a result of their work with the MCDM method in the construction industry. Gul (2018) reviewed the occupational health and safety risk assessment approaches based on MCDM methods and their fuzzy versions. It is stated that MCDM methods are widely applied for risk assessment as quantitative tools and will provide an understanding of the risk assessment process in hazardous industries. Seker et al. (2017) implemented MCDM methods in the analysis of occupational risks at construction sites. It was stated that traditional methods were not useful for solving human-centered problems due to the complexities arising from human factors, although they offered precise solutions. It has been noted by Ouédraogo et al. (2011) that MCDM methods provide a rigorous mathematical model for performing risk analysis. Ilbahar et al. (2018) proposed a new approach to risk assessment for occupational health and safety using integrated fuzzy AHP and Fine Kinney analyses. In the study by Heller et al. (2006), it was stated that MCDM methods together with risk scoring/indexing were methods used to measure subjective and objective judgments, and that the experience and knowledge of people were at least as valuable as the data itself.

It was seen that the AHP method came to the fore in risk assessment studies. AHP method is advantageous with the aspects listed below (Aycin, 2019).

- Ability of decision makers to create solutions by considering their personal preferences,
- Multiple main and sub-criteria can be used in decision making problems,
- Ease of calculation,
- Allowing multiple decision makers to make joint decisions,
- Facilitating the problem by presenting the complex problems in a hierarchical structure

Although AHP is a widely used analysis in risk analysis and risk assessment processes, it was applied for the first time in the analysis of root causes of industrial accidents in this study. Studies using AHP in the analysis of root causes of other accidents are also quite limited. The evaluation of the industrial accident risk of the organizations through root causes was carried out with the AHP method, which is promine nt in the literature and is suitable for our problem. In this context, the criteria that may be the root cause of industrial accidents were determined by taking into account the Pareto analysis of the occupational accidents data with death and limb loss between 2015-2020 in workplaces operating in the chemical industry. With the application of the sequential AHP method based on expert opinions, sample industrial organizations were listed in terms of industrial accident risk.

2. MATERIAL AND METHOD

The evaluation of the organization’s accident risk according to the root causes of industrial accidents with the AHP method was carried out according to the methodology presented in Figure 1.

In order to determine the main and sub-criteria that may be the root cause of industrial accidents and to realize the problem understanding stage of the root cause analysis, the "Communiqué on Occupational Health and Safety on Workplace Hazard Classes" was taken into consideration at the first stage. 19.xx.xx – 22.xx.xx NACE coded workplaces working in the chemical industry were selected from the Six Economic Activity Classification (NACE) codes. By using Social Security Institution (SSI) statistics, data on occupational accidents with death and limb loss between 2015-2020 in selected workplaces were collected and critical events were tried to be determined. Then, in order to determine the ideas about the cause of the problem, the main and sub-criteria were formed by brainstorming, taking into account the expert opinions as well as the literature research. The data collected to perform the data analysis process of root cause analysis were evaluated with Pareto analysis. After the Pareto analysis, the main criteria and sub-criteria that could be the root cause of industrial accidents were determined. The weighting of the criteria was done through AHP method and questionnaires. The questionnaire was applied to 6 experts from the Ministry of Labor and Social Security, Ministry of Environment and Urbanization, Disaster and Emergency Management Presidency, industry and university, who have roles and responsibilities within the scope of the relevant legislation. At the last stage, 3 industrial organizations within the scope of the legislation were evaluated in terms of industrial accident risk according to root causes by applying again the AHP method, and the most risky organization was determined.

2.1. Pareto analysis

Pareto Analysis was developed by the Italian Vilfredo Pareto (1848-1923). Pareto has carried out various researches in businesses and stated that the majority of the problems are usually caused by a small number of interconnected but dominant causes. According to the Pareto analysis, which is also called the “80-20 Rule” in the literature, it is concluded that “80% of the problems should be caused by 20% activity and this important 20% should be focused on”. This represents the philosophy of “apparent majority, effective minority” (Aycin, 2019).

In order to carry out the data collection process of root cause analysis, workplaces with the code 19.xx.xx – 22.xx.xx NACE were selected from the Six Economic Activity Classification (NACE) codes, taking into account the "Communiqué on Workplace Hazard Classes on Occupational Health and Safety". By using

Social Security Institution (SSI) statistics, occupational accidents data with death and limb loss between 2015-2020 in selected workplaces were considered. Accidents were grouped according to the European Statistics on Accidents at Work - ESAW methodology on the basis of declared causes, and accidents in other deviation codes were not taken into account when grouping (code 99). The causes of the accident were evaluated by the Pareto Analysis method and the 80% part was determined.

The data on occupational accidents with death and limb loss in 19.xx.xx – 22.xx.xx NACE coded workplaces working in the chemical industry are presented in Table 1.

According to the data in Table 1 and Figure 2, it was seen that the cause of the accident "acting without cooperation, unnecessary or untimely actions" constituted 15% (3 550) of 33 321 fatal and limb loss occupational accidents. In the analyzed statistics, it was shown that there were 9 367 (other) accident causes for which no accident cause was entered.

According to the Pareto approach, 80% of the accidents can be solved by eliminating 20% of the causes of these accidents. It was seen from Figure 2 that the first two causes of accidents in the sector reached 26%. Some of them were listed below:

- Action without cooperation (64),
- Loss of control (full or partial) - the hand tool (whether powered or not) or the material tool used by the tool (43),
- Slip - stumble and fall - Person fall - on the same level (52),
- Loss of control (full or partial) - machine (including unintentional start) or material tool (41).

The Organization will deal with these problems in order to the best of its ability. This list will contribute to the manager in terms of which reasons to focus on. When the results from the Pareto analysis were classified on the basis of 4 main criteria, people, management, process and equipment errors were considered as the main criteria. In order to strengthen the hand of the manager at the point of decision-making, the criteria that will be the main causes of accidents in the chemical industry were investigated through literature research and expert opinions. Dominoes, disasters and sabotage were added to the main criteria. In total, seven main criteria were reached. After the main criteria were determined, the sub-criteria for each main criterion were determined by taking the literature research and expert opinions again.

GU J Sci, Part A 12(2) 332-357 (2025) 10.54287/gujsa.1621519

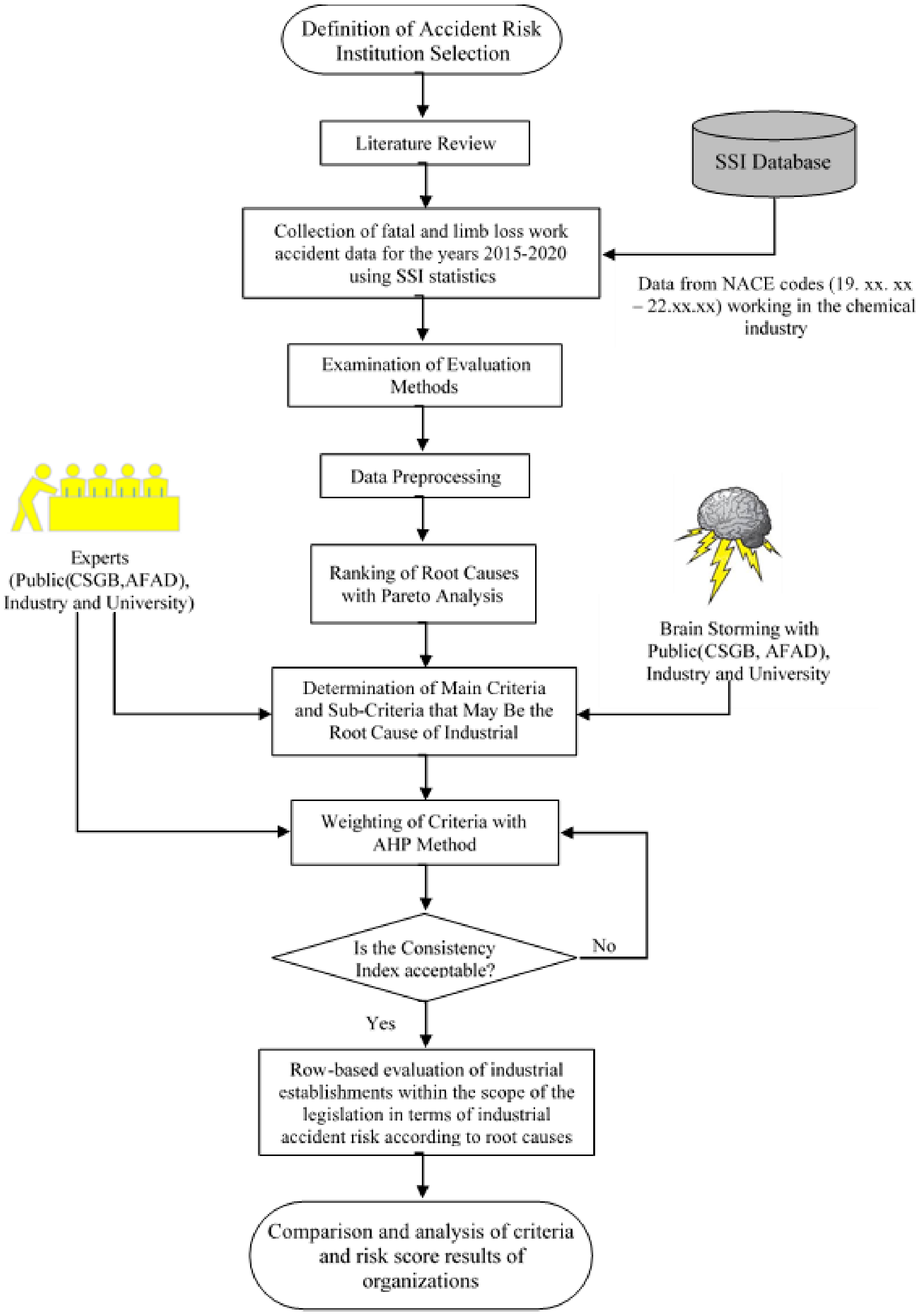


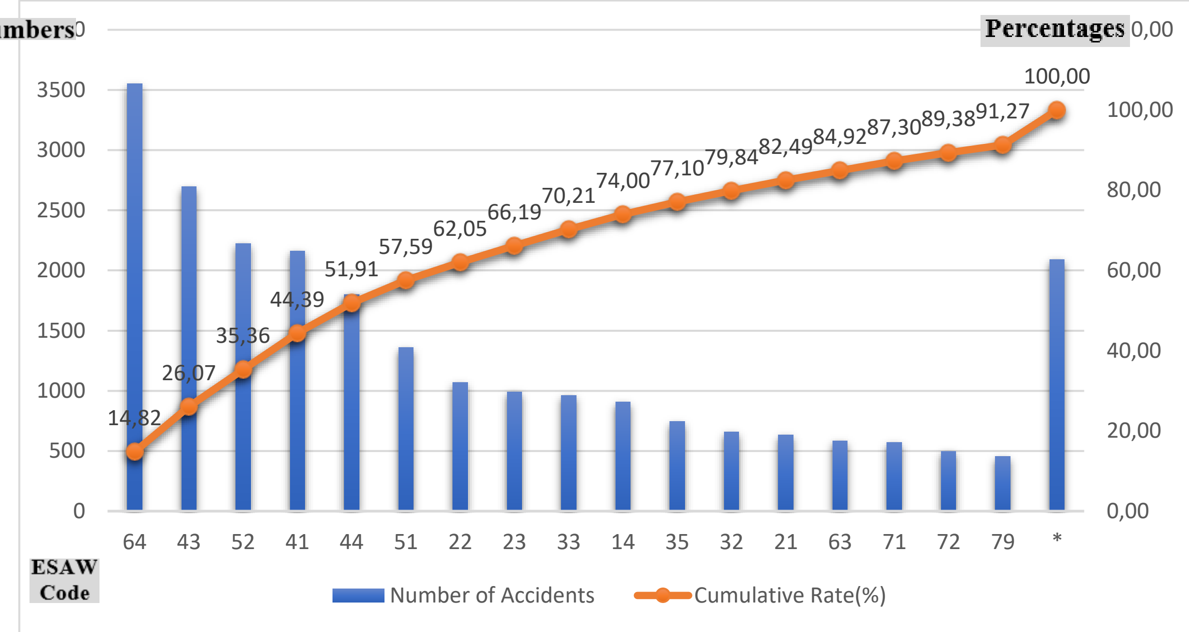
Figure 1. *Flowchart of the proposed methodology*

When Pareto steps were applied to the data presented above, Pareto analysis of accident causes is obtained (Figure 2).

GU J Sci, Part A 12(2) 332-357 (2025) 10.54287/gujsa.1621519

Table 1. *Causes of occupational accidents*

ESAW Code	Causes of Accident	Number of Accidents
11	Electrical problem due to electrical failure - leading to direct contact	51
12	Electrical problem - leading to direct contact	59
13	Explosion	17
14	Fire, ignition	908
19	Other 10-type deviations not listed above	21
21	In solid state - leash, tipping	633
22	In the case of a liquid - seepage, leakage, spill, splash, spray	1069
23	In gaseous state - evaporation, aerosol formation, gas formation	991
24	Powdery substance - smoke generation, airborne/emitted dust and particles	44
29	Other 20-type deviations not listed above	104
31	Breakage of matter - at joints, junctions	144
32	Breakage, explosion - splinter formation (wood, glass, metal, stone, plastic, others)	657
33	Slip, fall, collapse of material vehicle - from above (falling on the victim)	962
34	Slip, fall, collapse of material vehicle - from below (pulling the casualty down)	53
35	Sliding, falling, collapsing material vehicle - at the same level	744
39	Other 30-type deviations not listed above	176
41	Loss of control (full or partial) - machine (including unintentional start) or material tool	2163
42	Loss of control (full or partial) - use of vehicle or equipment (whether powered or not)	96
43	Loss of control (full or partial) - the hand tool (whether powered or not) or the material tool used by the tool	2696
44	Loss of control (full or partial) - object (moved, played, used, etc.)	1802
45	Loss of control (full or partial) - animal	9
49	Other 40-type deviations not listed above	357
51	One's downfall - to the lower level	1361
52	Slip - stumble and fall - Person fall - on the same level	2223
59	Other 50-type deviations not listed above	191
61	Walking on a sharp object	65
62	Kneeling, sitting, leaning	107
63	Grasping or being carried away - by something or momentum	583
64	Uncooperative action, unnecessary or untimely actions	3550
69	Other 60-type deviations not listed above	153
71	Lifting, carrying, standing	570
72	Push, pull	497
73	To drop down, to bend over	84
74	Twist, turn	106
75	Chewing, twisting of leg or ankle, gliding without falling	180
79	Other 70-type deviations not listed above	454
81	Shock, fear	6
82	Brutality, assault, threat - among company employees who are subject to the employer's authority	36
83	Brutality, assault, threat - by people outside the company (bank robbery, bus drivers, etc.)	7
84	Attack, poke - by animal	11
85	A third person or a person who creates a danger to himself/herself and others	5
89	Other 80-type deviations not listed above	9
99	Other Deviations not listed in this classification	9367



* It is the bar diagram denoted as "other". Accident causes with a cumulative contribution of 1% or less have been combined to make it readable.

Figure 2. *Pareto Analysis of Accident Causes*

2.2. AHP method

After determining the main and sub-criteria of the industrial accident root cause, analyzes were made with MCDM methods. In the study, the AHP method was chosen from MCDM methods because it allows to determine the relative weights of the criteria as well as its superior aspects. Various multi-criteria decision making methods are available in the literature. AHP method, which is one of these methods, stands out and is frequently used (Aycin, 2019; Ozguvenc, 2011; Dincer and Gorener, 2011).

<u>Mathematical background of AHP method</u>

The weights (w) of the main and sub-criteria are obtained as a result of pairwise comparisons. In this method, it is not obligatory for decision makers to make numerical comparisons. Linguistic comparisons can also be used. In the literature, Saaty's scale between 1-9 values is generally used in pairwise comparisons. In comparison matrices, the diagonals take the value 1(Yildirim and Oner, 2014; Saaty, 1986). This is because the criterion is compared with itself (Saaty, 1990).

If the criteria used in the method are $a_1, a_2, \ldots, a_n$, and the weights are $w_1, w_2, \ldots, w_n$, if it is desired to compare n criteria according to their relative importance weights, the general structure of the pairwise comparison matrix will be as in Equation 1.

$$A = \begin{bmatrix} a_{11} \dots a_{1j} \dots a_{1n} \\ \vdots \quad \vdots \quad \vdots \\ a_{i1} \dots a_{ij} \dots a_{in} \\ \vdots \quad \vdots \quad \vdots \\ a_{n1} \cdots a_{nj} \cdots a_{nn} \end{bmatrix} \tag{1}$$

where $a_{ij} = \frac{1}{a_{ji}}$ (according to the responsiveness) and $a_{ij} = \frac{a_{ik}}{a_{jk}}$

In real problems, the result of $\frac{w_i}{w_j}$ is often unknown. Therefore, what needs to be solved in AHP is to find a_{ij}value such that $a_{ij} \cong \frac{w_i}{w_j}$ (Yildirim and Oner, 2014).

The general form of the weight matrix is as in Equation 2.

$$W = \begin{matrix} w_1 \\ \vdots \\ w_i \\ \vdots \\ w_n \end{matrix} \begin{bmatrix} w_1 & \dots & w_j & \dots & w_n \\ w_1/w_1 & \dots & w_1/w_j & \dots & w_1/w_n \\ \vdots & & \vdots & & \vdots \\ w_i/w_1 & \cdots & w_i/w_j & \cdots & w_i/w_n \\ \vdots & & \vdots & & \vdots \\ w_n/w_1 & \cdots & w_n/w_j & \cdots & w_n/w_n \end{bmatrix} \tag{2}$$

Equation 3 is obtained by multiplying the W and w values with each other.

$$W.w = \begin{matrix} w_1 \\ \vdots \\ w_i \\ \vdots \\ w_n \end{matrix} \begin{bmatrix} w_1 & \dots & w_j & \dots & w_n \\ w_1/w_1 & \dots & w_1/w_j & \dots & w_1/w_n \\ \vdots & & \vdots & & \vdots \\ w_i/w_1 & \cdots & w_i/w_j & \cdots & w_i/w_n \\ \vdots & & \vdots & & \vdots \\ w_n/w_1 & \cdots & w_n/w_j & \cdots & w_n/w_n \end{bmatrix} \begin{bmatrix} w_1 \\ \vdots \\ w_i \\ \vdots \\ w_n \end{bmatrix} = n \begin{bmatrix} w_1 \\ \vdots \\ w_i \\ \vdots \\ w_n \end{bmatrix} \tag{3}$$

The equation obtained in Equation 3 is also shown as in Equation 4.

$$(W - nI)w = 0 \tag{4}$$

The solution to this equation is the eigenvalue finding problem. Their relative weights are calculated with the w eigenvector based on λ_{Maks}, which satisfies the equation $Aw = \lambda_{Maks}w$. Here, $\lambda_{Maks}$is the largest eigenvalue of the A matrix and depending on the w eigenvector $(A - \lambda_{Maks}I)w = 0$ equation is obtained (Saaty, 1990).

In addition, two coefficients, Consistency Index (CI) and Consistency Ratio (CR), are used to determine the consistency of subjective perceptions and the accuracy of relative weights. Consistency Index (CI) can be calculated as in Equation 5.

$$CI = \frac{(\lambda_{Maks} - n)}{(n-1)} \tag{5}$$

In the above equation, $\lambda_{Maks}$is the largest eigenvalue and n is the total number of criteria. For the results to be reliable, the CI value should not exceed 0.1. Calculation of the consistency ratio is done with the formula in Equation 6.

$$CR = \frac{CI}{RI} \quad (6)$$

In the above equation, RI stands for "Random Value Index". It is derived from a large sample of a randomly generated cross-comparison matrix. The scale used here is 1/9, 1/8, 1/7, 1/6, …, 1, …, 6, 7, 8, 9. RI values obtained according to different criteria numbers are shown in Table 2.

While determining the main and sub-criteria, SSI data were used because there is no database for industrial accidents in Turkey and it provides the widest data on accidents. A comprehensive literature search was also carried out, and the seven main criteria for the problem and the sub-criteria of these main criteria were obtained. The hierarchical structure of alternative organizations are presented in Figure 3.

Table 2. *Random Value Index*

n	1	2	3	4	5	6	7	8	9	10	11	12
Random Value Index (RI)	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49	1.54	1.54

Questionnaires were prepared for the main criteria and sub-criteria of root causes. Comparison matrices were created for each criterion to determine the weight levels of the main criteria and sub-criteria in the questionnaires. These prepared questionnaires were applied to experts consisting of academicians and field representatives, who have knowledge of national and international legislation on industrial accidents (1 Academician, 1 "Republic of Turkey Ministry of Labor and Social Security(CSGB), General Directorate of Occupational Health and Safety(ISGGM)" personnel, 1 "Republic of Turkey Ministry of Labor and Social Security, Guidance and Inspection Directorate" personnel, 1 "Republic of Turkey Ministry of Environment and Urbanization(CSB)" personnel, 1 "Republic of Turkey Ministry of Interior Disaster and Emergency Management Presidency(AFAD)" personnel and 1 industrial establishment personnel).

2.3. Evaluation of organizations based on root causes of industrial accident

Three industrial organizations in different locations within the scope of the relevant legislation were also evaluated by AHP method, and as a requirement of this method, pairwise comparison matrices of the sub-criteria were created. All of the organizations are high-level and operate in the province of Ankara in Turkey.

3. RESULTS AND DISCUSSION

3.1. AHP method

In order to perform AHP method, the main criteria and sub-criteria that may be the root cause of industrial accidents were determined by applying a questionnaire based on expert opinions. AHP method pairwise comparison matrices were prepared on the basis of both main criteria and sub-criteria. While performing the AHP method, the geometric averages for the main and sub-criteria were calculated, and pairwise comparison matrices were formed, in terms of combining the judgments of the questionnaires filled by six experts. AHP method was carried out in accordance with the equations and explanations given in Section 2.2. Weight values and consistency ratio of the main criteria are given in Table 3.

Table 3. *Weight values and consistency ratio of the main criteria*

Main Criterion	Sub Criteria	Weight Value/ Priority Value
Consistency Rate CR = 0.061 < 0.1	Management / Organization Errors	0.090
	Process Errors	0.190
	Equipment Errors	0.200
	Domino Effect	0.080
	Human Errors	0.350
	Disasters	0.050
	Sabotage	0.040

Weight values and consistency ratio of sub-criteria are given in Table 4.

The human errors criterion came to the fore as the most important criterion in industrial accidents with 35%. This was followed by the equipment errors criterion with 20% and the process errors criterion with 19%, respectively. When determining the causes of major industrial accidents, it is important to consider possible hardware and software failures, process and design deficiencies, and human errors. It should also be stated what action is required to prevent these failures and errors (Prevention of major industrial accidents, 1991). Regulations play a critical role in reducing the occurrence of industrial accidents. The importance of addressing human errors as a proactive measure is also highlighted (Simsek et al, 2024). As a result of the pairwise comparisons of the management/organization criteria, the "improper security management system " sub-criterion was found to be the most important criterion with a rate of 26%. This result is compatible with the literature (Ozdemir et al., 2018). This was followed by the criteria of “incorrect/missing procedures and instructions” and “inadequate trainings”, respectively. Botti et al. (2020) also emphasized the importance of voluntary adoption of an incorrect procedure, skipping a risk control measure, improper use of equipment and lack of coordination in accidents. There are positive and significant relationships among various factors such as procedure implementation, communication accuracy, communication satisfaction, work permit system, competence level and risk management. These factors have been shown to have a positive effect on the occurrence and frequency of maintenance related accidents (Gonyora et al., 2024). Given the critical role of employees in preventing major accidents, business management requires employees to have a broad understanding of the process used. Employees must be informed and adequately trained about the hazards of the materials used. This information and training must be in an appropriate language and format (Prevention of major industrial accidents, 1991). In process errors, “lack/insufficiency of process control” was determined as the most important criterion with a rate of 27%. “untested/experienced safety barriers” and “lack/insufficiency of passive safety barriers” were also determined at significant rates. The "vapor cloud explosion", which was under the domino effect main criterion, stood out as the most important criterion with a rate of 22%. This was followed by “BLEVE-Fireball” and “Thermal Runaway”. The analyses of past domino effect accidents also supported these results (Reniers and Cozzani, 2013). In equipment errors, the criterion of “faulty design/installation/assembly” was significantly ahead (29%). “improper equipment placement/safety distances " and " inappropriate/improper maintenance " criteria are also very important. Singh and Maiti (2020) also drew attention to poorly maintained equipment in their study (Sigh and Maiti, 2020). It is recommended that organizations in the chemical and process industry continue to prioritize maintenance practices as well as human and organizational factors to ensure safe and reliable operational performance. Focusing on these issues can minimize the occurrence of accidents and promote a safe working environment (Gonyora et al., 2024). "Lack of safety culture" was found to be the most important in human errors. The importance of safety culture in preventing accidents is known (Zhang et al., 2020). Subsequently, “insufficient knowledge/ignorance about the job” and “inexperience” were determined as important. As a result of the pairwise comparisons of the disasters criteria, the "earthquake" criterion came to the fore as the most important criterion with a rate of 33%. This was followed by the "lightening" criteria with 18% and the "storm/tornado" criteria with 12%, respectively. The importance weight of both geological and meteorological effects is remarkable. In the sabotage criterion, “sabotage with explosives” was found to be ahead with a significant rate (44%). The criterion of “tampering with fire” was determined as the second important one. Consistencies in all were determined at the appropriate value (<0.1).

The hazard analysis should include the analysis of the safety system for possible weaknesses, the determination of the residual risk with the safety system in place, and the development of the most appropriate measures for technical and organizational protection in the event of abnormal plant operation (Prevention of major industrial accidents, 1991).

Measures should also be taken to minimize the consequences of major accidents. The enterprise should plan and provide appropriate measures to mitigate the consequences of possible accidents. Mitigation should be done with security systems, alarm systems, emergency services, etc. For each major hazard facility, an on-site emergency plan should be prepared in consultation with the security team. Depending on local regulations, an external emergency plan should also be developed and implemented in cooperation with the relevant local authorities (Prevention of major industrial accidents, 1991).

Through the rigorous application of multi-criteria decision analysis (MCDA), a robust hierarchy was established by identifying specific nations as applicable examples for those aiming to increase industrial accident prevention strategies (Simsek et al., 2024). The effectiveness of the MCDM technique is also seen in the root cause analysis of other accidents. Weighting of the selection criteria for the causes of work accidents Using Fuzzy AHP, the criteria were ranked and evaluated by making pairwise comparisons of the experts' scores. The results of this study are noteworthy due to the scarcity of quantitative studies on shipboard accidents, which are considered a major problem for the maritime industry. Individuals' perception of safety culture is an important factor in accidents caused by human errors. Improving the perception of safety culture will contribute to the prevention of accidents caused by human errors (Ozdemir et al., 2018). An accident analysis model is proposed to identify the leading causes of accidents and then determine the most cost-effective safety measures to prevent accidents from occurring. In the first part of the model, HFACS and BN are utilized to investigate the causes and propose corresponding prevention measures. In the second part, the Best Fit method and ER approach are used to rank the proposed security measures in terms of cost-effectiveness. Case study of ship collision accidents demonstrated the effectiveness of the proposed model (Wang et al., 2013).

3.2. Evaluation of organizations based on root causes of industrial accident

In order to determine the organization that is more risky in terms of industrial accident, an application was made in 3 industrial organizations in Turkey, which are within the scope of the legislation. Again, pairwise comparison matrices were prepared on the basis of sub-criteria whose weights were determined by AHP method. The locations of the industrial organizations are shown in Figure 4.

All of the organizations are high-level organizations operating in the province of Ankara. Organization A was established in the 1990s and is an explosives production company. Within the organization; ammonium nitrate, packaged emulsion explosives, pibs, sodium thiocyanate, monoe thanol amine, sodium nitrate, sodium perchlorate, sodium nitrite, acetic acid, thiourea, EXAN etc. chemicals are used. Organization B was established in the 1960s and is a LPG filling company. Within the organization; special forklift tube, marine gas, LPGPRO, CUTPRO, IZOPRO, BETOPRO etc. products are filled. Organization C was established in the 2000s and is a LPG storage and filling company. Within the organization, there are many equipment such as tank farm, LPG pumps, fire pumps, gas compressors, etc.

The comparison matrices of the alternatives on the basis of sub-criteria and the priority vectors obtained as a result of the calculations are presented in Table 5. All ratios calculated in the comparison of alternatives on the basis of sub-criteria were less than 0.1 and were consistent. While evaluating the alternatives together with the

GU J Sci, Part A 12(2) 332-357 (2025) 10.54287/gujsa.1621519

sub-criteria, since the consistency ratio was calculated as 0 in most of them, it was not shown as a separate column in the relevant Table 5. The determination of the relative weight of each organization for the purpose was calculated as given in Equation 7 by multiplying the importance of the organizations on the basis of the sub-criterion, the relative weight of the sub-criterion and the relative weight of the main criterion.

$$S_l = \sum_{i=1,j=1}^{nm} w_i v_{ij} p_{ijl} \quad (7)$$

where

S_l: The relative weight of the 1st organization showing its ranking as a result of the AHP method

w_i: The weight of the ith main criterion

v_{ij}: The weight of the jth sub-criterion of the ith main criterion

p_{ijl}: The weight of the jth sub-criterion of the ith main criterion for the lth organization

$i = 1,2 \ldots n, j = 1,2 \ldots m$

When the calculation was made in accordance with the above equation, the scores of each organization's relative weight for the purpose determined by the AHP method were as follows.

S_1=0.354 (Organization A)

S_2=0.420 (Organization B)

S_3=0.226 (Organization C)

Organization B received the highest industrial accident risk score with a value of 0.420. This was followed by Organization A with a value of 0.354, and then by Organization C with a value of 0.226. Although all organizations were high-level, the potential for industrial accident risk differed. Although organizations B and C contain similar hazardous chemical and process equipment, they also differ in terms of industrial accident risk. In accordance with the relevant legislation, the organization level is determined only according to the type and amount of certain hazardous chemicals (Regulatin on Industrial Accidents, 2019). A comprehensive evaluation was provided by including expert opinions on the many criteria presented in this study, and the accident risk potential of the organizations was objectively revealed on the basis of root cause.

Solutions obtained with mathematical models represent optimum results that are precise and robust. In problems like this where managers are only interested in optimum solutions, it becomes important to find the range of variation of the coefficients that does not change the result. A similar approach, namely sensitivity analysis, is applied in the study with analytical methods within the MCDM methods such as AHP. The factor affecting the sensitivity here is the people involved in the process as experts. The individual differences of more than one expert are followed in the process and in case of a significant difference/inconsistency, the opinions of the relevant expert are taken again. If necessary, it is also possible to remove the relevant expert completely. Therefore, the effect of an expert on the overall weights will be limited. In case of a different nonconformity, the solution can of course be tried again, but when we go through the results we obtained, there is no risk of changing the final ranking and sensitivity analysis was not deemed necessary for this study (Zopounidis, and Doumpos, 2017; Gal et al., 1999).

The competent authorities should define appropriate safety objectives together with the major hazard control system for their implementation. Although the control of major hazards is primarily the responsibility of the company's management, it should be established in consultation with all relevant parties. The relevant system should include the following:.

(a) establishing an infrastructure;

(b) identifying and inventorying major hazard facilities;

(c) obtaining and evaluating safety reports;

(d) emergency planning and public information;

(e) site selection and land-use planning;

(f) inspecting facilities;

(g) reporting major accidents;

(h) investigating major accidents and their short- and long-term effects (Prevention of major industrial accidents, 1991).

4. CONCLUSION

In this study, a new approach based on evaluation of organizations according to the root causes of industrial accidents with AHP method was developed. The main and sub-criteria based on the root cause were determined through the Pareto Analysis of the past accident data. The weights of the main criteria and sub-criteria were determined through AHP method and expert opinions. Considering the criteria weights determined, three sample industrial organizations were ranked in terms of industrial accident risk with a second AHP method usage. As a result of the study, the original seven main criteria and sixtynine sub-criteria that could be the root cause were determined. As a result of the pairwise comparisons of the main criteria; “human errors” stood out as the most important criterion in industrial accidents with 35%. This was followed by equipment errors with 20% and process errors with 19%, respectively. As a result of the pairwise comparisons of the sub-criteria, the rates listed below and the most important criteria were determined.

“Improper security management system” criterion of the Management / Organization criterion was 26%

“Lack/insufficiency of process control” criterion belonging to the process criterion was 27%,

“Faulty design/installation/assembly” criteria of equipment criteria was 29%,

The "Vapor cloud explosion" criterion of the domino effect criterion was 22%,

“Lack of safety culture” criterion of human error criterion was 17%,

"Earthquake" criterion of disasters criterion was 33%,

“Sabotage with Explosives” criteria belonging to the sabotage criteria was 44%

It is thought that the degree of importance obtained from a significant number of main and sub-criteria analyzed as the root causes of industrial accidents determine the elements that should be considered primarily in risk analyzes to be made in organizations where industrial accidents may occur. The high importance of the "human errors" criterion has shown that the personnel of the relevant organization should have sufficient and experience in safety culture, work and processes. The high importance of the "equipment errors" criterion has revealed the necessity of taking into consideration the faulty design/installation/assembly, improper equipment placement/safety distances, inappropriate/improper maintenanceas a priority in the relevant organizations. The high importance of the "process errors" criterion has shown that the relevant organizations should especially analyze the lack / inadequacy of process control, untested / unexperienced safety barriers and passive safety barriers deficiency / inadequacy.

As a result of the analyzes made in three sample organizations, the organization B received the highest score with a value of 0.420. Organization A took the second place with a value of 0.354, and organization C took the last place with a value of 0.226. The risk potential of high-level organizations with high risks has been rated objectively according to many criteria. It has been shown that the relevant industry and public practitioners should pay attention to which root cause-based criteria in which organizations.

Industrial accidents are evaluated within the scope of the Regulation on the Prevention of Major Industrial Accidents and Reducing Their Effects(RPMIARTE). In this regulation, organizations are categorized as upper and lower level depending on the type and amount of hazardous chemicals involved. Higher level organizations are organizations that involve higher accident risks. Therefore, the application was made on selected higher level organizations that involve high risks. The methodology proposed in the study can be applied to every organization within the scope of RPMIARTE. Our country's legislative equivalent of the EU SEVESO directives is RPMIARTE. Therefore, the proposed methodology can be applied to all Seveso organizations and is not regional in nature. However, including lower-level organizations with similar risk levels among themselves and upper-level organizations among themselves in the process will provide more reasonable results.

There are many methods used in the literature under the title of decision-making problem, such as MCDM methods, fuzzy logic and Bayesian approach. The problem addressed in the study poses a decision problem because there are alternatives. In addition, the problem is closer to solution with MCDM methods due to the criteria affecting the decision. Saaty scale was used in AHP. This scale works with all integers between 1 and 9. If survey evaluators are hesitant to give values 2-4-6-8 and have a sensitivity problem, they can manage the process with values 1-3-5-7-9. The evaluation of this situation is controlled by the consistency ratio (CR) values and the CR value is expected to be below 0.1. No negative effects were encountered in the study. It is seen that using membership degrees ranging from 0 to 1 in the fuzzy logic method produces a solution in cases where experts cannot solve the sensitivity/instability problem (Zopounidis and Doumpos, 2017; Gal et al., 1999).

It has been shown that AHP method, which is one of the MCDM methods used in the evaluation of organizations accident risk according to the root causes of industrial accidents, is an appropriate analysis for such problems aiming to compare multiple criteria. With the AHP method, quantitative and qualitative evaluation criteria were included in the model simultaneously. An objective result could be obtained by simultaneously evaluating the thoughts and judgments of decision makers with different education and experience. In future studies, analyzes can be carried out by using fuzzy MCDM methods at the stage of determining the importance levels of the criteria that may be the root cause, and by using another MCDM method in the stage of comparing organizations in terms of industrial accident risk. The results to be obtained can be compared with the results of this study.

GU J Sci, Part A 12(2) 332-357 (2025) 10.54287/gujsa.1621519

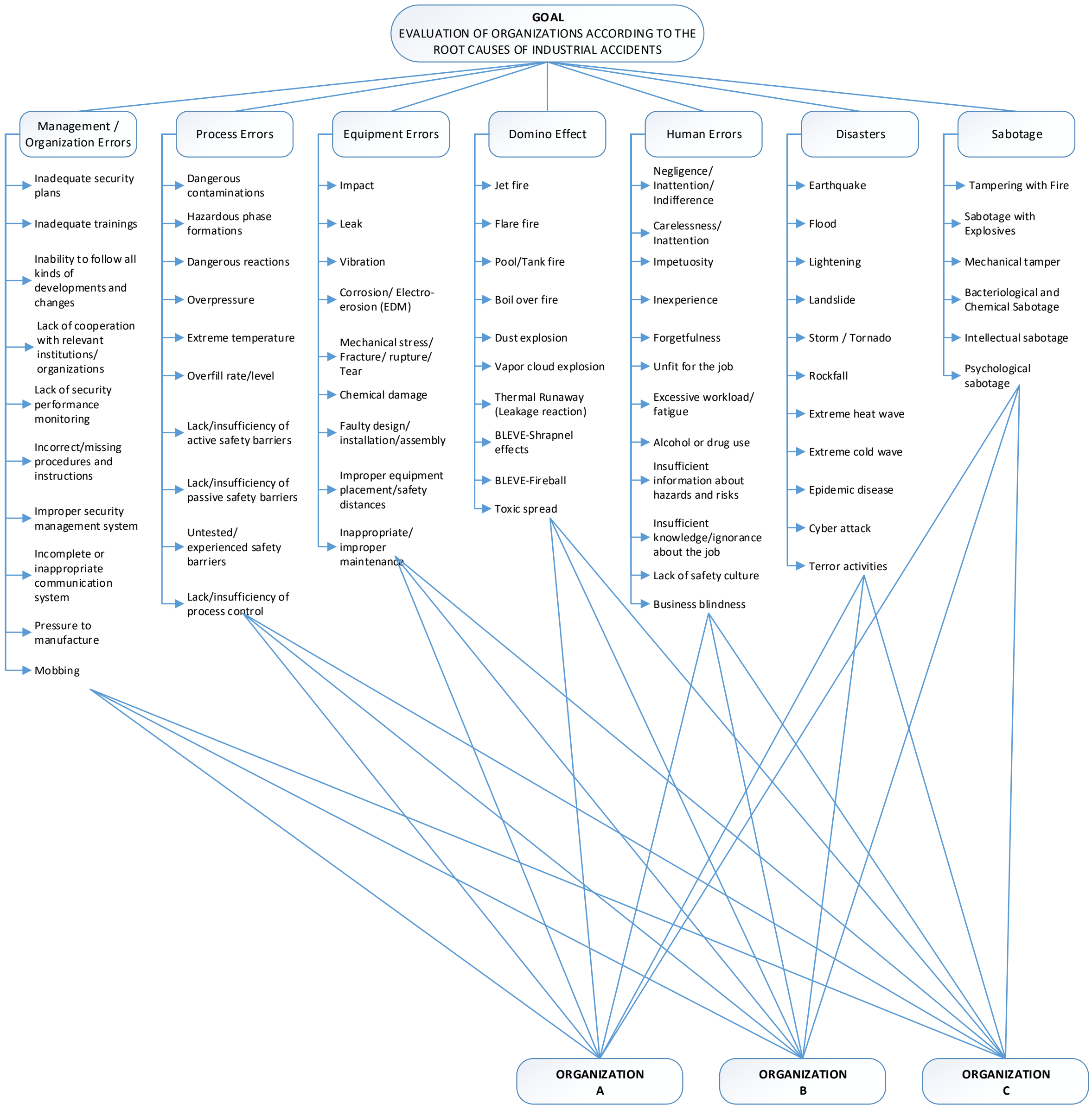


Figure 3*. The hierarchical structure of alternative organizations*

Table 4. *Weight values and consistency ratio of sub-criteria*

Main Criterion	Sub Criteria	Weight Value/ Priority Value
Management / Organization Errors CR = 0.037 < 0.1	Inadequate security plans	0.130
	Inadequate trainings	0.140
	Inability to follow all kinds of developments and changes	0.040
	Lack of cooperation with relevant institutions/organizations	0.050
	Lack of security performance monitoring	0.080
	Incorrect/missing procedures and instructions	0.150
	Improper security management system	0.260
	Incomplete or inappropriate communication system	0.080
	Pressure to manufacture	0.040
	Mobbing	0.020
Process Errors CR = 0.033 <	Dangerous contaminations	0.030
	Hazardous phase formations	0.030
	Dangerous reactions	0.040

	Overpressure	0.070
	Extreme temperature	0.070
	Overfill rate/level	0.050
	Lack/insufficiency of active safety barriers	0.120
	Lack/insufficiency of passive safety barriers	0.130
	Untested/experienced safety barriers	0.190
	Lack/insufficiency of process control	0.270
Equipment Errors CR = 0.066< 0.1	Impact	0.080
	Leak	0.040
	Vibration	0.020
	Corrosion/ Electro-erosion (EDM)	0.070
	Mechanical stress/ Fracture/ rupture/ Tear	0.110
	Chemical damage	0.100
	Faulty design/installation/assembly	0.290
	Improper equipment placement/safety distances	0.180
	Inappropriate/improper maintenance	0.120
Domino Effect CR = 0.049< 0.1	Jet fire	0.120
	Flare fire	0.070
	Pool/Tank fire	0.030
	Boil over fire	0.030
	Dust explosion	0.050
	Vapor cloud explosion	0.220
	Thermal Runaway	0.160
	BLEVE-Shrapnel effects	0.140
	BLEVE-Fireball	0.160
	Toxic spread	0.010
Human Errors CR = 0.029 < 0.1	Negligence/ Inattention/ Indifference	0.060
	Carelessness/ Inattention	0.050
	Impetuosity	0.030
	Inexperience	0.140
	Forgetfulness	0.040
	Unfit for the job	0.100
	Excessive workload/fatigue	0.070
	Alcohol or drug use	0.040
	Insufficient information about hazards and risks	0.120
	Insufficient knowledge/ignorance about the job	0.140
	Lack of safety culture	0.170
	Business blindness	0.040
Disasters CR = 0.056 < 0.1	Earthquake	0.330
	Flood	0.110
	Lightening	0.180
	Landslide	0.100
	Storm / Tornado	0.120
	Rockfall	0.030
	Extreme heat wave	0.030
	Extreme cold wave	0.030
	Epidemic disease	0.020
	Cyber attack	0.030
	Terror activities	0.030
Sabotage CR = 0.074 < 0.1	Tampering with Fire	0.310
	Sabotage with Explosives	0.440
	Mechanical tamper	0.120
	Bacteriological and Chemical Sabotage	0.070
	Intellectual sabotage	0.030
	Psychological sabotage	0.030

GU J Sci, Part A 12(2) 332-357 (2025) 10.54287/gujsa.1621519

Figure 4. *Google Earth image of sample industrial organizations*

Table 5. *Priority vectors for alternatives on basis of sub-criteria and priority vectors obtained for organizations*

Main Criterion	Sub Criteria	Weight Value/ Priority Value	A	B	C
Management / Organization Errors CR = 0.037 < 0.1	Inadequate security plans	0.130	0.278	0.500	0.222
	Inadequate trainings	0.140	0.278	0.389	0.333
	Inability to follow all kinds of developments and changes	0.040	0.412	0.353	0.235
	Lack of cooperation with relevant institutions/organizations	0.050	0.357	0.357	0.286
	Lack of security performance monitoring	0.080	0.350	0.400	0.250
	Incorrect/missing procedures and instructions	0.150	0.368	0.368	0.263
	Improper security management system	0.260	0.318	0.409	0.273
	Incomplete or inappropriate communication system	0.080	0.333	0.467	0.200
	Pressure to manufacture	0.040	0.389	0.444	0.167
	Mobbing	0.020	0.438	0.375	0.188
Process Errors CR = 0.033 < 0.1	Dangerous contaminations	0.030	0.389	0.333	0.278
	Hazardous phase formations	0.030	0.389	0.389	0.222
	Dangerous reactions	0.040	0.412	0.412	0.176
	Overpressure	0.070	0.333	0.429	0.238
	Extreme temperature	0.070	0.389	0.444	0.167
	Overfill rate/level	0.050	0.389	0.444	0.167
	Lack/insufficiency of active safety barriers	0.120	0.278	0.500	0.222
	Lack/insufficiency of passive safety barriers	0.130	0.188	0.438	0.375

GU J Sci, Part A 12(2) 332-357 (2025) 10.54287/gujsa.1621519

	Untested/experienced safety barriers	0.190	0.313	0.375	0.313
	Lack/insufficiency of process control	0.270	0.333	0.400	0.267
Equipment Errors CR = 0.066 < 0.1	Impact	0.080	0.300	0.600	0.100
	Leak	0.040	0.231	0.615	0.154
	Vibration	0.020	0.273	0.545	0.182
	Corrosion/ Electro-erosion (EDM)	0.070	0.200	0.600	0.200
	Mechanical stress/ Fracture/ rupture/ Tear	0.110	0.313	0.500	0.188
	Chemical damage	0.100	0.313	0.438	0.250
	Faulty design/installation/assembly	0.290	0.350	0.400	0.250
	Improper equipment placement/safety distances	0.180	0.350	0.400	0.250
	Inappropriate/improper maintenance	0.120	0.333	0.429	0.238
Domino Effect CR = 0.049< 0.1	Jet fire	0.120	0.350	0.400	0.250
	Flare fire	0.070	0.350	0.400	0.250
	Pool/Tank fire	0.030	0.286	0.500	0.214
	Boil over fire	0.030	0.333	0.500	0.167
	Dust explosion	0.050	0.333	0.467	0.200
	Vapor cloud explosion	0.220	0.333	0.467	0.200
	Thermal Runaway (Leakage reaction)	0.160	0.333	0.467	0.200
	BLEVE-Shrapnel effects	0.140	0.263	0.421	0.316
	BLEVE-Fireball	0.160	0.313	0.500	0.188
	Toxic spread	0.010	0.333	0.500	0.167
Human Errors CR = 0.029 < 0.1	Negligence/ Inattention/ Indifference	0.060	0.450	0.400	0.150
	Carelessness/ Inattention	0.050	0.474	0.368	0.158
	Impetuosity	0.030	0.450	0.350	0.200
	Inexperience	0.140	0.474	0.263	0.263
	Forgetfulness	0.040	0.438	0.375	0.188
	Unfit for the job	0.100	0.500	0.333	0.167
	Excessive workload/fatigue	0.070	0.389	0.444	0.167
	Alcohol or drug use	0.040	0.450	0.350	0.200
	Insufficient information about hazards and risks	0.120	0.450	0.350	0.200
	Insufficient knowledge/ignorance about the job	0.140	0.429	0.333	0.238
	Lack of safety culture	0.170	0.368	0.474	0.158
	Business blindness	0.040	0.409	0.409	0.182
Disasters CR = 0.056 < 0.1	Earthquake	0.330	0.100	0.700	0.200
	Flood	0.110	0.111	0.556	0.333
	Lightening	0.180	0.412	0.353	0.235
	Landslide	0.100	0.125	0.625	0.250
	Storm / Tornado	0.120	0.125	0.625	0.250
	Rockfall	0.030	0.167	0.667	0.167
	Extreme heat wave	0.030	0.167	0.667	0.167
	Extreme cold wave	0.030	0.167	0.667	0.167
	Epidemic disease	0.020	0.385	0.462	0.154
	Cyber attack	0.030	0.385	0.385	0.231
	Terror activities	0.030	0.111	0.667	0.222

Sabotage CR = 0.074 < 0.1	Tampering with Fire	0.310	0.429	0.381	0.190
	Sabotage with Explosives	0.440	0.409	0.364	0.227
	Mechanical tamper	0.120	0.400	0.400	0.200
	Bacteriological and Chemical Sabotage	0.070	0.273	0.545	0.182
	Intellectual sabotage	0.030	0.538	0.308	0.154
	Psychological sabotage	0.030	0.500	0.357	0.143

AUTHOR CONTRIBUTIONS

Investigation and visualization, S.U.; conceptualization, supervision, and writing - original draft, S.C.; writing - review & editing, T.C.; methodology, E.C. All authors have read and legally accepted the final version of the article published in the journal.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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