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Research article

# Using fuzzy cognitive map in bow tie method for dynamic risk assessment of spherical storage tanks: A case study

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ABSTRACT

The present study aimed to perform a dynamic risk assessment of liquefied petroleum gas (LPG) in spherical storage tanks using the Hazard and Operability (HAZOP) method. The "LPG release from spherical storage tank" scenario was determined to be a top event based on the risk level. The causes and consequences of this scenario were then specified using the Bow-Tie method. Additionally, fuzzy cognitive mapping (FCM) was utilized to identify the most critical threats, consequences, and effective barriers in a dynamic approach. Results showed that fracture/rupture in pipelines/a storage tank due to fire had the highest output degree and was identified as the most influential threat in the occurrence of the LPG release. Fatality/injury due to fire and explosion had the highest input degree and was more influenced by the release of LPG as the main consequence in the selected scenario. The findings of this study enabled us to make a logical decision about effective barriers for avoiding and minimizing the release of LPG and its threats and consequences based on the fuzzy cognitive map. Moreover, the results of this study showed that the FCM method could determine the most critical nodes with a higher degree and represent their relationships.

## 1. Introduction

Chemical Process Industries (CPIs), such as refineries and petrochemical industries, have elaborate systems in which chemical reactions occur at high temperatures and pressures, processing raw materials into products [1,2]. Different types of tanks are used to store the various compounds in CPIs, and the hazards associated with these tanks vary according to the chemical substance and type of storage; any defect can lead to chemical release from tanks, pipes, joints, or other equipment [3].

One type of tank is a pressure vessel. Designing these storages is hugely crucial, as any event can lead to injury, fatality, property damage, environmental damage, or a combination of them. One chemical substance that is in gas form at normal temperatures and at atmospheric pressure and is stored in pressure vessels is liquefied petroleum gas (LPG). LPG is a colorless, odorless (if pure), non-corrosive, water-insoluble gas, with a boiling point above −44 °C, vapor pressure above 1atm, high flammability, and explosion

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limits of 1.5–9.9% [4].

LPG consists of light hydrocarbons with vapor pressures of above 40 $lb/m^2$ at 100 °F. The most important constituents of LPG gases are propane, butane, or a mixture. LPG's vapor is heavier than air, consequently, tends to accumulate on the ground, settle in low spots, and not dissipate into the air [4]. Examples of events associated with LPG include those in Ludwigshafen, Germany (1984), Port Newark, New Jersey (1951), Indianapolis, Indiana (1963), Feyzin, France (1966), Rast Saint, Illinois (1972), Kingman, Arizona (1973), Texas City, Texas (1978), Romeoville, Illiinois (1984), and San Juan Ixhuatepec, Mexico City (1984) [5]. Therefore, it is essential to determine the potential risks associated with the release of LPG in CPIs.

A Hazard and Operability (HAZOP) study was utilized as an appropriate risk assessment to prevent such events. To do this, the study integrated the Bow-Tie method (BT) with the Fuzzy Cognitive Map (FCM) to determine the most critical barriers for the LPG tank. Consequently, the objective of this study was to identify the worst-case scenario of LPG spherical storage tanks using the HAZOP technique, determine the causes and consequences of this scenario through the BT method, and identify the most critical threats, consequences, and effective barriers as a dynamic approach using the FCM.

We have organized this paper as follows. Section 2 reviews the relevant literature concerning the HAZOP, BT and its drawbacks, and FCM in three separate subsections. Section 3 discusses the study method and provides information on the location (field) of the study, a description of the storage tanks, HAZOP, Standard BT (SBT), and FCM. Section 4 presents the findings of the study. Section 5 discusses the results and provides a discussion of the study. Finally, Section 6 offers the conclusion.

### 1.1. Literature review

This stage of the study reviewed the literature related to the HAZOP, BT, and FCM techniques, which is presented as follows.

#### 1.1.1. The Hazard and Operability study

Considering the discussions above, failures in process industries can have disastrous outcomes, and thus, it is necessary to identify potential hazards and take necessary steps to minimize their likelihood. Various risk assessment methods have been developed [6], with the HAZOP study technique being the most impressive and accepted in process industries [7]. The HAZOP method is a systematic and structured approach developed for analyzing chemical process systems. In this method, a team with knowledge and experience of the specific process divides the different parts of the process into smaller parts called nodes using a piping and instrumentation diagram (P&ID) and a process flow diagram (PFD) [8,9]. They also identify possible deviations of operational parameters (such as temperature, pressure, flow, transfer, viscosity, PH, level, and other parameters) through questions using guide words (e.g. no, more, less, reverse, as well as, and so on) [9]. This method has been employed in different studies to assess a complex hydrogen production system [10], a sour crude-oil refinery [11], a sewage sludge granulation process [12], and petrol (gasoline) release in a petrochemical plant [13]. In all of these studies, the HAZOP method was combined with other methods. The HAZOP method has a section-by-section and inductive approach, focusing on the causes of an event resulting from one deviation and may not identify hazards common among different groups. Therefore, to compensate for this shortcoming, the BT method is used to identify hazards resulting from two or more separate deviations [14,15].

#### 1.1.2. Bow-tie method

The BT method is widely used to assess process safety, risk assessment, and management in incidents. Moreover, this method illustrates the relationship between causes and incident scenarios [16,17]. It also depicts the association between all initiating events and the consequences of a specific scenario along with the safety barriers used to prevent, control, or mitigate an event [18,19]. Numerous studies related to process industries such as those on LPG storage risk assessment [20], and the improvement of natural gas pipeline risk management [21], have identified major causes and consequences of condensate gas leaks [17], and have made use of this method. One new model of the BT is the Standard Bow Tie (SBT), which is a standardized model introduced by the Chemical Center of Process Safety (CCPS) and the Energy Institute (EI) [22]. In the SBT method, the Top Event (TE) and hazard are at the center, and threats (causes or initiating events leading to the TE), preventive barriers (PB), degradation factors (DF), and degradation controls (DC) are on the left; while consequences, mitigation barriers (MB), degradation factors (DF), and degradation controls are on the right.

Despite the advantages of the BT method, there are some disadvantages such as its limited capability for dealing with uncertainties, multi-state variables, and failures associated with the use of simple Boolean functions in analyzing the fault tree, the use of deterministic probability values, and the inability to model complex correlations between variables [15,23], as well as its purely static nature [24]. These limitations have led to more advanced safety assessment methods in recent years that are dynamic. For instance, Khakzad et al. [25] used Bayes' theorem for dynamic risk analysis in the BT method; Ferdous et al. [19] developed a dynamic safety and risk assessment under uncertainty using a bow-tie diagram; Abimbola et al. [26] proposed a dynamic safety assessment approach based on the BT and real time barriers failure probability assessment; Xin et al. [6] utilized a dynamic methodology to identify hazards and scenarios using a Bayesian network; Chang et al. [27] performed a dynamic risk analysis based on the mapping of the BT into a Bayesian network; Li et al. [28] showed a risk assessment based on the fuzzy Bayesian network for mine ignition sources; Wu et al. [29] presented a dynamic Bayesian risk analysis for modelling the influence of uncertainty in accident probability and consequences, which is reflected in failure rates; Borgheipour et al. [30] determined the type and relationship between the effective causes of catastrophic accidents by integrating the BT technique and Bayesian network; Pang et al. [31] also used a dynamic Bayesian network-based reliability in safety assessment of subsea Christmas tree; and Sarvestani et al. [32] developed a dynamic Bayesian risk assessment for propane storage tanks. In this regard, Zarei et al. [33] proposed a dynamic approach for analyzing the event of hydrogen release scenarios, which used the BT technique and Bayesian network in integration with improved D Numbers Theory and Best-Worst

Method. Furthermore, Qing-Yun Zhou et al. [34] used the BT model to determine key risk factors of storage tank failure in oil depots, and then fuzzy set theory and expert judgments were used to calculate the probability of basic events, after which the model was mapped to a Bayesian network. In addition, Souvik Das et al. [35] used a BT in integration with a type II fuzzy set for risk quantification.

### *1.2. Fuzzy cognitive maps*

In addition to the descriptions above, the possibility theory and experts' opinions based on fuzzy logic [28,36,37] as well as FCMs are suitable for decreasing uncertainties and updating the probability of events and their consequences in event scenarios. FCMs have been used in various studies for advanced risk assessment in complex and dynamic systems [38], assessment of influential factors in accidents [39], failure prioritization in systems [40], assessment of resilience engineering factors in high-risk environments [41], risk perception determination [42], assessment of risk factors for garlic cancer [43], selection of a suitable site for mineral processing plants [44], prediction of the reputation risk for pharmaceutical supply chains [45], identification of potentially dangerous effects of pesticides on the environment [46], and assessment of the potential risks of workplace accidents in underground mining [47].

Robert Axelrod first introduced cognitive maps in the field of political science in 1976 [38], which are directed graphs used to present the relationships between cause and effect in the variables of the nodes [48]. Fuzzy cognitive mapping is a soft computing technique combining fuzzy logic and neural networks and has the potential to deal with complex systems in different situations using

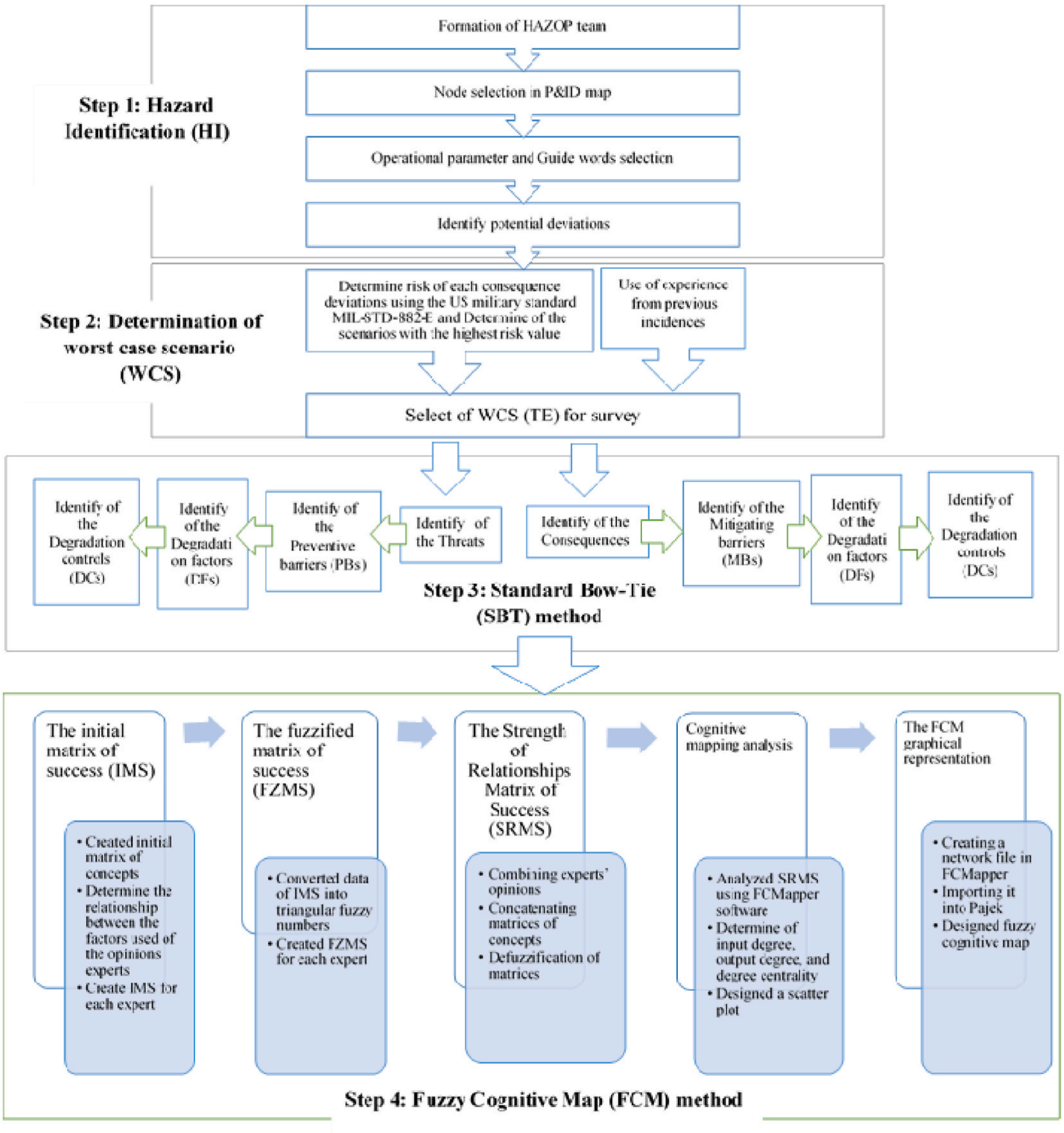


**Fig. 1.** Main steps of the study.

logical processes that contain features of uncertainty and ambiguity; moreover, this method can transition from a static and inflexible tool to a dynamic and flexible one [49]. FCM is considered one of the practical artificial intelligence techniques for making decisions [43], and has been successfully used to assess risks in complex and critical environments [38]. Through the opinions of experts, this technique can identify the most influential indicators by considering the interdependencies of the factors on each other [46] leading to the determination of the most essential and appropriate selection by ranking several factors [44]. Therefore, with its capacity to present the correlation among various factors, FCM can assess the importance of different barriers in risk assessment and provide stakeholders with helpful information for controlling the release of LPG in the petroleum industry.

## 2. Material and methods

Considering the hazards associated with LPG spherical storage tanks, the present study was conducted in 2019 at an oil refinery in Iran to assess the risks and perform a dynamic risk assessment regarding LPG release. The HAZOP method and a risk ranking were used to identify and specify the worst-case scenario. Subsequently, the causes and consequences of the scenario were specified using SBT, and a cognitive map of the worst-case scenario was designed in FCMapper software [50] and Pajek Vs. 5.11 [51]. The main steps of the study are shown in Fig. 1.

### *2.1. Case study: spherical storage tank*

The study focused on the LPG spherical storage tanks of the refinery. These tanks were fed with LPG through a 10-inch pipe, either from blending or directly from the LPG-producing unit. The specifications of the tanks are presented in Table 1.

Each tank was equipped with a Radar Level Transmitter (RLT) and a Multipoint Temperature Element (MPTE) connected to the Tank Gauging System (TGS). Other separate radar level transmitters are available, showing high and low levels, and an on-off valve, along with associated pumps. The control room controlled the low/high level and temperature indicator alarms, and level indicators were also locally available. Each tank also had two 50% Pressure Safety Valves (PSVs) set at 18.8 bars, designed for fire conditions, as well as a regular inlet/outlet line with an Emergency Shutdown (ESD) valve. The storage tank's volume was between the high liquid level and the low liquid level. Fig. 2 illustrates the process of the unit mentioned above.

### *2.2. Hazard identification*

A HAZOP team of professionals was formed to obtain technical data, and according to the P&ID map, the storage tank was identified as a node. The experts of the study included a site process engineer, a maintenance engineer, a mechanical engineer, a safety engineer, a chemical engineer, an operability engineer, and an instrumentation engineer. Subsequently, the potential deviations from design intents, their possible causes, and consequences were identified, and necessary recommendations were made to eliminate them. In this stage, possible deviations were determined using a combination of operational parameters and guidewords [9,52,53].

### *2.3. Determination of a worst-case scenario (WCS)*

Critical points were identified in this study based on experience gained from prior incidents in the industry and similar industries. Experts' knowledge was relied upon to identify hazards using the HAZOP method and rank them. Severity (S) and probability (P) of deviations were determined, and the resulting risk (R) was calculated using the US Military Standard MIL-STD-882-E (Table 2Table 3) [7]. The scenarios with the highest risk value were considered the Worst-Case Scenarios (WCSs) and used in the SBT analysis.

### *2.4. Standard bow-tie (SBT) method*

CCPS's standard method [22] is among the new BT methods and consists of the following parts (Fig. 3):

- Top Event (TE): The event between the threats and consequences in the SBT diagram which can lead to adverse outcomes, resulting from the loss of control of the hazards.
- Hazard: An activity, operation, or material with the potential to cause harm to people, equipment, environment, or the business.
- Threats: Causes or initiating events leading to the TE.
- Preventive Barriers (PB): Barriers preventing a threat from becoming a TE.
- Degradation Factors (DF): Factors reducing the effectiveness of PB and MB. DFs cannot directly lead to a TE.
- Degradation Controls (DC): Controls that lack PB and MB characteristics but act as barriers to DFs.

**Table 1**
Specifications of spherical LPG tanks.

| Tag | Product | Diameter (m) | Pressure (Bar) | | Temperature ($^0$C) | | Net capacity (m$^3$) |
|---|---|---|---|---|---|---|---|
| | | | Operating | design | operating | design | |
| SPH-X1/X2/X3/X4 | LPG | 19.4 | 8.2 | 18.8 | 40 | 85 | 3180 |

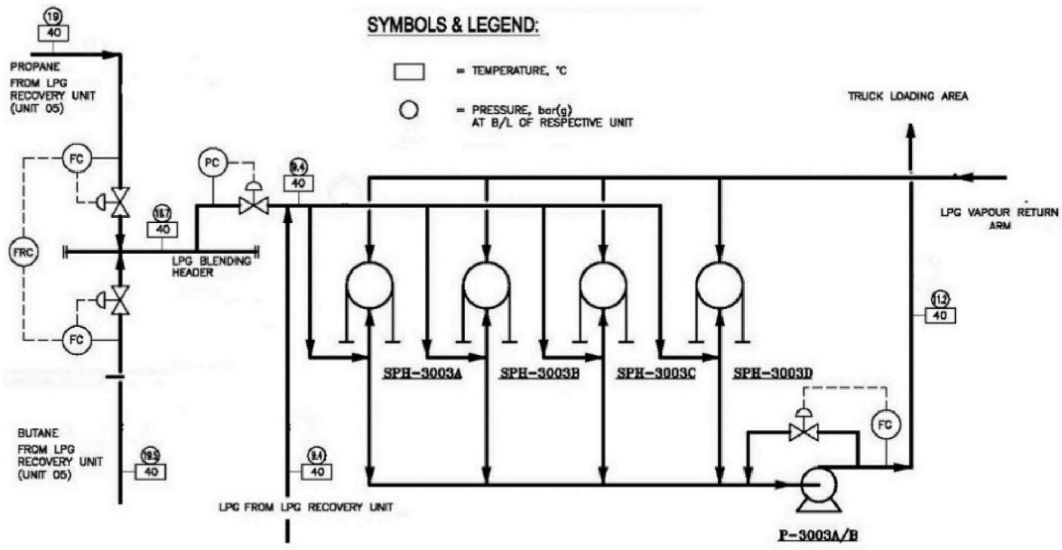


**Fig. 2.** Process of the LPG storage unit in the company.

**Table 2**
Risk assessment scoring matrix [7].

| Probability | Severity | | | |
|---|---|---|---|---|
| | Catastrophic (1) | Critical (2) | Marginal (3) | Negligible (4) |
| Frequent (A) | High (1A) | High (2A) | Serious (3A) | Medium (4A) |
| Probable (B) | High (1B) | High (2B) | Serious (3B) | Medium (4B) |
| Occasional (C) | High (1C) | Serious (2C) | Medium (3C) | low (4C) |
| Remote (D) | Serious (1D) | Medium (2D) | Medium (3D) | low (4D) |
| Improbable (E) | Medium (1E) | Medium (2E) | Medium (3E) | low (4E) |
| Eliminated (F) | Eliminated (1F, 2F, 3F, 4F) | | | |

**Table 3**
Decision criteria based on risk level [7].

| Risk level | Risk index |
|---|---|
| **High risk** | 1A, 1B, 1C, 2A, 2B |
| **Serious risk** | 1D, 2C, 3A, 3B |
| **Medium risk** | 1E, 2D, 2E, 3C, 3D, 3E, 4A, 4B |
| **Low risk** | 4C, 4D, 4E |
| **Eliminated** | 1F, 2F, 3F, 4F |

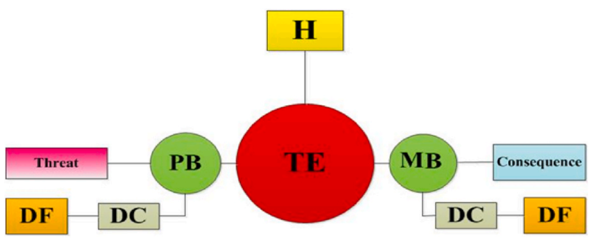


**Fig. 3.** Elements of the SBT diagram [22].

- Consequences: Results from TE occurrence in case of MBs failure.
- Mitigating Barriers (MB): Barriers preventing TE from leading to consequences.

The required information for the SBT was acquired by investigating the process and interviewing experts working in the unit, and the SBT diagram was designed using Microsoft Visio 2010.

### 2.5. Fuzzy cognitive map (FCM) method

The FCM was used to identify and model causal relationships and correlations between causes, TEs, consequences, and the like. In addition to identifying the type of relationship between different factors, the impact of variables on each other was determined using weighted arcs (Fig. 4). After identifying and determining the causes and consequences of critical events, the inputs were specified using expert knowledge and experience. Ci and Cj were considered as two nodes, and the weight of the arcs was equal to Wij, an m × n matrix with a value in the [−1, 1] interval. Therefore, Wij represents the direct or inverse relationship between the two nodes. Moreover, its value can be greater than zero (showing a positive causal relationship between two concepts), equal to zero (no relationship), or less than zero (negative causal relationship) [48,49]. The degree is the sum of all direct relationships between a node and others in the network. In this model, the value of each repeating node was calculated using Eq. (1).

$$A_i^{(k+1)} = f\left( A_i^{(k)} + \sum_{\substack{j=1 \\ j \neq 1}}^{n} W_{ij} A_j^{(k)} \right) \tag{1}$$

In this equation, $A_i^{(K+1)}$ is the value of Ci in thek+1 repetition, $A_i^k$ is the value of Ci in the k repetition, and f(x) is the normalization function; f is the threshold function to ensure the conversion of the node value in [0, 1] interval and is shown as Eq. (2). In this equation, a $\lambda$ value greater than zero determines the slope of the continuous function [48,49].

$$f(x) = 1/(1 + e(-\hat{\lambda} x)\ ) \tag{2}$$

In this study, the approach of study [54] was used to determine the relationships between causes/threats and consequences and create FCM as follows:

#### 2.5.1. The initial matrix of success (IMS)

At this stage, the initial matrix of threats and consequences was created based on the SBT diagram. To determine the relationship between the factors, the opinions of 10 experts were used. The experts used the range provided in Table 4 to determine the relationship between the factors, and the acquired data was entered into each expert's IMS for causes and consequences.

#### 2.5.2. The fuzzified matrix of success (FZMS)

The data collected in the previous stage was converted into triangular fuzzy numbers using the range of Fig. 5 and Table 5. Triangular numbers were chosen due to their simplicity and fluency, which have been used in many studies [43–46].

#### 2.5.3. The strength of relationships matrix of success (SRMS)

This stage included combining the experts' opinions, concatenating matrices of causes and consequences, and defuzzifying the matrices. To combine the experts' opinions, the ordered weighted averaging (OWA) operator was used, which is equivalent to the arithmetic mean in mathematics. The weight of the experts was considered to be equal [55]. Furthermore, the centroid method (the center of gravity) was used for the defuzzification of the matrices [43].

#### 2.5.4. Cognitive mapping analysis

The strength of the relationships matrix of success was analyzed using the FCMapperVs. 1.0 software. The outputs of this software include input degree, output degree, and degree centrality. The output degree indicates the strength and impressiveness of a node in the network, and higher values mean that this factor affects more factors. These factors are root causes, and therefore, managing such nodes can reduce the occurrence of other nodes. A high input degree shows the popularity of a node in the network, and due to the

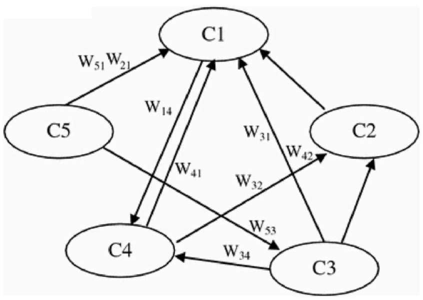


**Fig. 4.** Sample fuzzy cognitive mapping [48].

**Table 4**
Ranges used by experts to determine the degree of relationship between Concept in SBT [54].

| Negative connection | | | | | Positive connection | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Very high | high | Medium | Low | Very low | Very low | low | Medium | High | Very high |
| −5 | −4 | −3 | −2 | −1 | 1 | 2 | 3 | 4 | 5 |

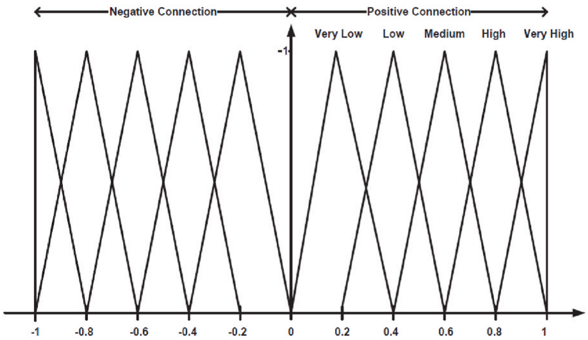


**Fig. 5.** Linguistic fuzzy sets [54].

**Table 5**
Linguistic variables for the ratings [54].

| Linguistic variables | Intuitionistic fuzzy numbers |
|---|---|
| Very High Positive | (0.8, 0.9, 1) |
| High Positive | (0.6, 0.75, 0.9) |
| Medium Positive | (0.3, 0.5, 0.7) |
| Low Positive | (0.1, 0.25, 0.4) |
| Very Low Positive | (0, 0.1, 0.2) |
| Very Low Negative | (-0.2, −0.1, 0) |
| Low Negative | (-0.4, −0.25, −0.1) |
| Medium Negative | (-0.7, −0.5, −0.3) |
| High Negative | (-0.9, −0.75, −0.6) |
| Very High Negative | (-1, −0.9, −0.8) |

strong correlation of these groups, they are challenging to manage. The sum of each factor's input and output degrees is called degree centrality [56–58]. In order to compare the factors in each group, a scatter plot was designed in Microsoft Excel 2016 and divided into four areas, each of which is interpreted as follows [57,58]:

**Table 6**
Threats, Preventive Barriers, degradation controls, and degradation factors in the LPG release from spherical storage tank scenario.

| | |
|---|---|
| Threats (T) | Leakage due to storage tank overfill ($T_1$), storage tank rupture due to overpressure ($T_2$), sampling valve left open by the operator ($T_3$), leakage due to rupture in storage tank joints ($T_4$), fracture in the storage tank wall and pipelines due to damage caused by external object/contractors ($T_5$), fracture/rupture in indirect pipelines and vents due to erosion-corrosion ($T_6$), fracture/rupture in pipelines or storage tank due to sabotage ($T_7$), fracture/rupture in pipelines or storage tanks due to fire ($T_8$) |
| Preventive Barriers (PB) | Installing level transmitters, which alarm in 16670 mm level and close the inlet valve and shuts down the transfer pumps ($PB_{1.1}$), installing control valves on the storage tanks for vapor discharge ($PB_{1.2}$), balancing lines between spherical storage tanks ($PB_{2.1}$), installing two PSVs on each spherical storage tank ($PB_{2.2}$), selecting qualified personnel ($PB_{3.1}$), installing two PSVs on each spherical storage tank ($PB_{4.1}$), issuing permit to work and monitoring operations ($PB_{5.1}$), selecting qualified personnel for operations ($PB_{5.2}$), periodic (routine) inspections ($PB_{6.1}$), implementing passive defense/limiting peopl's movements ($PB_{7.1}$), issuing permit to work and monitoring operations ($PB_{8.1}$), designing and installing storage tanks and pipes according to standards ($PB_{8.2}$), providing automatic fire suppression systems ($PB_{8.3}$), controlling and eliminating causes of spark ($PB_{8.4}$) |
| Degradation Controls (DC) | Periodic inspection and calibration ($DC_{1.1.1}$), periodic inspection and calibration ($DC_{2.2.1}$), training ($DC_{2.2.2}$), assessment of design documents by the engineering team ($DC_{2.2.3}$), creating and implementing standard operational instructions ($DC_{3.1.1}$), training ($DC_{3.1.2}$), periodic inspection and calibration ($DC_{4.1.1}$), creating and implementing standard operational instructions ($DC_{5.1.1}$), training ($DC_{5.1.2}$), training ($DC_{5.2.1}$), creating and implementing passive defense instructions ($DC_{7.1.1}$), training ($DC_{7.1.2}$), having periodic drills and exercises ($DC_{8.3.1}$), periodic inspections ($DC_{8.3.2}$) |
| Degradation Factors (DF) | Corrosion overtime ($DF_{1.1.1}$), damage to PSV spring ($DF_{2.2.1}$), wrong choice of PSV ($DF_{2.2.2}$), human error ($DF_{3.1.1}$), damage to PSV spring ($DF_{4.1.1}$), improper implementation of operational instructions ($DF_{5.1.1}$), human error ($DF_{5.2.1}$), human error ($DF_{7.1.1}$), human error ($DF_{8.3.1}$) |

- High output degree -high input degree: These factors are responsible for changes due to their strong impact; therefore, managing these factors greatly affects the prevention of TE; however, their high susceptibility makes them challenging to manage.
- High output degree -low input degree: These factors affect other connected factors easily and are more controllable due to their low susceptibility; therefore, they can be managed effortlessly.
- Low output degree -high input degree: These factors are highly susceptible but have a low effect on other factors; therefore, they are challenging to manage.
- Low output degree -low input degree: These factors are insignificant in management plans.

*2.5.5. The FCM graphical representation*

After that, the fuzzy cognitive map was designed by creating a network file (net-file) in FCMapper software and importing it into Pajek Vs.

## 3. Results

In order to determine the TE in spherical storage tanks, the risk resulting from each consequence was calculated after performing HAZOP using the US Military Standard MIL-STD-882-E. According to the HAZOP results, the “pressure vessel” was identified as a hazard, and the “LPG release from spherical storage tank” scenario was identified as a critical TE. After determining the value of risks resulting from different consequences using the HAZOP method and determining TE, the causes leading to TE and PBs, DCs, and DFs associated with each cause (Table 6) and the outcomes resulting from the TE and MBs, DCs, and DFs associated with each consequence (Table 7) were determined. Additionally, the SBT diagram was designed using Microsoft Visio, which is presented in Fig. 6.

In this stage, the SBT diagram of LPG release from the spherical storage tank scenario was created, and initial matrices of success (IMS), a fuzzified matrix of success (FZMS), and strength of relationship matrix of success (SRMS) were created to determine the relationship between causes and effects. Subsequently, the SRMS was analyzed using FCMapper. The output and input degrees of causes and consequences leading to TE were presented in Figs. 7 and 8, and Table 8 respectively. In Fig. 7, threats with the highest input and output degrees indicate that they are the most susceptible and effective factors (on the left side of TE factors). Additionally, threats with lower output and input degrees are of lower importance for management. Furthermore, PBs with high output degrees are effective barriers in preventing threats from becoming TE.

According to Fig. 8, C2 and C1 have the highest input degrees among consequences (on the right side of the TE factors). In addition, factors including MBs have high input and output degrees. Moreover, DFs and DCs for PBs and MBs were shown in Figs. 7 and 8. In each line, DFs with the highest input and output degrees indicate that they are important, as these factors reduce the effectiveness of PBs or MBs; thus, it is recommended to strengthen or change the DCs in these lines. Furthermore, the graphical model of LPG release from a spherical storage tank scenario was designed as presented in Fig. 9. This figure depicts the relationship and effect of the factors on one another, with black lines showing positive effects; and black dotted (dashed) lines showing negative effects. The direction of the directed lines indicates the direction of factors’ effects on one another.

## 4. Discussion

This research demonstrated an attempt to use HAZOP to identify the most important top event as the worst possible scenario for the LPG in a refinery. Using the HAZOP method and considering the consequences of process deviations, the risks resulting from process deviations were classified into three groups with different levels of risks, and considering the result with the highest risk, the “LPG release from a spherical storage tank” was regarded as the TE for further investigation. This is due to its significance in the identification of process hazards [59], as demonstrated by studies conducted by Refs. [11,20,60]. Thus, the HAZOP method was employed to identify hazards in this study. Aliabadi et al. [20] used the HAZOP method to determine the TE in spherical storage tanks and identified

**Table 7**

Consequences, mitigating barriers, degradation controls, and degradation factors in the LPG release from spherical storage tank scenario.

| | |
|---|---|
| Mitigating barriers (MB) | Eliminating and prevention of potential Ignition source ($MB_{1.1}$/$MB_{2.1}$), activating the F&G system and emergency shut down for isolating spherical storage tanks ($MB_{1.2}$/$MB_{2.2}$), Fire and gas alarm and peoples Escape and evacuation ($MB_{2.3}$), first aid/medical response ($MB_{2.4}$), Evacuation of the hazard zone ($MB_{2.5}$) |
| Degradation Controls (DC) | Prevention of using electrical devices ($DC_{1.1.1}$/$DC_{2.1.1}$), using lightning protection systems ($DC_{1.1.2}$/$DC_{2.1.2}$), bounding and grounding of storage tanks and equipments ($DC_{1.1.3}$/$DC_{2.1.3}$), selecting proper of vehicles (Internal combustion engine) ($DC_{1.1.4}$/$DC_{2.1.4}$), preventing smoking, using matches, etc. ($DC_{1.1.5}$/$DC_{2.1.5}$), controling maintenace activities that can cause sparks/hot surfaces/naked flames ($DC_{1.1.6}$/$DC_{2.1.6}$), Restricting the use of vehicles ($DC_{1.1.7}$/$DC_{2.1.7}$), F&Gas detection and push the ESD button in control room ($DC_{1.2.1}$/$DC_{2.2.1}$), F&Gas detection and close manually shut-off valves by operators for isolate the spherical storage tanks ($DC_{1.2.2}$/$DC_{2.2.2}$), detection by the operator (e.g. during inspection) and responding to the circumstance ($DC_{1.2.3}$/$DC_{2.2.3}$), Fire and Gas detection and Automatic fire system activation ($DC_{1.2.4}$/$DC_{2.2.4}$), detection of fire and gas and use of manual fire protection systems such as hydrants, monitor nozzles, …($DC_{1.2.5}$/$DC_{2.2.5}$), communication equipment ($DC_{1.2.6}$/$DC_{2.2.6}$), taking action according to emergency instructions ($DC_{2.4.1}$), communication equipment ($DC_{2.4.2}$), use of medical equipment from other companies ($DC_{2.4.3}$) |
| Degradation Factors (DF) | Not following operational insttrcutions/human error ($DF_{1.1.1}$/$DF_{2.1.1}$), system does not function correctly (deficiency in detection or spherical storage tank isolation) ($DF_{1.2.1}$/$DF_{2.2.1}$), human errors ($DF_{2.4.1}$) |
| Consequences (C) | Damage to the process unit due to fire and explosion ($C_1$), fatality/injury due to fire and Explosion ($C_2$), Safe dispersion of chemicals ($C_3$) |

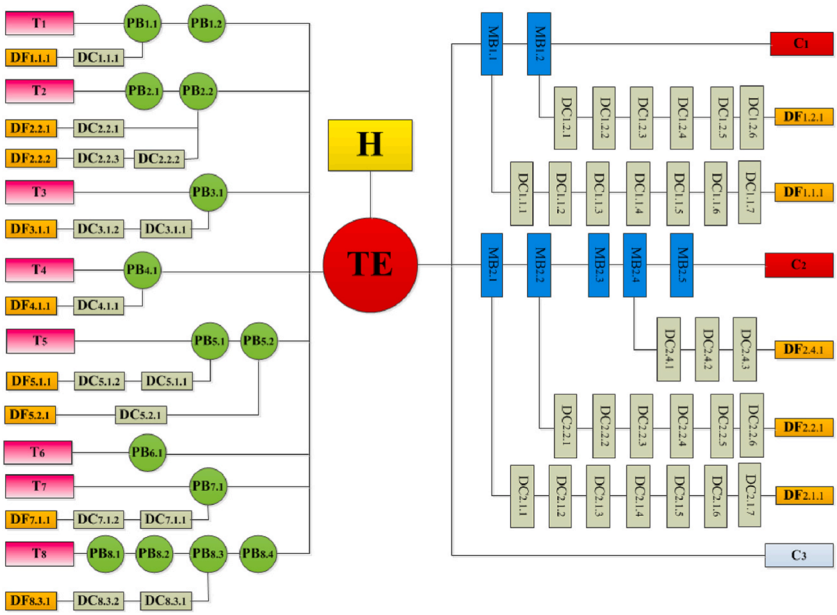


**Fig. 6.** SBT diagram "LPG release from spherical storage tank" scenario.

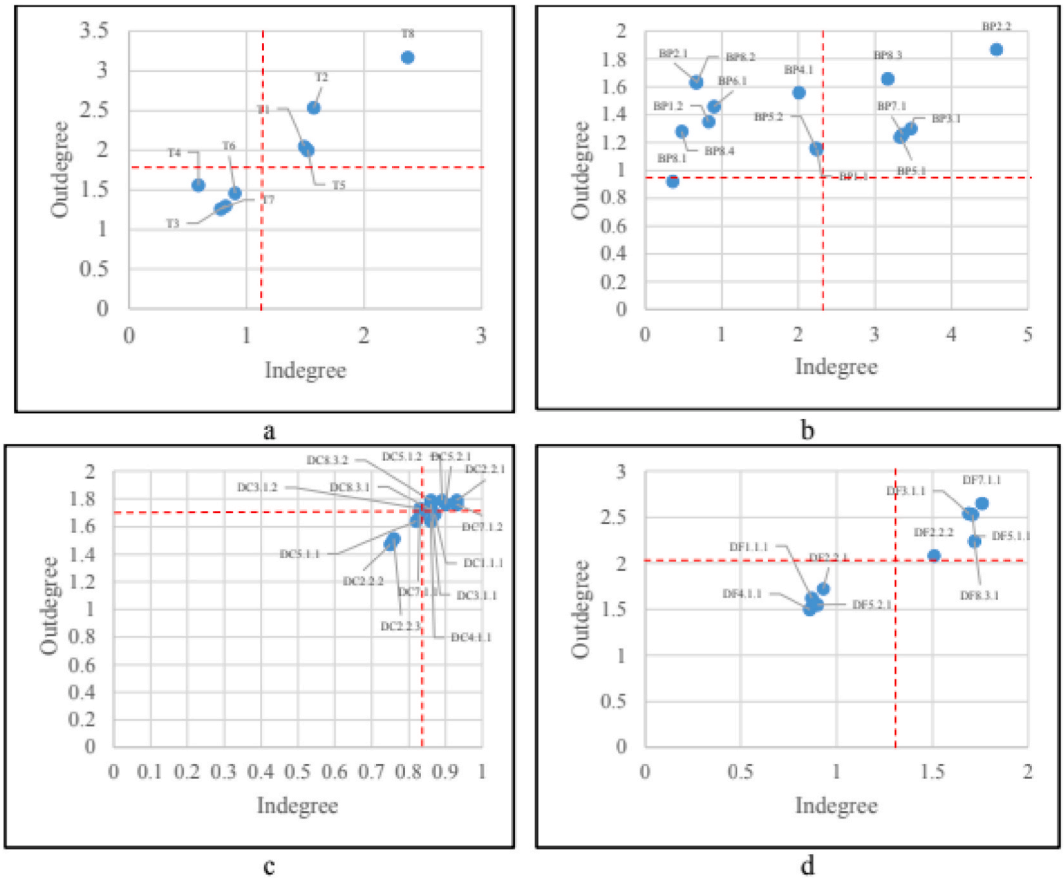


**Fig. 7.** Scatter plot graphs of output and input degrees a) Threats, b) Preventive Barriers c), Degradation Controls, d) Degradation Factors.

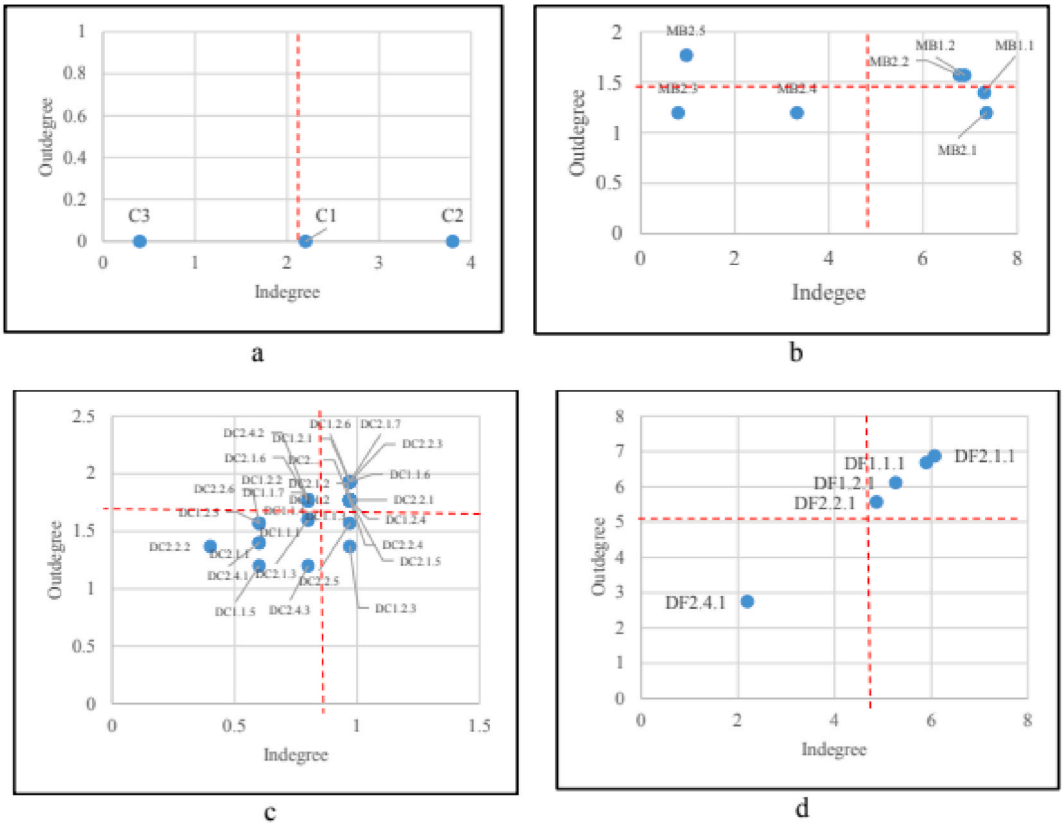


**Fig. 8.** Scatter plot graphs of output and input degrees a) Consequences, b) Mitigating Barriers, c) Degradation Controls, d) Degradation Factors.

LPG release from storage tanks as the TE. Similarly, Ouache and Adham [61], in their study on storage tanks containing flammable substances, identified LPG release from spherical storage tanks as the TE.

The main factors leading to TE, causes leading to TE, negative consequences of TE, PBs, MBs, DCs, and DFs were identified using the SBT method. Aliabadi et al. [20] in their LPG release study using BT identified the causes leading to TE and Zhao et al. [62] demonstrated failures of valve sealing, flange sealing, and tanks as the main causes of LPG leakage when assessing the hazards of explosion and fire incidents in spherical storage tanks by the BT method. The relationship and effect of the factors on each other were identified using the opinions of experts and the FCM method [20,25,25–27,30,33–35], which provided an understanding of the factors influencing LPG release and the relations between different barriers, helping decision-makers determine the important nodes in preventing the LPG incident. Utilizing the FCM to determine the critical nodes in the LPG release is a helpful method for developing dynamic approaches based on computer models, which has been approved by other studies [63,64].

Khanzadi et al. [57] indicated that "changes in plans, scope, specifications, and design" had higher output and input degrees, which affected the probability of other factors of change in construction projects. However, due to its high input degree (influenced by other factors of change), changes were challenging to manage. Nasirzadeh et al. [58] showed that factors such as "workforce knowledge, the satisfaction of project neighbors, giving responsibility to employees, and considering sustainability principles in housing policy" with higher input and output degrees should be given priority for social sustainability, although due to their high input degree, they were difficult to manage. Moreover, Mago et al. [63] indicated that education with the highest degree was the strongest social factor that affects homelessness.

According to determining the relationships between threats using the FCM, fracture/rupture in pipelines or storage tanks due to fire ($T_8$) was identified as the most influential factor in the occurrence of the LPG release, having the highest output degree. The study by González-González et al. [65] showed that nodes with the highest output degrees strongly influence other nodes in a system. Thus, it is important to consider high-reliability barriers and sufficient degradation controls with the least failure in order to control this threat (fracture/rupture in pipelines or storage tanks) as much as possible. In addition, other threats including storage tank rupture due to overpressure ($T_2$), leakage due to storage tank overfill ($T_1$), and fracture in the storage tank wall and pipelines due to damage caused by external objects/contractors ($T_5$) had higher output and input degrees. The high output degrees represented the vital role of these threats, which could be considered as root causes for the LPG release, and therefore, were crucial to be managed due to their critical impact on the LPG release. However, their high input degree proved that they were challenging to manage, and also demonstrated their significance in controlling the LPG release from spherical storage tanks. These findings aligned with those of [57,58], which determined that variables with higher output and input degrees had more roles in controlling the system. On the other hand, threats

**Table 8**
FCM indices including out-degree (out), in-degree (In) of concepts (conc).

| CONC | TE | BP1.1 | BP1.2 | BP2.1 | BP2.2 | BP3.1 | BP4.1 | BP5.1 | BP5.2 | BP6.1 | BP7.1 | BP8.1 | BP8.2 | BP8.3 | BP8.4 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **OUT** | 7.50 | 1.15 | 1.35 | 1.64 | 1.87 | 1.3 | 1.56 | 1.24 | 1.16 | 1.46 | 1.26 | 0.92 | 1.63 | 1.67 | 1.28 |
| **IN** | 20.22 | 2.24 | 0.83 | 0.67 | 4.59 | 3.47 | 2.01 | 3.33 | 2.23 | 0.9 | 3.36 | 0.36 | 0.67 | 3.17 | 0.48 |
| **CONC** | T1 | T2 | T3 | T4 | T5 | T6 | T7 | T8 | C1 | C2 | C3 | DCPB1.1.1 | DCPB2.2.1 | DCPB2.2.2 | DCPB2.2.3 |
| **OUT** | 2.05 | 2.54 | 1.3 | 1.56 | 2 | 1.46 | 1.26 | 3.17 | 0.00 | 0.00 | 0.00 | 1.69 | 1.79 | 1.47 | 1.51 |
| **IN** | 1.49 | 1.57 | 0.82 | 0.59 | 1.52 | 0.9 | 0.78 | 2.37 | 2.20 | 3.80 | 0.40 | 0.87 | 0.93 | 0.75 | 0.76 |
| **CONC** | DCPB3.1.1 | DCPB3.1.2 | DCPB4.1.1 | DCPB5.1.1 | DCPB5.1.2 | DCPB5.2.1 | DCPB7.1.1 | DCPB7.1.2 | DCPB8.3.1 | DCPB8.3.2 | DFPB1.1.1 | DFPB2.2.1 | DFPB2.2.2 | DFPB3.1.1 | DFPB4.1.1 |
| **OUT** | 1.76 | 1.73 | 1.64 | 1.64 | 1.79 | 1.76 | 1.69 | 1.76 | 1.72 | 1.79 | 1.62 | 1.72 | 2.08 | 2.54 | 1.50 |
| **IN** | 0.86 | 0.83 | 0.86 | 0.82 | 0.89 | 0.90 | 0.83 | 0.93 | 0.86 | 0.86 | 0.87 | 0.93 | 1.51 | 1.69 | 0.86 |
| **CONC** | DFPB5.1.1 | DFPB5.2.1 | DFPB7.1.1 | DFPB8.3.1 | MB1.1 | MB1.2 | MB2.1 | MB2.2 | MB2.3 | MB2.4 | MB2.5 | DCMB1.1.1 | DCMB1.1.2 | DCMB1.1.3 | DCMB1.1.4 |
| **OUT** | 2.53 | 1.55 | 2.65 | 2.24 | 1.40 | 1.57 | 1.20 | 1.57 | 1.20 | 1.20 | 1.77 | 1.60 | 1.77 | 1.77 | 1.77 |
| **IN** | 1.71 | 0.90 | 1.76 | 1.72 | 7.29 | 6.88 | 7.34 | 6.77 | 0.80 | 3.32 | 0.97 | 0.80 | 0.97 | 0.97 | 0.80 |
| **CONC** | DCMB1.1.5 | DCMB1.1.6 | DCMB1.1.7 | DCMB1.2.1 | DCMB1.2.2 | DCMB1.2.3 | DCMB1.2.4 | DCMB1.2.5 | DCMB1.2.6 | DCMB2.1.1 | DFMB1.1.1 | DFMB1.2.1 | DFMB2.1.1 | DFMB2.2.1 | DFMB2.4.1 |
| **OUT** | 1.20 | 1.93 | 1.77 | 1.93 | 1.77 | 1.37 | 1.77 | 1.57 | 1.93 | 1.40 | 6.69 | 6.12 | 6.88 | 5.57 | 2.75 |
| **IN** | 0.60 | 0.97 | 0.80 | 0.97 | 0.80 | 0.97 | 0.97 | 0.60 | 0.97 | 0.60 | 5.90 | 5.27 | 6.07 | 4.87 | 2.20 |
| **CONC** | DCMB2.1.2 | DCMB2.1.3 | DCMB2.1.4 | DCMB2.1.5 | DCMB2.1.6 | DCMB2.1.7 | DCMB2.2.1 | DCMB2.2.2 | DCMB2.2.3 | DCMB2.2.4 | DCMB2.2.5 | DCMB2.2.6 | DCMB2.4.1 | DCMB2.4.2 | DCMB2.4.3 |
| **OUT** | 1.77 | 1.60 | 1.77 | 1.77 | 1.77 | 1.93 | 1.77 | 1.37 | 1.93 | 1.77 | 1.57 | 1.57 | 1.40 | 1.77 | 1.20 |
| **IN** | 0.97 | 0.80 | 0.97 | 0.97 | 0.80 | 0.97 | 0.97 | 0.40 | 0.97 | 0.97 | 0.97 | 0.60 | 0.60 | 0.80 | 0.80 |

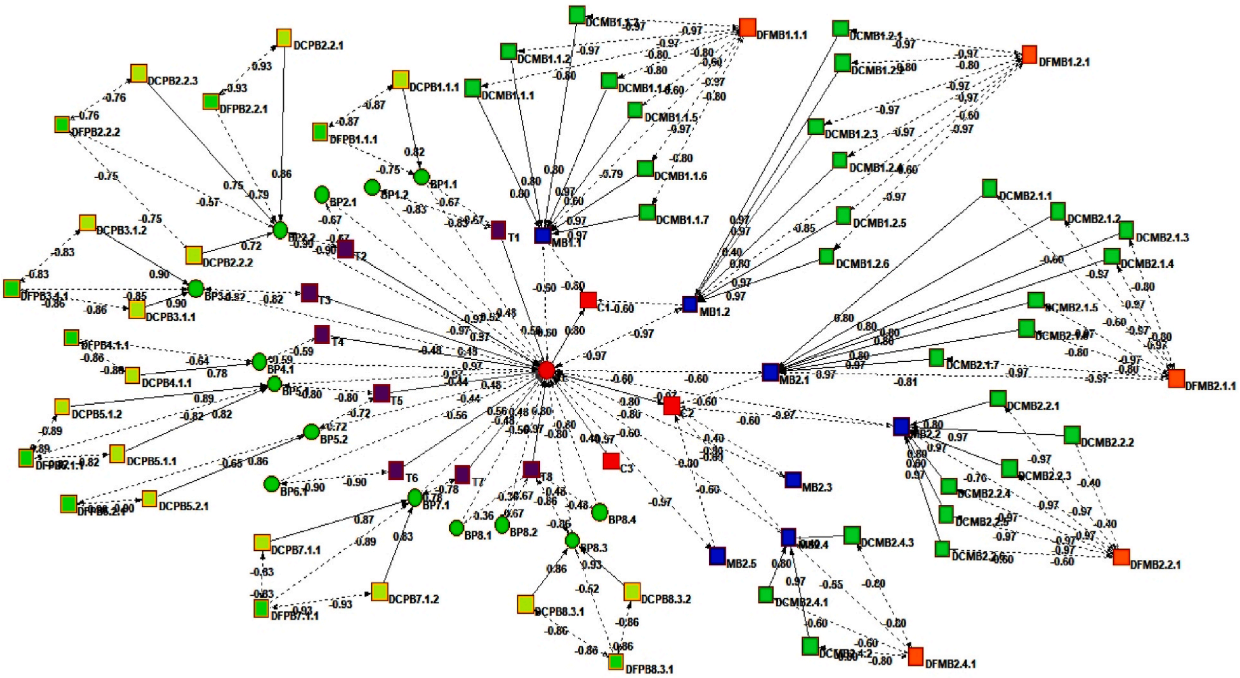


**Fig. 9.** Fuzzy cognitive map of LPG release from spherical storage tank scenario (Red circle: Top Event (TE), Red Violet box: Treats (T), Green circle: Prevention Barrier (PB), Green Yellow box: Degradation controls that can prevent DFPB (DCPB), Red Orange box: Consequence (C), Blue box: Mitigation Barrier (MB), Jungle Green box: Degradation controls that can mitigate DFMB (DCMB), Yellow Orange box: These Degradation factors that can lead to failure of MB (DFMB). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

including $T_3$, $T_4$, $T_6$, and $T_7$ had low output and input degrees. Their low input degree showed that few factors affected these threats, indicating they could be easily controllable, but they had low significance due to their low output degree. In this regard, Ouache and Adham [61] combined the BT method and fuzzy sets and consequently identified storage tank rupture and leakage due to overfilling as the main factors of an LPG release event. Aliabadi et al. [20] also determined the significance of events by the BT method and identified storage tank overflow, release from the safety valve, leakage from the storage tank, and rupture as the most significant factors leading to LPG release. Therefore, it is crucial to pay attention to barriers to $T_8$, $T_2$, $T_1$, and $T_5$ in order to prevent the threats from leading to an LPG release event.

According to the findings, some PBs have higher output degrees, meaning they are more effective in preventing threats that lead to TE. However, some PBs has higher input degrees than others, meaning there are challenges in managing these barriers. For instance, PBs with higher output degrees, such as “designing and installing storage tanks; and pipes according to standards (PB8.2)" and “providing automatic fire suppression systems (PB8.3)" are more crucial barriers in controlling and mitigating the LPG release from the spherical storage tanks. Furthermore, fatality/injury due to fire and explosion ($C_2$) with the highest input degree was identified as the main consequence in the event of LPG release from the spherical storage tank; this indicates that this consequence is more likely to be affected by the release of the LPG, especially if the barriers have low reliability.

Among barriers to $C_1$, the barrier “activating the F&G system and emergency shut down for isolating spherical storage tanks ($MB_{1.2}$)" has a high output degree in reducing the effect of the consequences. However, this barrier is also faced with challenging problems in its management and control due to the high effectiveness of its DF (deficiency in the detection of spherical storage tank isolation; $DF_{1.2.1}$). These findings highlight the vital role this mitigation barrier and its degradation controls play in having a more efficient reduction of the $C_1$ consequence. In addition, the barrier of “eliminating and preventing potential ignition sources ($MB_{1.1}$)”, which is a mitigating barrier in the pathway of $C_1$, has a low output degree but a high input degree; this suggests that mitigation has more dependence on its DF. Therefore, it is necessary to pay more attention to its DCs. Additionally, among the mitigating barriers to “fatality/injury due to fire and explosion ($C_2$),” the barriers of “evacuating the hazard zone ($MB_{2.5}$)” and “activating the F&G system and emergency shut down for isolating spherical storage tanks ($MB_{2.2}$)” were identified as barriers with higher output degrees. According to these findings, $MB_{2.2}$ has a high input degree, so it might be prone to failure. In addition, other MBs in this pathway have low output degrees. Therefore, these mitigating barriers can have a significant impact on reducing the negative consequences of TE. However, it is necessary to pay attention to strengthening or changing the DCs of these pathways in order to reduce the effects of TE on people, equipment, and processes.

Moreover, installing two PSVs on each spherical storage tank as preventive barriers and evacuating the hazard zone as a mitigating barrier with higher output levels were identified as the most important barriers. In line with this study, Nasserzadeh et al. [64]

identified the most important nodes with the strongest impacts on customer satisfaction for improving services, giving insights into managers' views to spend more of the organization's resources on factors with stronger impacts. Thus, the barriers with a higher influence over other nodes are more effective in controlling and reducing the release of the LPG.

The findings of this study can graphically demonstrate the relationship between threats, PBs, MBs, and consequences related to the release of a LPG. Planners can use the results to prioritize and invest in preventive and mitigating barriers that are more important in preventing the occurrence of TEs as well as controlling the negative consequences of a TE. Unit managers can use these results to review operators' tasks and review poorly designed barriers. However, the study has a number of limitations, most of which suggest avenues for future research. One limitation of this study is that it did not assess the probability of success or failure of mitigation barriers; it is recommended to include this in future studies. Another limitation was that it was impossible to investigate the simultaneous occurrence of two or more threats leading to a TE, which is often the case in practice. Some barriers are designed to prevent multiple threats from occurring, so the simultaneous occurrence of threats can affect their effectiveness. Furthermore, this method is dependent on the knowledge of experts. Therefore, it is essential to use more experts to overcome this drawback in the decision-making process.

## 5. Conclusions

The aim of this study was to perform a risk assessment of a LPG release from spherical storage tanks as the top event using the HAZOP method. After identifying the top event, the fuzzy set theory and expert knowledge were combined to create the SBT method, which was then analyzed through the FCM to determine the most important factors. The correlation between the factors was obtained from the opinions of experts. Consequently, the most significant barriers and their effectiveness in preventing threats from leading to the TE and mitigating negative consequences if the TE occurs, as well as the effectiveness of degradation factors and degradation controls were determined. According to the findings, fracture/rupture in pipelines/storage tanks due to fire with the highest output degree was identified as the most influential threat in the occurrence of the LPG release. Accordingly, it is recommended to implement proper permits to work and monitor operations for the prevention of fracture/rupture in pipelines or storage tanks. The results of this study showed that although the SBT method is a critical step in guiding safety experts, it has several drawbacks, including not determining and presenting the significance of the barriers and the relationship between them. As the results of FCM are graphical and compensate for these deficiencies, this method can be helpful. In summary, this study showed that the SBT method is capable of identifying effective control factors in an event; the effectiveness and susceptibility of these factors and the most important factor can be determined using FCM. Moreover, using a combination of these methods can be useful in planning operational programs and control interventions.

## Data availability

Data used in this article are duly referenced.

## CRediT authorship contribution statement

**Keyvan Sarebanzadeh:** Writing – original draft. **Naser Hasheminejad:** Methodology, Conceptualization. **Moslem Alimohammadlou :** Software, Methodology. **Mahboubeh Es'haghi:** Writing – review & editing, Methodology, Investigation, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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