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Analyzing Resilience in Chemical Industry: A Cross-Sectional in a Process Industry

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ABSTRACT

Background: This study aimed at developing and using a semi-quantitative method for analyzing safety resilience in the chemical industry. This cross-sectional, descriptive-analytical study aimed to develop a semi-quantitative method for analyzing resilience.
Methods: This study was carried out based on the Delphi method including 18 experts in chemical and process engineering as well as the health, safety and environment (HSE) engineering in 2018-2020.
Results: The development of the semi-quantitative method for analyzing safety resilience took place after three rounds of the Delphi study. In this Delphi study, all the members of the experts' panel approved the three components of preparedness, likelihood, and severity with an 80% acceptance level. The results of the field study revealed 131 hazardous elements. The maximum and minimum values of resilience were found to be 500 and 100 belonging to failure in utility and failure in the distributed control system, respectively.
Conclusion: The developed semi-quantitative method has acceptable reliability for the analysis of safety resilience in the chemical industry. Therefore, the analysis in the chemical industry can be considered an effective, necessary decision-making instrument for predicting and preventing dangers threatening the process, manpower, and nature of the chemical industry.

1. Introduction

Safety hazards and their detrimental consequences prove a hindrance to the stability and resilience of the chemical industry. Research shows several chemical companies have to shut down every year due to their weak resilience to chemical threats [1, 2].

Resilience engineering is defined as the inherent ability of a system to adjust its capabilities in an unforeseen disturbance and change. Creating structures and subsets that are involved in ensuring the safety of process systems can directly impact the resilience level [3, 4]. It can be claimed that catastrophic accidents in the chemical industry are not varied and mainly include emission of toxic gas, gas steam

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cloud formation, fire, and explosion. The question that begs to be answered is why such accidents cannot be prevented? The fact is that the majority of these accidents are not only preventable but also predictable in terms of severity using different analysis methods. Nevertheless, for such methods to be effective, they need to be devised on time with effective vulnerability analysis algorithms, corrective measures be taken, safety standards be met, and knowledge management be performed efficiently [5,7]. Indeed, resilience analysis is a process that reduces the vulnerability of chemical companies to the negative consequences of accidents [8, 9]. A study conducted by Jain *et al.* (2018). Focusing on building an algorithm for analyzing hazards and resilience in the industry showed that the parameters of software and hardware protection layers, manpower, process and equipment hazards, technical process examination, and critical processes are amongst the most significant factors influencing the identification and analysis of hazards following a resilience analysis approach in the industry (10). In another study, Mann *et al.* (2018) developed a process resilience model. They demonstrated that hazard identification, hazard tolerance, recovery, preparedness, and system flexibility/dynamicity are the most important factors affecting the resilience of a process system from the perspective of risk management [10].

Today, the biggest challenge of fostering a stable development in the chemical industry, such as refineries, is safety issues including accidents occurring as a result of technology-based protection layers, human error happening as a result of interaction with technology, infrastructure wear and tear, and lack of trust in technical, instrumental, or infrastructure technology. These challenges and threats may grow over time and thus increase the risk of accidents in the long run [11].

One way to improve safety factors via resilience is to analyze different aspects and parameters of vulnerability based on hardware risk factors (equipment, facilities, and materials safety), system software, manpower, and working methods [12]. Therefore, developing a method for analyzing safety resilience in the chemical industry can help identify and evaluate risk sources and reduce the damage of accidents arising from threats, increase system resilience, act as a powerful tool for large-scale decisions, and eventually improve resilience levels in industrial systems [13].

Given that safety risks and their resulting emergency situations can seriously threaten the existence or efficiency of chemical companies, it is of great importance to consider the newest safety science approaches to reduce threats on the one hand and develop approaches to increase safety resilience on the other. Some studies show that safety resilience in the process industry is a function of factors that prevent various threats and then, by taking the limitations of preventive systems, develop and present a limiting plan to minimize the damages severity in the shortest time possible. Consequently, it is important to pay attention to parameters such as preparedness for reducing accident damages and swiftness for improving system operations [14, 15]. Therefore, this study aimed to develop a semi-quantitative method for analyzing safety resilience in the chemical industry and conduct a relevant field study to analyze safety resilience in this industry.

2. Materials and Methods

This cross-sectional, descriptive-analytical study was conducted in two phases in 2020. In the first phase, a semi-quantitative method was developed based on the Delphi method and experts' opinions to analyze safety resilience in the chemical industry. In the second phase, a field study was conducted in a gas sweetening unit of a refinery to analyze safety resilience.

2.1. Developing a Semi-Quantitative Method for Analyzing Safety Resilience in the Chemical Industry

In this phase, the relevant literature on the analysis of safety resilience and its main components was first reviewed. Then, a semi-quantitative method was developed based on experts' opinions in terms of three components: likelihood, severity, and preparedness. The reason for selecting these components is first the opinion of the panel of experts. Their argument about the very close relationship of these components to the resilience level of a process industries and the result of structural modeling has confirmed this issue. Many of the items mentioned in other studies are subdivided into these three components. In this study, some of the most important of them are considered as subdivisions of the above three components and they are weighted depending on the degree of impact.

The Delphi method is a structured process designed to collect and categorize existing knowledge in the panel of experts. The basis of the Delphi method is that the opinion of experts in every scientific field is the most valid one. Unlike survey research, the validity of the Delphi method is not dependent on the number of participants but on the scientific credibility of the experts. The participants of the Delphi method usually range from 5 to 20 experts [16, 17]. In this study, 18 experts holding master's and Ph.D. degrees in chemistry, chemical engineering, process engineering, and HSE engineering participated.

In the first Delphi round, the structure of the semi-quantitative method for analyzing safety resilience in the chemical industry, including three components (likelihood, severity, and preparedness), was developed and presented to the experts. A total of 18 experts were asked to express their opinions about the appropriateness of components based on a 5-point Likert scale (highly inappropriate to highly appropriate). Moreover, they were asked to add any component that they thought was missed for safety resilience in the chemical industry. Afterward, the results of the first round were analyzed. In the second Delphi round, the suggested changes and modifications were done on the structure of the semi-quantitative method, and the method was sent to the experts again. The experts were asked to share their opinions about the appropriateness of components. Finally, in the third Delphi round, the structure and coordinates of the semi-quantitative method for analyzing safety resilience in the chemical industry were sent to the experts to ask for their opinions. After collecting experts' opinions in the third round and analyzing the data and given that the coefficient of variation (CV) was almost the same compared to the second round (< 20%), the Delphi study was finished after the third round; based on the results, the final semi-quantitative method for analyzing safety resilience in the chemical industry was developed. The inclusion criterion for each of the three components was set at a mean ≥ 4 [18].

2.2. Field Study for Analyzing Safety Resilience

The field study was conducted on one of the most important refinery units: sweetening gas unit 101. The main goal of building this unit is to remove hydrogen sulfide gas (H_2S) from sour gas with *methyldiethanolamine* (MDEA). Natural gas includes a combination of H_2S, CO_2, and mercaptan that should be removed from the main gas before distribution. In this unit, a kind of Amine called MDEA is used to remove H_2S gas. The analysis was done using the semi-quantitative method for analyzing safety resilience in the chemical industry in three steps.

2.3. System Description

In the first step, the studied unit was selected, and the description of the system was done based on parameters affecting resiliency. All equipment and processes in the system were analyzed by process flow diagram (PFD) and piping and instrumentation diagram (P&ID). The study group consisted of 18 experts (shift managers, process engineers, maintenance engineers, HSE engineers, technical inspectors, crisis managers, and passive defense experts). To do the analysis, first, the boundary of the analysis unit was defined. The analysis unit consisted of determining process trends, facilities, and sensitive parts of the sweetening unit. Next, nodes were selected according to four critical process parameters: temperature, pressure, volume, and level. Of note, these four critical parameters were presented in all nodes and analyzed accordingly. In this step, the existing hardware in the system (facilities, equipment, instruments, materials, deficiency, and reliability) and existing activities and executive processes (process and description of jobs or operational activities) were completely described. It is noteworthy that in this study, hazard and operability (HAZOP) method has been used to examine the nodes and HAZID and root causes analysis (RCA) and hazard triangle methods have been used to analyze the threats in the whole system as well as the external environment of the system.

2.4. Hazard Identification (HAZID)

Hazard identification (HAZID) is a systematic method to identify potential hazards in a system. In this method, hazards and their ensuing consequences are analyzed completely. Identifying hazards is a decisive step in securing processes in the petroleum and gas industries. Hence, it is important to design and implement measures that can help identify potential hazards. In this step, HAZID was done according to the hazard-threat triangle method with the two backward and forward approaches [19]. Additionally, a review of previous studies shows that all known methods can be used to identify hazards that threaten the resilience of a system. Therefore, in this study, we have used the HAZID method to identify hazards and information required to assess resilience. It should be noted that HAZID does not mean the calculation of resilience. So, the method of resilience calculation is the new formula presented in the following sections.

2.5. Safety Resilience Assessment

In this step, safety resilience analysis and levels of resilience appropriateness was conducted based on the semi-quantitative method of safety resilience analysis in the chemical industry (Equation 1 and Tables 1-2).

3. Results and Discussion

3.1. Results of Developing the Semi-Quantitative Method for Analyzing Safety Resilience in the Chemical Industry

The expert's panel mean age and work experience were 39.6±8.49 and 9.2 ± 6.22, respectively. Ten experts were married (55.6%) and eight experts were single (44.4%). Six experts held a master's degree (33.3%), and 12 experts had a Ph.D. degree (67.7%).

The results of the first round of the Delphi study revealed that all the experts expressed their opinions regarding the appropriateness of the components of the semi-quantitative safety resilience analysis (participation rate = 100%). Moreover, one of the experts suggested a new parameter for the severity component called "damage to, disconnection, or cessation of the industrial production process". After applying the required modifications and running the second round, the analysis showed that no parameter and component were added to the model anymore. The results of the third round of the Delphi study demonstrated that the CV index of the third round increased only by 15%, which was significantly lower than the standard coefficient (>20%) set for this study. Eventually, considering the over served CV, the Delphi study ended in this round.

The previous studies show the relationship between the components used in this relationship and the degree of resilience. In this study, an attempt has been made to provide a logical and scientific relationship between the elements affecting resilience in the form of a mathematical equation. The semi-quantitative method for analyzing safety resilience in the chemical industry was developed based on Equation 1 and Tables 1-2. The results of validity analyses comprising content validity ratio (CVR) and content validity index (CVI) revealed that CVR and CVI indexes were 0.915 and 0.94 for this method. Besides, the resiliency was categorized into three levels: level 1/safe condition (101-500), level 2/alert condition (41-100), and level 3/critical condition (4-40) (Table 2).

The classification in Table 2 is based on the impact and importance of each threats on the refinery production system and production process. The groupings related to their predictability or normal and abnormal are not considered.

$$\mathbf{R} = \left(\frac{\mathbf{P}}{\mathbf{L \times S}}\right) \times \mathbf{100} \qquad (1)$$

R: Resiliency index (4-500)

P: Preparedness index (1-5): The preparedness index includes the availability of hardware equipment, software equipment (control systems), and outside resources to prevent and reduce the negative consequences of accidents.

L: Likelihood index (1-5): The likelihood index includes reliability data, frequency of occurrence in particular times in a chemical company, experimental data of past and similar events in international chemical companies, information and frequency of technical inspections conducted, and professional qualifications of the staff such as expertise, education, and capabilities of operational, engineering, managerial, and support staff.

S: Severity index (1-5): The severity index is measured based on human injuries (from minor ones to death), environmental damages (from minor ones to the destruction of the ecosystem), and process damages (number of days a process is halted).

3.2. *The Results of Using the Semi-Quantitative Method of Safety Resilience in the Sweetening Unit of a Gas Refinery*

The results of the hazards identification showed that there were 131 hazardous elements in this unit.

Table 1: Guidance on the determination of resilience components

Index	Likelihood	Severity	Preparedness
1	Very low (< 10%)	Very low (<5%)	Very low (<10%)
2	Low (10 %-< 20%)	Low (5 %-< 10%)	Low (10 %-< 30%)
3	Medium (20 %-< 30%)	Medium (10 %-< 20%)	Medium (30 %-< 50%)
4	High (30 %-< 50%)	High (20 %-< 30%)	High (50 %-< 75%)
5	Very High (50%-100%)	Very High (30%-100%)	Very High (75%-100%)

The highest resilience index belonged to utility failure (resilience = 500). Safety resilience analysis results revealed that 21.4% (28 hazards) of identified hazardous elements belonged to the weak threat range (safe/almost safe condition), 59.5% (78 hazards) belonged to the moderate threat range (alert condition), and 19.1% (25 hazards) belonged to the severe threat range (critical condition).

The analyzed system had the highest level of resilience to ten kinds of threat including utility failure (resilience = 500), level increase, temperature decrease, system utility deficit (resilience = 250), feed compounds changing, reverse flow, shortage or disconnection of nitrogen, furnace gas flow disconnection, backflow, and pressure increase/decrease (resilience = 167) (Table 3).

On the other hand, the analyzed system had the lowest level of resilience to ten kinds of threats, including failure in the distributed control system (resilience = 10), human error threat (resilience = 16), malfunction in the control system, and DCS (resilience = 17), threat in maintenance, and failure in utility air feeding (resilience = 19), leakage of drum content, the threat of vessels, threat of flooding, threat of earthquake, emission of toxic and flammable materials in the air (resilience = 20), and the threat of pressure increase (resilience = 20) (Table 4).

A combination of plans, processes, and activities capable of reducing accidents and their ensuing consequences and sufficient preparedness for dealing with any event can all boost safety resilience in an industry [20-22]. Moreover, given nature and unique characteristics of the chemical industry with its critical process parameters, chemical companies are constantly exposed to different types of threats, negative consequences, and vulnerabilities. Thus, designing, developing, and using an efficient method to increase safety resilience to various types of threats can help these companies come to minor and major decisions about dealing with threats and increasing safety resilience [23, 24].

Based on the study results, three components (likelihood, preparedness, and severity) were utilized to analyze safety resilience in the chemical industry. Similarly, some studies have reported that these three components are the most important components for analyzing systems' safety resilience to different hazards and threats [10, 25].

Table 2: Resiliency Levels

Resilience level	Threat	Descriptions
Level 1	Weak threat / safe condition	A type of threat whose possible consequences are limited to the area it occurred (threatening a section of the industry) (resiliency = 101-500)
Level 2	Moderate threat/alert condition	A type of threat whose possible consequences can cover a larger area than it originally occurred (the expansion of the threat to further sections of the industry) (resiliency = 41-100)
Level 3	Severe threat / critical condition	A type of threat whose possible consequences can cover the whole industry or severely threaten its whole existence (resiliency = 4-40)
Note: If the resiliency index is higher than 100, but one of the conditions of P = 1, L = 5, or C = 5 is met, resilience is categorized into level 3.		

In agreement with the findings of this study, Jain *et al.* (2018) showed that hardware and software protective layers, manpower, process and equipment hazards, technical inspection of the process, and critical process are amongst the most significant factors affecting the identification of hazards and analysis of safety resilience in the chemical industry [10]. In another study, Mannan *et al.* (2018) developed a resilience model. They reported that hazard detection, designing error tolerance, system retrieval and preparedness, and system flexibility/dynamicity factors are important factors influencing safety resilience in a process system [26].

The results of 131 hazardous elements identified in this study revealed that the result of most hazardous elements and threats include fire, explosion, emission of toxic materials, manpower injuries, and damage to equipment and the environment, each of which can result in disastrous consequences. Furthermore, the findings also demonstrated that despite protective layers, if such threats and hazards are realized, serious damages and injuries will ensue. As observed, the lowest resilience level belonged to failure in the distributed control system, malfunction in control system and DCS, human error, malfunction in maintenance, failure in utility air feeding, leakage of drum content, threat of vessels, threat of earthquakes, emission of toxic and flammable materials, and threat of pressure increase. It was found that these issues all lacked sufficient protective layers. Additionally, 21.4% of identified hazardous elements belonged to the weak threat boundary (safe/almost safe), 59.5% to the moderate threat boundary (alert condition), and 19.1% to the severe threat boundary (critical condition), showing that the studied refinery was in an appropriate condition in terms of safety resilience. Nevertheless, the severity of consequences can arise in particular cases and thus negatively affect the safety resilience of the system.

The study results showed that given the nature of chemical processes and critical parameters in the chemical industry, potential hazards and threats can result in catastrophic consequences for chemical companies and the whole society [27]. Hence, developing and using effective methods for analyzing safety resilience to threatening hazards can help efficiently evaluate safety resilience in the chemical industry and eventually lead to more effective preparedness strategies to prevent or reduce accidents [28, 29].

Table 3: Hazardous Elements with the Highest Level of Resilience

No.	Hazardous element	likelihood	Severity	Preparedness	Resilience index
1	Utility failure	1	1	5	500
2	Decrease in temperature	2	1	5	250
3	System utility deficit	2	1	5	250
4	Level increase	2	1	5	167
5	Feed compounds changing	3	1	5	167
6	Reverse flow	3	1	5	167
7	Shortage or disconnection of nitrogen	3	1	5	167
8	Furnace gas flow disconnection	3	1	5	167
9	Backflow	3	1	5	167
10	Increase or decrease in pressure	1	3	5	167

Table 4: Hazardous Elements with the Lowest Level of Resilience

No.	Hazardous element	likelihood	Severity	Preparedness	Resilience index
1	Failure in instrument air	4	5	2	10
2	Human error	5	5	4	16
3	Malfunction in control system and DSC	3	4	2	17
4	Threats in maintenance	4	4	3	19
5	Failure in utility air feeding	4	4	3	19
6	Leakage in drums and vessels content	4	5	4	20
7	Flooding	4	5	4	20
8	Earthquake	4	5	4	20
9	Emission of toxic and flammable materials in the air	4	5	4	20
10	Increase in pressure	3	4	3	25

4. Conclusion

The authors sought to provide a practical and scientific method for assessing resilience in this study. Therefore, finding common ground between system safety and resilience and creating their communication structure to establish a mathematical relationship to assess resilience using any scientific method can be a step forward in resilience analysis. The current study is among a few studies aiming at developing and using a semi-quantitative method for analyzing safety resilience in the chemical industry based on the three components of likelihood, severity, and preparedness. Therefore, the results can help develop a new approach to analyze safety resilience in the chemical industry. Moreover, the application of this analysis method can be considered a decisive step towards having a comprehensive consequence management plan and increasing safety resilience in the chemical industry. This semi-quantitative analysis method can also improve the resilience of the systems by using various mechanisms such as increasing preparedness against threats, reducing the chance and frequency of accidents, and improving recovery power.

Authors' Contributions

Hossein Amouei: Conceptualization; Data curation; Funding acquisition; Investigation; Writing-original draft; Writing-review and editing. **Mahnaz Mirza Ebrahim Tehrani**: Conceptualization; Project administration; Supervision; Validation; Visualization; Writing-review and editing. **Seyed Ali Jozi:** Formal analysis; Resources; Software; Writing-original draft; Writing-review and editing. **Ahmad Soltanzadeh:** Conceptualization; Formal analysis; Methodology ; Resources; Software; Supervision; Validation; Writing-original draft; Writing-review and editing.

Conflicts of Interest

The Authors declare that there is no conflict of interest.

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