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ORIGINAL ARTICLE

Vulnerability Analysis against Natural and Technological Threats: A Comparative Assessment in Tehran Metropolis Gas Supply Network

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ABSTRACT

Resilience as a counterpoint to vulnerability can reduce the vulnerability of various natural, man-made, and technological threats in complex technical systems. The present study was designed and conducted with the aim of comparative assessment of the vulnerability of a gas supply network to natural and technological threats. This descriptive-analytical and cross-sectional study was carried out in Tehran metropolis gas supply network including town board stations, gas supply, and distribution networks in 2019-2020. The study was based on the vulnerability analysis method including three factors of likelihood, severity of consequences, and the degree of preparedness for threats. Comparative vulnerability assessment in these three sections of the gas supply network was performed using IBM SPSS software v. 23.0. Out of eleven identified hazardous elements, the vulnerability index for three hazardous elements was estimated as a weak level threat; four hazardous elements as a medium level threat and the vulnerability index for four hazards were evaluated as a severe threat. The results of comparative vulnerability assessment based on three parts of gas supply network showed that the highest vulnerabilities related to the gas distribution network (133.66±24.63), gas supply network (115.0±35.35), and town board stations (79.49±68.51. In addition, the results of Kruskal-Wallis test showed that the vulnerability difference in these three sections was not significant ($p>0.05$). The findings of the comparative assessment of vulnerability between different parts of the gas supply network including town board stations (TBS), gas supply and distribution network indicated that the resilience of these parts is relatively low and requires special attention in order to reduce vulnerability in Tehran metropolis gas supply network.

KEYWORDS: *Comparative Assessment; Vulnerability Analysis; Resilience; Gas Supply Network; Tehran Metropolis*

INTRODUCTION

Resistance to all kinds of hazards that threaten and challenge the safety, health, and even security and survival of a system is known as the approaches that are known to protect a system against a variety of threats and as very vital solutions against a variety of hazards [1-3].

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Different studies have shown numerous types of events and the ensuing injuries caused by them for whatever reason including natural disasters such as floods and earthquakes, man-made threats such as intentional injuries, accidents caused by human error that occur with interaction to technology and the deterioration of facilities or loss of reliability of technology. These events have devastating effect on manpower, economy, environment, and an adverse impact on the productivity and competitiveness [4]. Since industrialization of societies, a large number of harmful events occur every year around the world. These events impose various human, economic, and sometimes strategic consequences on the system, organization or even society [5].

An increase of various hazards and threats would be a major challenge over a time period to achieve the goals of sustainable development in technology-based systems that threaten the survival and productivity of the organization [6-7]. Therefore, new technical approaches are required to reduce the incidence of threats orneutralize them as well as provide new scientific and technical approaches to reduce vulnerability or increase the resilience of a technology-based system [8]. Consequently, a structured model and template application, analyzing the extent of damage imposed by these threats, and a comparative assessment of a complex technological system vulnerability elements may provide an effective step in reducing the vulnerability of a system and improve resilience against hazards types that threaten a system or organization [9].

The consequence management approach as a novel vulnerability analysis method in fields of safety, emergency, and crisis management by considering both reactive and action approaches in this area seeks to fill the gaps of these two approaches and strengthen them. In addition, this approach utilizes a powerful and efficient algorithm to analyze the vulnerability in each set and related parameters to obtain a correct and accurate assessment of the extent and status of the vulnerability, and ultimately increase the resilience to related threats [10-11].

Results of previous studies showed that the resilience engineering due to its new approach point of view brought a lot of attention to the safety. Thus, vulnerability and resilience assessments enable managers to identify weaknesses and challenges in their system [12-14]. For instance, the role of reliability of fires and explosions extinguisher equipment and system resilience is very important, particularly in assessing the special feature of intensifying in the occurrence of catastrophic accidents in technology-based systems such as gas supply networks as well as gas stations. A key point in assessing the likelihood of exacerbation in severe accident scenarios in such systems is that in most cases both incidence and exacerbation factors may be corrected by the installation and application of protective layers and appropriate emergency measures. However, there is still a lack of a comprehensive strategy for quantitatively assessment of the protective layers associated with reducing or preventing the domino effects. Thus, a comprehensive vulnerability assessment of these systems, as well as an analysis of the likelihood of exacerbation should exist in the analysis of existing protection systems. In addition, yet there has no comprehensive strategy to evaluate the performance of all classes of active and passive protective layers in reducing the likelihood of occurrence and exacerbation [15-17].

The gas supply network of Tehran metropolis threats can be classified into human, social, economic and sometimes political consequences. Tehran Gas Company should be able to provide dependable services to the largest human community in the capital city of Iran, including various economic, industrial, service, residential, commercial, etc. Therefore, it is of particular importance to limit the hazardous elements and the extent of threats and vulnerabilities. Consequently, increasing resilience in this network decreases the occurrence of various accidents, as well as reducing the rate of various injuries, including industrial, urban, service and natural accidents [18]. Therefore, the present study was designed and conducted with the aim of comparative assessment of the vulnerability of the gas supply network to natural and technological threats in Tehran metropolis.

METHODS

This study was implemented based on the systematic analysis and using the hazard triangle technique to identify system hazards, threats. The vulnerability analysis technique was used to assess the vulnerability of the system to various threats in 2019-2020.

The study population in this study was the gas supply network in one of the areas of Tehran metropolis and the study sample included town board stations (TBS), gas supply network (250 lbf/in^2 or psi), and urban gas distribution network (60 lbf/in^2 or psi).

The TBSs were installed on the boundaries and inside the cities to reduce the gas lines pressure from medium to low pressure. Exhaust gas from the City Gas stations (CGS) is directed to the TBS by power lines and its pressure brakes and reduces during different stages. The inlet pressure to the TBS station is 250 lbf/in2 and the outlet pressure to the station is 60 lbf/in2. With this pressure, the gas is directed to the consumers by urban networks. The regulators then reduce the gas pressure for consumers use to 1.4 lbf /in2. Additionally, TBSs were designed to filter, clean, and reduce gas pressure. The gas supply network is the line that transports gas from CGS to TBS. The urban gas distribution network is a network of gas pipes that transmit gas at low pressure from TBS to consumption points.

Hazard Identification:

Hazards identification in the current study was based on the hazard triangle technique (see Figure 1). The hazard triangle consists of three dimensions: (1) the hazardous element, (2) initiating mechanism, and (3) the target/threat [19-20]. Each hazardous element can lead to one or more threats and consequences. Therefore, the worst case scenario was identified for each hazardous element. These scenarios could be happening due to any source of threats, including natural, technological, and man-made threats.

Furthermore, we used a list of identified high-risk scenarios resulting from the previous studies, records of accidents, information on external hazards, information on hazards, and regional threats related to geographical and security hazards, and information on texts and technical books in the process of identifying threats.

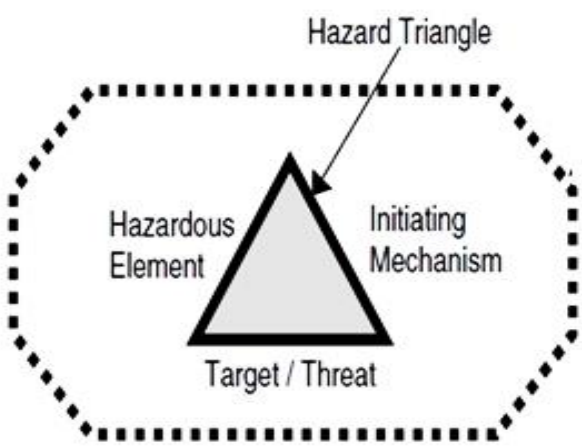

Fig 1. Hazard Triangle

Vulnerability Assessment:

For vulnerability assessment, a vulnerability analysis technique consisting of three factors of likelihood of occurrence, severity of injury, and degree of preparedness against threats was used. It is noteworthy that the purpose of vulnerability assessment in this study was to increase system resilience based on measuring the vulnerability in Tehran metropolis gas network against natural and technological threats, assessing the level of vulnerability of this network against identified hazards and threats, and prioritizing preventive and restrictive measures vulnerability was calculated and estimated based on Equation (1) and Table (1).

Estimation of numbers related to the three factors of severity, likelihood, and preparedness levels were performed based on the levels of threat and tolerable damage by the study organization (Tehran Gas Company) and the opinions of a study team consisting of 22 experts including operation, maintenance, engineering, asset management, technical inspection, health, safety and environment (HSE), crisis and passive defense (Table 1). This estimation was based on the consensus of more than 70% of the members of the vulnerability assessment team. In addition, the assessment of the level of vulnerability of this gas supply network was categorized based on four threat levels including weak, medium, severe, and critical threat levels (Table 2).

$$\boldsymbol{Vulnerability} = \frac{\boldsymbol{Likelihood \times Severity}}{\boldsymbol{Preparedness}} \times \mathbf{10}$$

Equation (1)

Vulnerability: Vulnerability index against the incidence of threats (1-1000)

Likelihood: Frequency of threats during a specified duration (1-10)

Severity: Consequences of the incidence of threats (1-10)

Preparedness: Preparing to face threats (1-10)

Table 1. Level of severity, likelihood, and preparedness factors

Score	Severity (US Dollars, $)	Likelihood (%)	Preparedness (%)
1	Very low, Financial loss<1000	5>	5>
2	Low, No hospitalization, Financial loss<2500	5-10	5-10
3	Hospitalization≤3 days, Financial loss<5000	11-20	11-20
4	Hospitalization≤7 days, Financial loss<10000	21-25	21-30
5	Hospitalization≤14 days, Financial loss<20000	26-30	31-40
6	Hospitalization>2 weeks, Financial loss<30000	31-40	41-50
7	Hospitalization>1 month, Minor limb defects, Financial loss<50000	41-50	51-70
8	Hospitalization>2 months, Critical organ failure, Financial loss<75000	51-60	71-80
9	Hospitalization>3 months, Death 1 person, Financial loss<100000	61-75	81-90
10	Hospitalization>6 months, Death> 1 person, Financial loss>100000	75<	91-100

Table 2. Level of vulnerability

Vulnerability index		Level and type of threat
64≥	Weak	The possible consequences are ultimately within the scope of that event, such as a threat in an area of the gas supply network.
65-124	Medium	The range of consequences is wider, the spread of the threat is estimated beyond the scope of the damage, but within the studied gas supply network.
125-215	Severe	It can threaten and challenge almost the entire the studied gas supply network.
216≤	Critical	Its possible consequences could threaten other gas supply areas.

RESULTS

A total of 11 hazardous elements were identified in the three sections of the studied gas supply network including town board stations (TBS), gas supply network (250 lbf/in^2 or psi), and urban gas distribution network (60 lbf/in^2 or psi).

The findings of the hazard triangle technique showed six hazardous elements related to TBS included insulating connection, shut-off valves, station line pipes, sensors, regulators, and filters, and two hazardous elements including steel feed pipe (medium pressure) and the valves of supply line (medium pressure) were related to supply network (250 lbf/in2 or psi). In addition, three hazardous elements of the urban gas distribution network (60 lbf/in2 or psi) were included gas-carrying steel pipe, gas valve, and riser pipe.

Generally, hazard identification results showed a threat or consequence associated with these hazard elements included earthquake, subsidence, collapse, corrosion and erosion, flood, destruction, gas leakage, fire, explosion, human injury, financial damage, operational interruption, and strategic consequences.

In addition, these results showed that being on a fault, water level lowering, the presence of canals, water network leaks, human error, underground mechanical operations, long life of the gas supply network, improper maintenance, high gas consumption and gas velocity in the pipe, the effects of induced currents in other facilities, the impacts of stray currents, and torrential rains were among the most important processes causing these threats.

The findings of the vulnerability assessment of hazardous elements and identified threats related to the gas supply network showed that out of eleven identified hazardous elements, the vulnerability index of three hazards took place in the weak threat level, the vulnerability index of four hazards was assessed in the medium threat level and the vulnerability index of four identified hazards was estimated in the severe level.

The results related of TBS showed that vulnerability indices of three hazardous elements including shut-off valves, insulation connection, and regulator were equal to 30, 36 and 40 (weak threat level. Additionally, vulnerability indices of two hazardous elements including sensors and station line pipes were evaluated to be 112 and 120 (medium threat level). The results showed that vulnerability of filter hazardous element was estimated to be 140 and in severe threat level (Table 3). In addition, the results of vulnerability analysis technique in the gas supply network (250 lbf/in2 or psi) showed that the hazardous element of the supply line valves (medium pressure) and the hazardous element of steel feed pipe (medium pressure) were estimated in the medium and severe level threat (vulnerability index=80, and 150 (refer to Table 3). Furthermore, the results of the vulnerability assessment related to hazardous elements in the urban gas distribution network (60 lbf/in2 or psi) showed that the vulnerability caused by riser pipe took place in the medium threat (vulnerability index=96) and vulnerability due to two hazardous elements including the gas valve abd gas-carrying steel pipe was calculated to be 125 and 180. Therefore, these two hazardous elements were in the severe threat (Table 3). The results of comparative assessment of the vulnerability of Tehran metropolis gas supply network based on three parts including town board stations (TBS), gas supply network, and urban gas distribution network using Kruskal-Wallis non-parametric test showed that the vulnerabilities in these three parts was different, but this difference was not statistically significant (p>05).

This result showed that the highest vulnerability was related to the urban gas distribution network (133.66±24.63), gas supply network (115.0±35.0), and town board stations (TBS) (79.68±49.51), respectively (Table 4).

Table 3. Findings of vulnerability assessment in the studied gas supply network

Gas Supply Network	Hazardous Element	Likelihood	Severity	Preparedness	Vulnerability Index
TBS	Insulating Connection	4	3	3	36
	Shut-Off Valves	5	2	3	30
	Station Line Pipes	4	6	5	120
	Sensors	4	7	4	112
	Regulators	5	2	4	40
	Filters	5	7	4	140
Gas Supply Network	Steel Feed Pipe	5	6	5	150
	Valves Of Supply Line	4	5	4	80
Urban Gas Distribution Network	Gas-Carrying Steel Pipe	6	6	5	180
	Gas Valves	5	5	5	125
	Riser Pipe	6	4	4	96

Table 4. Findings of comparative assessment of vulnerability

Gas Supply Network	Vulnerability Index	P-value
TBS	79.6849.51	
Gas Supply Network	115.0±35.0	0.326
Urban Gas Distribution Network	133.66±24.63	
Total Of Gas Supply Network	100.81±49.67	

DISCUSSION

The findings of present study indicated that although the average vulnerability in the studied gas supply network was in the medium threat level (average vulnerability index of the studied gas supply network= 100.81±49.67), the vulnerability caused by the occurrence of one-third of these hazardous elements was in the severe threat level (these hazards included filters, steel feed pipe, gas-carrying steel pipe and gas valves). Based on the findings, the level of vulnerability due to natural and technological threats in the studied gas supply network was relatively high, so necessary corrective measures should be designed and implemented to reduce vulnerability and increase the resilience of this important gas supply network. Furthermore, the results of the comparative assessment of vulnerability revealed that the threats posed by the three studied sections in the gas supply network were not significantly different. However, the degrees of vulnerability due to hazardous elements were different in these three areas.

Vulnerability in the technology-based systems was affected by the performance of protective layers. Comprehensive assessment of scenarios of accidents and threats showed that the vulnerability was a reaction due to various causes such as the factors of events incidence, parameters affecting the range of consequences, and the degree of preparedness of a system or organization against threats [21]. Accordingly, a series of laws were set by the EU to assess and prevent the vulnerability of organizations. In addition, several technical standards identify the use of protective systems or layers to reduce the likelihood as well as to control the consequences of catastrophic events. In technology-based systems such as gas supply network, protection of subsystems as well as hardware and software was usually achieved using multi-layers of safety and protection, which includes process control systems, safety systems, active and passive devices, safety shutdown systems, protection systems, and emergency response programs [22].

Furthermore, the special feature of intensifying the occurrence of various catastrophic accidents in technology-based systems such as fire and explosion in gas supply networks showed the role of reliability as well as system resiliency of these pieces equipment will be very important in scenarios that lead to intensification of events. A key point in assessing the likelihood of exacerbation in severe accident scenarios in such systems was that in most cases both incidence and severity factors may be corrected by the installation of appropriate protective layers and emergency measures. Therefore, a thorough assessment of the likelihood of exacerbation should include an analysis of existing protection systems. However, there is still a lack of a comprehensive strategy for quantitative assessment of the protective layers involved in reducing or preventing vulnerability and promoting resilience. In addition, the lack of a comprehensive strategy to evaluate the performance of all classes of active and passive protective layers in reducing the likelihood and severity of vulnerability indicates a major unresolved challenge [23-24].

Based on the findings and the requirements of design and implementation preventive protective layers, it is recommended to consider measures such as design and installation of emergency shut-off valves at the inlet and outlet of town board stations (TBS) outside the stations, establishing a remote control mechanism, designing and increasing network emergency shut-off valves, installation of sensors to detect gas leakage, vibration and movement of pipes for gas supply and distribution networks, ensuring the existence of GIS maps, availability of technical information and mechanism of valves closing, and rescuers complete understanding about mechanism of valves closing [25-26].

Furthermore, vulnerability in different parts of gas supply network could be decreased by designing and implementing a reducing protective layer such as the use of good and qualified materials, retrofitting, a comprehensive radiographic program, close monitoring of routine and non-routine activities, ensuring that input lines are not stressed, the use of new technologies to increase resiliency to all kinds of threats (such as non-steel pipes), reviewing and analyzing gas flow and analyzing gas velocities in pipelines, reducing network pressure during low consumption and opening and closing valves with remote control [26-27].

CONCLUSION

The findings of this study indicated that the resilience of the studied gas supply network was low due to the occurrence of the hazardous elements, threatening centers, and the results obtained from the evaluation and calculation of the vulnerability caused by each of these hazardous elements. These findings revealed that despite the insignificance of the differences between the three parts of studied gas supply network, the level of vulnerability in this network was relatively high and the occurrence of threats due to these hazardous elements can cause severe damage to this system. In addition, there may be side effects including human, financial, social, and political effects.

The findings of this vulnerability analysis and comparative assessment of vulnerabilities between the hazard centers showed that the resilience of different parts of the gas supply network including TBS, gas supply network, and urban gas distribution network was relatively low and requires more attention to reduce vulnerability in the gas supply network in the Tehran metropolis. Additionally, these results indicated that improving resilience and reducing vulnerability can be achieved by attention to different factors and parameters, as well as technical and managerial attention to protective layers with different functions. Therefore, resilience in the gas supply network should be analyzed with models such as what was evaluated in this study. As such, improvement of the resilience of the gas supply network system will be available by considering these findings and addressing these challenges.

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CONFLICT OF INTEREST

The authors declare that they had no conflict of interest in this study.

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