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ORIGINAL RESEARCH PAPER

Identification and Assessment of health, safety and environmental risk factors of Chemical Industry using Delphi and FMEA methods (a case study)

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ABSTRACT

Today, accidents, explosions, environmental damages and any defects in chemical industry are inevitable events. The ever-increasing of such industries makes effective risk management of these projects necessary to prevent environmental and health pollution and damage. The present study aimed to identify the possible risks caused by chemical industries in the south of Tehran (Iran) by examining the documents available in the health, safety and environment (HSE) units, interviewing experts, and using the Delphi technique and questionnaire. FMEA method was used to prioritize potential risks based on the risk priority number. Data analysis identified 17 risks in four environmental (n=6), health (n=5), safety (n=3) and occupational (n=3) categories. Based on the results of both Delphi and FMEA methods, the highest level of risk was related to three environmental aspects of "air pollution and air quality change", "surface water and groundwater pollution" and "soil pollution". According to the results of the FMEA method, in addition to the three environmental risks mentioned, the occupational risks including "failure to use personal protective equipment by personnel and lack of warning signs for personnel" and "human and operational errors, inappropriate equipment, and failure to comply with workplace safety instructions" were also detected as high-level risks. The findings of the current study revealed that despite the applicability of the FMEA technique in determining the risk factors caused by the activity of the chemical industry, preliminary hazard analysis is also suggested for a more accurate and complete assessment of this process.

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1. Introduction

Various chemical industries in the south of Tehran (the capital of Iran) are among the largest and most important industries in Iran. The capacity of some factories has elevated up to 10 times over the last 20 years. As expected, this growth in both the number and capacity of factories has increased the risk (both within the factory and to the general public) from the consequences of their potential industrial events, leading to enhanced attention to safety in these industries . Different methods of risk assessment can be used as an effective tool in identifying environmental hazards. Environmental hazards can be defined as the probability and consequences of environmental pollution (Hoseini et al., 2022; Khajeh Hoseini et al., 2021). Health risk assessment tools allow determining the exposure rate and risks of contact with environmental pollutants in people (Hassanpour Kourandeh and Fataei, 2013; Ravan Nakhjavni and Fataei, 2015; Jabraeil Nejad and Fataei, 2015; Cheraghi et al., 2018; Bahmanpour et al., 2020).

Risks are an inherent part of all industrial projects, and it is impossible to eliminate them completely. Although risks can be effectively managed to reduce their impact on the achievement of project goals, they are likely to occur in different dimensions of the project. Therefore, risk identification, analysis and prioritization can play a significant role in the success of industrial projects (Masoumi et al., 2020; Fataei, 2020). In a study, Lyu et al. (2018) addressed the damage reduction strategy against chemical accidents in South Korea. To this end, an innovative risk management plan was proposed to reduce the side effects of the chemical industry. Thus, a mitigation barrier was built 30 meters outside the factory so that after a chemical accident, people were safe from the incidents caused by chemical emissions. The simulation results showed that the barrier helped reduce the concentration of chemicals in the region and subsequently relieve the anxiety of residents near the factory. Finally, it was found that this project could be a good example of risk management in the industry.

Eskandari et al. (2020) presented a technique for semi-quantitative risk assessment of chemicals exposure to evaluate the exposure status of chemical workers using the chemical exposure risk assessment methods. They investigated three influencing factors in the risk of employees being exposed to chemicals, including the Health Hazard Index (HHI) indicating the inherent toxic characteristics of chemicals, the Occupational Exposure Index (OEI) indicating the properties related to process conditions and material traits and also control of effectiveness index (CEI) considering the engineering and management measures effective on exposure to chemical substances. In conclusion, according to the role of control measures and their impact on the risk score, their proposed method will be able to calculate the working conditions of employees exposed to chemicals more accurate. Soltanzadeh et al. (2019) in the comprehensive causal analysis of the severity of occupational accidents in chemical industries based on algorithm techniques determined that occupational accidents and injuries in chemical industries have caused severe human and financial losses.

Among the various risk identification and assessment methods, Failure Modes and Effects Analysis (FMEA) is more accurate because of considering the probability of risk detection (Sekhavati et a;., 2021; Omidvar and Nirumand, 2017). Babaei and Mohammadzadeh (2013), by reviewing different risk management techniques to choose the right technique in the Water and Sewage Company of East Azarbaijan Province (Iran), introduced FMEA as the best and most effective risk assessment method in this company.

Vazdani et al. (2018) conducted a study to identify health, safety and environment (HSE) risks caused by facilities and human activities of Gas Condensates Storage Tanks of Parsian Gas Refining Company in Iran using the Delphi technique. Based on the results of risk identification using AHP (analytical hierarchy process) and FMEA methods, the greatest environmental risks were "fire caused by intentional and terrorist factors" with a risk priority number (RPN) of 1.824 and "inhalation of vapors during repairs" with the RPN of 3.384.

Jozi et al. (2013) performed a research for identifying and evaluating environmental risks in the South Pars Phases 15 and 16 Utility using the FMEA method. They identified 147 environmental risks in the Utility construction, 20% of the aspects were at low risk level, 62% at medium risk level and 18% at high risk level. The highest RPN was 210 and related to H_2S gas storage in Phases 9 and 10 and then emergency conditions (RPN=160). In a research, Jozi et al. (2011) showed that environmental aspects with RPN higher than 19.5 had a very high risk level in the Olefin Plant in Arya Sasol Petrochemical Complex, Iran.

Sadaqat et al. (2018) investigated the analysis of storage modes and effects of chemicals in the storage area of the chemical laboratory of Malardalens University, Vasteras, Sweden using the FMEA method. They found that the laboratory had been established in a hazardous situations and therefore it was necessary to move it to a safer place.

If chemicals are not managed properly, they may cause environmental damage. Moreover, the chemical industry complex provides storage and transportation of flammable, explosive, toxic and hazardous chemicals. Pollution incidents have occurred many times due to the large number and different types of chemical storage tanks, as well as the fragile setting in chemical industry complexes, which pose significant risks to the environment and human health (Shi and Duo, 2010). Most of the environmental risks caused by chemical industries are considered highly hazardous. A coherent environmental risk management and monitoring program can reduce environmental risks and improve environmental indicators in areas affected by chemical industries. Accordingly, the current study uses Delphi and FMEA techniques in the field of environmental risk assessment and management of chemical industries in relation to air pollution, sewage, waste and sludge with the aim of identifying the type of polluting industries, the type of polluting processes, the types of polluting outputs of industries, identifying parts of the production line that produce more pollution, estimating the level of risk, controlling and reducing the level of risk to preserve the health of personnel, equipment, capital and the damaged environment.

2. Materials and Methods

The current study investigates the impact of active chemical industries in the south of Tehran (Iran) on the safety of employees and the surrounding environment. Thus, all the different activities in terms of safety, health and environment as well as the documented statistics of the HSE and environmental or professional health units were identified in these industries regarding annual accidents and events leading to health and environmental risks. By reviewing the theoretical foundations of the research, generalities, records and findings obtained from national and international studies, the necessary information was collected in relation to the methods, techniques and results in the field of introducing and presenting the list of relevant components, factors and criteria. Then, we prepared a checklist containing the effective components, factors and criteria used in assessing the potential risks and determining the current status of these industries from an environmental point of view. This checklist was used to identify the types of environmental risks and potential risks for survey experts to confirm their applicability and complete them through the design of a semi-closed offline questionnaire. Since there was a need to design a questionnaire and a survey of experts for identifying environmental risks of chemical industries, the next step was to determine the statistical population and sample size. In order to identify potential risks of chemical industries in south of Tehran, Delphi questionnaire was used. For this purpose, we asked the opinions of 15 experts, including university professors, as well as environmental and HSE experts based in chemical industries in south Tehran.

Delphi is a systematic approach or method in research to elicit the opinions of a group of experts on a topic or a question (McKenna et al., 2002). It is a multi-stage survey method to collect opinions on subject matter and uses written responses instead of gathering an expert group, and also provides the goal of consensus by allowing free expression of opinions and revision of opinions with numerical estimates (Hsu and Sandford, 2007). The classical Delphi method consists of four rounds, which are usually shortened to two to three rounds to achieve the research goals (Windle, 2004). The identification of experts is an important point in Delphi, as the achievement of goals depends on the careful selection of participants. The selected experts in Delphi should have sufficient knowledge of the subject area, participate in the discussion and influence the outcome of the process. However, non-experts and interested people can also be included (Kennedy, 2004).

Then, the identified risks were qualitatively analyzed. In this regard, the FMEA technique was used to divide the levels of probability of occurrence and severity of the identified risks into three levels: low (L), medium (M), high (H). In the next step, the risks were quantified for analysis and prioritization. The research steps are shown in Figure 1.

The FMEA method was introduced by NASA in 1963 to meet the reliability requirements of its systems. Since then, it has been widely used as a powerful technique to analyze the security and reliability of products and processes in a wide variety of industries, especially aerospace, nuclear, chemical, automotive and pharmaceutical. This technique is a robust tool used by security and system reliability engineers to determine critical functions whose failure could lead to undesirable outputs such as lost production,

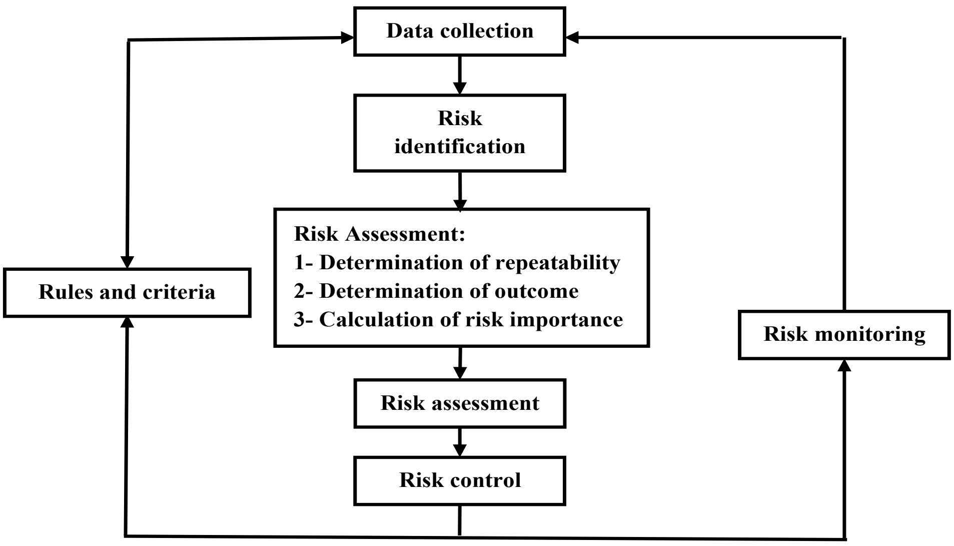

Figure 1. Flow chart of risk management steps

damage, or customer dissatisfaction (Cheraghi et al., 2018). The variables of FMEA include the following:

Probability of Occurrence (O): is a type of ranking or value that is estimated for the probability of occurrence of any cause. The possibility of error can be reduced by eliminating and controlling a number of causes. The best way to measure the degree of failure is to use process data, which shows the process capability in the form of an information table. When actual data on a failure are unavailable, the highest degree of failure occurrence should be considered.

Assigning a detection level (D): For each potential failure pattern or its effect, the detection level indicates the probability of a failure and its impact.

Assigning a severity level (S): for each effect, the severity indicates the seriousness of the effect of a potential failure, and there is a direct relationship between the effect and the severity. Severity ranking is actually an assessment of the seriousness of the effects of a failure if it occurs. Assessment of the severity of each effect should be done based on the knowledge and expertise of the group members, because none of the people have previous experience in assessing the severity of the effect. Since each failure has different effects, we should rank the effect of the failure, not the failure itself. If there are several effects for potential failure, the degree of severity of each effect should be determined (Habibinia and Dashti, 2018). Table (1) shows failure modes versus risk factors in a conventional way using a 10-point assessment scale for S, O, and D variables.

RPN is used to determine the risk level of each failure mode. In fact, RPN determines the critical value of each item. Risk patterns with higher RPN are more critical. How to calculate RPN is shown in equation (1) (Vazdani, 2018):

$$RPN = O \times S \times D \qquad \text{Equation (1)}$$

Table 2 was used to determine the importance coefficient of each risk.

The weight used in the three risk factors of Occurrence (O), severity (S) and detection (D) are presented in Table 3.

Table 1. Scoring of risk factors in the FMEA method (Liu et al, 2013)

Score	Probability of detection	Severity of effect	Detectability
10	Extremely high (≥ 1 in 2)	Hazardous with no warning	Almost uncertain
9	Very high (1 in 3)	Hazardous with warning	Very rarely
8	Frequent (1 in 8)	Extremely	Rarely
7	High (1 in 30)	Many	Very low
6	Moderately high (1 in 80)	Significant	Low
5	Moderate (1 in 400)	Moderate	Moderate
4	Relatively low (1 in 2000)	Low	Moderately high
3	Low (1 in 15,000)	Minimal	High
2	Rarely (1 in 150,000)	Very minimal	Very high
1	Nearly impossible (≤ 1 in 150,000)	None	Almost certainly

Table 2. Four-priority classification of corrective actions in environmental risk assessment by FMEA method

No.	RPN	Degree of risk	Priority of corrective actions
1	0-90	Low	4
2	90-120	Moderate	3
3	120-150	High	2
4	>150	Critical	1

Table 3. Weight of risk factors

Risk factor	Detection	Severity	Occurrence
Weight	0.222	0.455	0.322

3. Results

The questionnaire used in the Delphi technique had four main environmental, technical-safety, health and occupational risks with 17 potential risks. A 5-point Likert scale was used to evaluate the responses of potential risks (Table 4).

Table 4. Quantification of responses to questions based on 5-point Likert scale

Selective option	Very low	Low	Moderate	High	Very high
Score	1	2	3	4	5

The expert (Delphi) questionnaire was completed by 15 experts, faculty members, academic elites and executive managers in the fields of environment, experts in the environmental risks of chemical industries. The questionnaire was provided to them in person and, if necessary, in virtual form. Delphi group members reviewed the risks in the first phase and did not propose any new risks. The risks were given to the Delphi group for the

Table 5. Dimensions of potential environmental risks of chemical industries in South Tehran, Iran

Risk type	Potential risks	Risk code	Delphi group agree with potential risks		Agreement percentage (%)	Rank
			Yes	No		
Environmental	Air pollution and air quality change, emission of SO_x and NO_x pollutants, Particulates, volatile organic compounds (VOCs) in the air	E_1	16	1	94.1	1
	Surface water and groundwater pollution (discharge of chemicals into sewage)	E_2	16	1	94.1	1
	Soil pollution due to increased release of heavy metals, garbage and industrial waste	E_3	16	1	94.1	1
	Noise pollution	E_4	15	2	88.2	2
	Destruction of the ecosystem and wildlife of the region due to the increase in pollutants from the factories	E_5	15	2	88.2	2
	Toxicity and non-degradability of hazardous substances (phenolic compounds in the environment)	E_6	14	3	82.3	3
Health	Human exposure to chemical pollutants and toxic or corrosive substances: epichlorohydrin, methyl ethyl ketone, sulfuric acid, phenol, chlorobenzene, toluene, acetone, etc.	H_1	13	4	76.4	4
	Exposure to fatal dose of chemicals in wrong operation	H_2	13	4	76.4	4
	Inhalation of SO_x and NO_x pollutants from the output of chemical factories Inhalation of VOCs from the tanks of the industrial units	H_3	13	4	76.4	4
	The effect of noise pollution of equipment and machines on the hearing system of workers	H_4	13	4	76.4	4
	Failure to observe personal, social and dressing room hygiene	H_5	12	5	70.5	5
Safety	Falling of employees or objects from a height while working in various industrial units	S_1	11	6	74.7	5
	Risks caused by working with machines and equipment in various industrial units	S_2	13	4	76.4	4
	Explosion and fire caused by leakage of chemical tanks or during transportation of chemicals	S_3	11	6	74.7	5
Occupational	Disaster caused by working with flammable substances: hydrogen, propylene gas, propane, gasoline, hexane, liquid pentane, paraffin, etc.	O_1	10	7	78.8	4
	Explosion of steam boilers and failure of devices, etc	O_2	9	8	73.3	5
	Physical injuries caused by the manual activity of workers	O_3	9	8	73.3	5

second round and the members confirmed their previous opinions. Based on the consensus of the Delphi group, whose criterion was 70% agreement among the members on each of the risks, the risks with a frequency percentage higher than 70% were extracted and ranked for the next stage. As the Delphi group members did not propose new risks in both Delphi rounds, the Delphi method ended in two rounds.

In this section, by using the risks ranked in the Delphi rounds and their relationship with the environmental risks

Table 6. Failure modes and their causes and consequences, and assessment of environmental risks of chemical industries in south of Tehran (Iran) based on FMEA

Risk type	Potential risk code	Causes of risk	Consequences of risk	Risk management			RPN
				Severity of effect	detectability	Probability of occurrence	
Environmental	E_1	Combustion process, catalyst regeneration, waste incinerators, non-standard exhaust gas	Air pollution, acid rain, photochemical smog, increasing greenhouse gases	6	3	7	126
	E_2	Human error	Water pollution (change in the quantity and quality of groundwater and surrounding soils)	6	3	8	144
	E_3	Failure to use standard equipment, human error (incorrect management)	Soil pollution (change in soil quality for the growth of plants in the area, etc.), decrease in the price of land around the area	6	3	7	126
	E_4	Failure to use standard equipment, human error	Noise pollution in the workplace	6	3	6	108
	E_5	Fossil fuel consumption (50 times more)	Regional ecological change, reduction of regional fauna and flora, loss of plant density, damage to the river bed due to the deposition of chemicals.	2	7	8	112
	E_6	Inefficient treatment of septic tank wastewater	Environmental tensions in the region (pollution of the region, especially residents around the industrial area)	6	6	3	108
Health	H_1	Failure to use personal protective equipment (hats, earplugs, shoes, gloves, glasses and insulated clothing) by personnel, lack of warning signs for personnel	Mortality, burns, threats to the health of personnel (pulmonary problems, swallowing problems, severe mouth, throat and stomach burns, severe tissue wounds, skin and eye irritation)	7	4	5	140
	H_2	Insufficient training, lack of experience and knowledge	Severe burns, acute systemic infection of workers	2	6	7	84

	H3	Failure to use equipment, Failure to use standard equipment, increase in traffic caused by oil tanker traffic	Regional ecological damage (wildlife, birds, etc.)	7	4	4	112
	H4	Human errors, failure to observe health tips	Different kinds of diseases	6	4	4	96
	H5	Human errors, failure to observe safety precautions	Bronchoconstriction, eye irritation, cough, runny nose	10	5	2	100
Safety	S1	Human and operational errors, inappropriate equipment, and failure to comply with workplace safety instructions	Human injuries (personnel health threat)	2	9	8	144
	S2	Lack of necessary controls, human and operational errors, employment of non-specialists, lack of personnel training, failure to use personal protective equipment	Human injuries (personnel health threat)	3	4	8	96
	S3	Lack of necessary controls, human and operational errors, employment of non-specialists, lack of personnel training, failure to use personal protective equipment	Human injuries (personnel health threat), threats to nearby residential areas, unemployment due to network disruption	2	6	9	108
Occupational	O1	Failure to observe safety precautions, failure to use proper face mask by personnel (human error), operational error	Nausea, confusion, drowsiness, loss of balance and coordination, anesthesia, coma, respiratory failure and death	6	2	8	96
	O2	Insufficient training, lack of experience and knowledge	Severe burns, acute systemic infection of workers	4	3	7	84
	O3	Human errors, failure to observe safety precautions	Transformation of spinal curvature due to long standing, carrying and moving,	4	4	7	112

of chemical industries, a researcher-made questionnaire was prepared based on a 5-point Likert scale (from very low = 1 to very high = 5). At this stage, 17 questions were prepared and evaluated in four categories of environmental, health, technical-safety and occupational risks (Table 5).

Based on the results of both Delphi and FMEA methods (Table 4), the highest level of risk was related to three environmental aspects of "air pollution and air quality change", "surface water and groundwater pollution" and "soil pollution" with 94.1% agreement. The occupational

risks such as "Explosion of steam boilers and failure of devices, etc." and "Physical injuries caused by the manual activity of workers" were ranked last with an agreement percentage of 73.3%.
In the next step, the risks identified through the Delphi technique were evaluated and ranked using the FMEA method (Table 6).

4. Discussion

The present research aimed to identify the risks caused by chemical industries in the south of Tehran (Iran) by examining the documents available in the health, safety and environment (HSE) units, interviewing experts, and using the Delphi technique and questionnaire. Among the 17 identified risks, the FMEA results showed that the safety aspect of "Falling of employees or objects from a height while working in various industrial units" (S1, RPN = 144) had the highest priority and the health aspect of "Insufficient training, lack of experience and knowledge" (H2, RPN = 84) and the occupational aspect of "Insufficient training, lack of experience and knowledge" (O2, RPN = 84) had the lowest priority. It should be noted that the safety aspect of "Explosion and fire caused by leakage of chemical tanks or during transportation of chemicals" (S3) requires corrective measures due to the probability of risk severity of 9, and is considered one of the intolerable safety risks. The results also revealed that 52.94% of the environmental risks of chemical industries in South Tehran were of medium significance, while 35.29% were of high significance and 11.76% were of low significance.

Comparing the results of determining the level of 17 risks identified in the chemical industries of South Tehran based on the Delphi method (Table 5) showed that three environmental risks of "Air pollution and air quality change (E1), "Surface water and groundwater pollution (E2)" and "Soil pollution (E3)" were identified as significant risks with a high agreement of 90%. It should be noted that in the FMEA technique, among the 17 risks, in addition to the three mentioned risks, the health risk of "H1, Table 6" and the safety risk of "S1, Table 6" were determined as high-level risks. Habibinia and Dashti (2018) evaluated the HSE risks in the industrial sector using the Delphi method and the integrated FMEA&TOPSIS model, and identified 21 intolerable risks out of 57 studied risks. Based on the results obtained in two studies, there are differences in the prioritization of distinct risks between the two studied methods. Since there are various methods for environmental risk assessment, each of which may have advantages and disadvantages in a specific environment, so it is impossible to rule out or rule in the method with high certainty. To what extent the desired method is effective in the industry depends on conditions such as design, structure, type of activity and environmental conditions of the study area (Josie and Saffarian, 2011).

As mentioned earlier, in general, risks cannot be completely eliminated, but they can be reduced to an acceptable or tolerable level. Therefore, the risk management aims to establish a systematic and continuous framework to identify, evaluate, eliminate, control, prevent, reduce and introduce risks (Setare, 2005). Hence, during the risk management process, decisions are made based on the comparison of risk assessment results and determined risk levels.

5. Conclusions

The growth and development of chemical industries in recent years has increased people's exposure to environmental, health and safety (HSE) risks caused by accidents in this industry, so it is necessary to pay attention to risk management due to their hazardous nature.

Data analysis of the present investigation on the chemical industries in the south of Tehran (Iran) identified 17 risks in four environmental (n=6), health (n=5), safety (n=3) and occupational (n=3) categories. The findings showed that the distinct risks of the chemical industry in the study area require the formulation of a planned management mechanism, which needs not only the creation of a scientific management structure, but also the infrastructure of facilities. Therefore, it seems necessary to establish the HSE management competently and effectively through the formulation of an efficient policy with goals appropriate to the volume and type of HSE aspects and risks of the chemical industries to implement and achieve the set goals. In addition, training and interacting with the employees of these industries are among the best measures to reduce and control HSE risks. Since the results indicated that the highest risk priority number was related to environmental risks including "air pollution and air quality change", "surface water and groundwater pollution", and "soil pollution", so it seems necessary to use clean technologies to control and reduce pollutants in the studied chemical industries in order to protect the environment and achieve sustainable development (green industry)..

Authors' Contributions

All authors have contributed equally in writing different parts of the paper. This publication has been approved by all co-authors, if any, as well as by the responsible authorities – tacitly or explicitly – at the institute where the work has been carried out. The publisher will not be held legally responsible should there be any claims for compensation.

Conflict of interest

The Authors declare that there is no conflict of interest.

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