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# A fuzzy multi-attribute HAZOP technique (FMA-HAZOP): Application to gas wellhead facilities

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## Abstract:

Hazard and Operability analysis (HAZOP) is a popular technique for hazard identification and risk ranking in hazardous facilities. Conventional HAZOP, however, has some drawbacks: (i) it considers a limited number of risk factors, i.e., only the frequency and the severity of hazards; (ii) it assumes equal weights for the risk factors, thus ranking low-probability high-consequence hazards equally important as high-probability low-consequence hazards; and (iii) it uses crisp and precise data which is rarely available or highly uncertain, especially in the case of complex oil and gas facilities.

The present study is an attempt to alleviate the foregoing drawbacks of conventional HAZOP via a Fuzzy Multi-Attribute HAZOP technique (FMA-HAZOP). To do this, Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) are used, both in a fuzzy environment, to determine the weight of risk factors and to prioritize the hazards. The application of the FMA-HAZOP on a gas wellhead facility shows that FMA-HAZOP presents a more transparent and more detailed information about the rank of hazards compared to conventional HAZOP.

**Keywords:** Risk assessment; HAZOP; Gas wellhead facility; Fuzzy logic; TOPSIS; AHP

## 1. Introduction

Failures in the oil and gas industry can lead to catastrophic accidents. In addition to casualties of such accidents, their financial, societal, and environmental impacts are very important (Guo et al. 2016). Accidents at oil and gas facilities usually occur in the form of major hydrocarbon release, explosion, and fire (Khakzad et al., 2013; Cheraghi et al. 2018), threatening the integrity of the facilities and the assets of the stakeholders. The importance of safety in oil wells and relevant process facilities and the challenges faced in their hazard identification have been reported in the previous studies (Brandsæter 2002, Khakzad et al. 2013, Ataallahi and Shadizadeh 2015, Lavasani et al. 2015). Despite the development in design techniques and safety systems, faults still occur in gas wellhead facilities. For instance, failure of gas wellhead – a safety critical system in oil wells – resulted in blowouts and subsequent fires in southern Iran in 2007 (ADAMS and MAKVANDI 2007) and BP's Macondo well in the Gulf of Mexico in 2010 (Vinnem 2018).

Hazard and Operability (HAZOP) study is a well-known and effective risk assessment technique for identifying potential hazards and operability problems in hazardous industries (Dunjó et al. 2010; Ahn and Chang 2016, O Herrera et al. 2018). In HAZOP, after the identification of the hazards, the risk index of the hazards is calculated by a risk matrix or simply by multiplying the Frequency (F) and the Severity (S) of the consequence of each hazard. HAZAOP, like other traditional risk evaluation techniques, suffers from major drawbacks (Grassi et al. 2009), and a large amount of research has been conducted to improve and respond to these limitation (Marhavilas et al. 2011; Khakzad et al., 2011). In this regard, the drawbacks of HAZOP can be explained in three categories:

(I) Conventional HAZOP only considers F and S as the risk factors, ignoring other fundamental aspects of risk such as workplace characteristics and human factors although the inclusion of such factors can significantly improve the quality of risk evaluation. In this regard, factors such as the capability of organization in reaction to risk (Mikulak et al. 2008), sensitivity to personal protective equipment (Grassi et al. 2009), sensitivity to maintenance (Grassi et al. 2009), safety culture (Pinto 2014), the number of risk sources (Biyikli and Aydogan 2016), the number of persons exposed (Djapan et al. 2018), and stress (Aras et al. 2014) have been introduced as risk factors.

(II) HAZOP uses absolute and precise numbers to identify risk factors, which in the case of complex systems and rare failures turns out to be very challenging. For instance, numerical quantification of the severity of the consequences by experts is very subjective if not practically impossible; furthermore, due to data scarcity and incomplete knowledge of the experts, the accurate estimation of the frequencies in the form of crisp and precise probabilities is usually prone to a high level of uncertainty (epistemic uncertainty).

Regarding the disadvantage of using crisp and precise expert judgments, several researchers have used uncertainty analysis to show the inconsistencies in the experts' opinion (Nilsen and Aven 2003). One effective way to deal with this type of uncertainty, which arises due to data scarcity and incomplete knowledge of experts, is fuzzy logic (Zadeh 1965). Fuzzy logic has been effectively used to improve the performance and credibility of risk assessment techniques (Sii et al. 2001; Jamshidi et al. 2013).

(III) HAZOP gives equal weights to the risk factors, resulting in the same ranks for both a low-probability high-consequence hazard and a high-probability low-consequence hazard. Multi-attribute decision making (MADM) techniques such as Analytic Hierarchy Process (AHP) (Saaty 1977) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Hwang and Yoon 1981) can be used to identify the weights and ranks of risk factors (Othman et al. 2016, Kokangül et al. 2017, Raviv et al. 2017). Integration of fuzzy logic and MADM techniques can further improve the performance of decision making under uncertainty. For instance, Fuzzy AHP (Chang, 1996) has been employed to determine the relative weight of risk factors (Patil and Kant 2014; Gul and Guneri 2016; Wang et al. 2016, Zhou et al. 2017). Fuzzy TOPSIS (Chen 2000) has also been widely used for ranking the hazards (Akyildiz and Mentes 2017; Carpitella et al. 2018).

There have been several attempts to integrate fuzzy theory and MADM techniques in HAZOP study. For instance, Fuzzy theory has been used to evaluate the importance of parameters (Pan et al. 2012, Gao and Wang 2018), to improve the risk matrix (Ahn and Chang 2016; Fuentes-Bargues et al. 2016; Markowski and Siuta 2018),and to assess the frequency factor (F)(HU et al. 2009; Wei et al. 2009). In addition, AHP has been used for defining weight of parameters and deviations (Kang et al. 2015, Othman et al. 2016, Aziz et al. 2017) and optimal allocation of HAZOP resources (Kang et al. 2015).

As discussed above, the fuzzy theory and MCDM techniques have been applied, mostly separately, to improve the performance of HAZOP in the previous studies. Thus, the present study aims to integrate the previous methodologies to develop a Fuzzy Multi-Attribute HAZOP (FMA-HAZOP) technique, where AHP and TOPSIS are used in a fuzzy environment to weigh the risk factors and to rank the hazards, respectively. Besides, a new risk factor, sensitivity to failure of safety measures, is defined to account for the influence of the failure of safety measures on risk. The technique is applied to a gas wellhead facility. The rest of the work is organized as follows: gas wellhead facilities are described in Section 2. The FMA-HAZOP is developed in Section 3. Results of the conventional HAZOP and the FMA-HAZOP are compared in Section 4. Section 5 presents the conclusions of the study.

## 2. System Description

Gas wellhead facilities are used in the production of natural gas and condensate. These facilities convey the fluids to manifolds in a cost-effective and safe (Lavasani et al. 2011). A gas wellhead facility includes a wellhead, flow lines, corrosion inhibitor injection facilities, a heater facility, a flare, a burn pit, a hydraulic shut down system, pig receiver facilities, a methanol system, a header, and a trunk line.

In our case study, the heater facility and the methanol system have been eliminated from the wellhead facility since the site is located in tropical areas (the site location is in Kangan, Bushehr Province, southern Iran; the average temperature in February: 23 °C). The surface pressure is controlled by a Christmas Tree installed on top of the wellhead. The Christmas Tree consists of spools, fittings, and valves. Wellhead facilities have two main safety valves, a Sub-Surface Safety Valve (SSSV) and a Surface Safety Valve (SSV), to control and safely convey the fluids to the surface. In addition, two types of choke valves, fixed and adjustable, are used to control the flow of fluids during production. There are also valves on wellhead facilities such as the Lower Master Valve (LMV), the Upper Master Valve (UMV), the production valve, and the Pressure Safety Valve (PSV) (Standard 2004, Lavasani et al. 2011). A separator is located in the flow line to separate the production fluids into liquid and gaseous components. Wellhead facilities have many instrumentation systems such as transmitters, controllers, alarms and switches. The flare and the burn pit are used for unplanned (over pressure) or planned (start up, shutdown, or testing) combustion of fluids. The flare line has a knockout drum (K.O. drum) upstream of the flare to remove any liquid from gases (Devold 2013).

The corrosion inhibitor injection facilities are used to mitigate corrosion by injecting chemical corrosion inhibitors into the flow lines. The corrosion inhibitor tank works in atmospheric condition. A Pig is a device which traverses inside the pipe for performing various maintenance operations (e.g., internal cleaning, pipeline drying, internal coating and inspection). A pig launcher is a device to launch the pig into the pipeline, and a pig receiver is a device to retrieve the pig (Devold 2013). The Piping and Instrumentation Diagram (P&ID) of wellhead facilities is represented in Fig. 1.

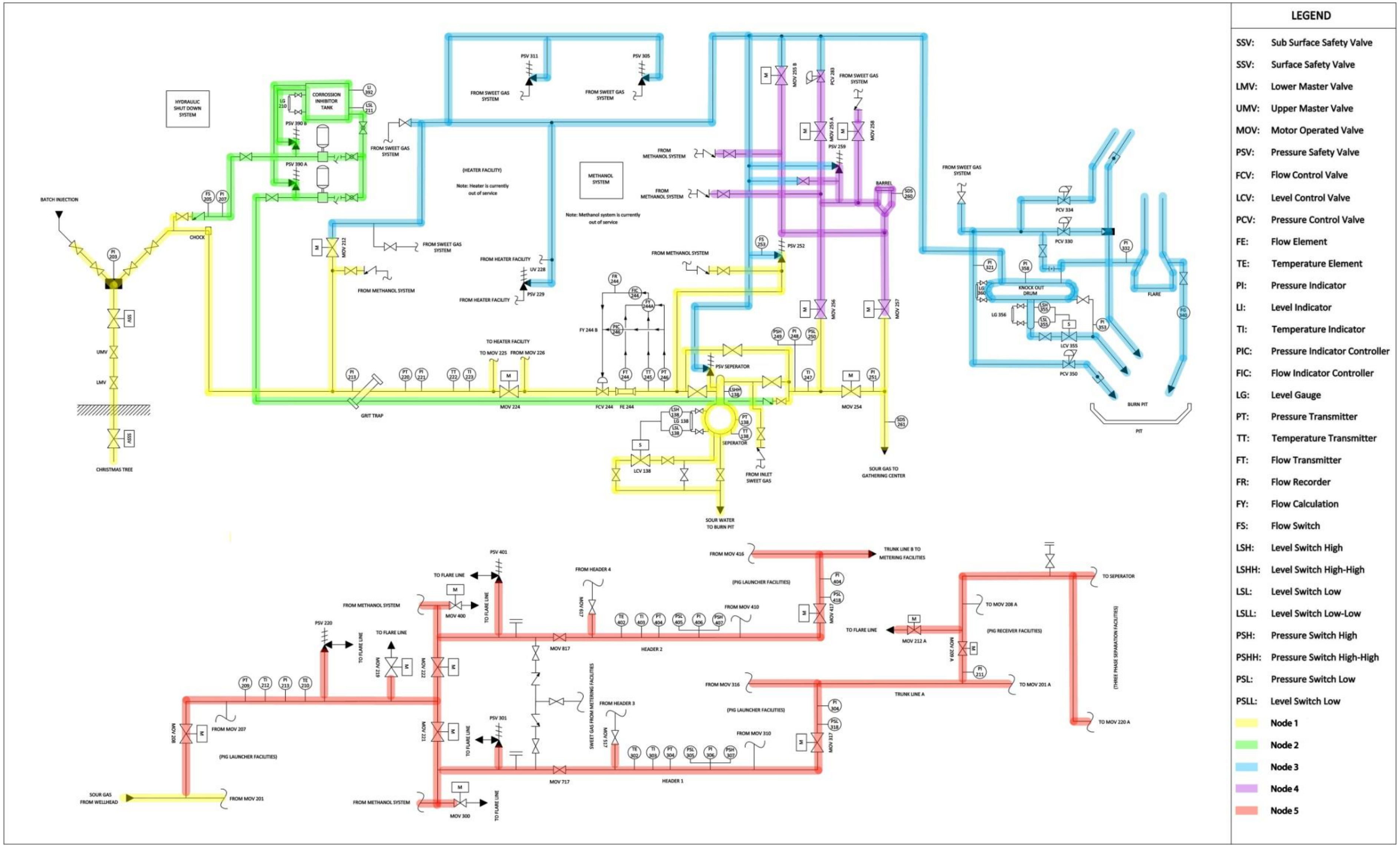

**Fig. 1.** P&ID of a wellhead facility. Nodes of HAZOP analysis have been denoted with different colors.

## 3. Materials and Method

Compared to the conventional HAZOP, which considers two risk factors of equal importance, in the FMA-HAZOP, we consider five risk factors the weight of which to be determined using AHP. Having the hazards and their corresponding risk indices determined, TOPSIS is used to prioritize and rank order the hazards. To tackle the uncertainty in experts' opinion, we combine both AHP and TOPSIS with fuzzy logic. The steps for developing the FMA-HAZOP are presented in Fig. 2, and will be described in more detail in the following subsections.

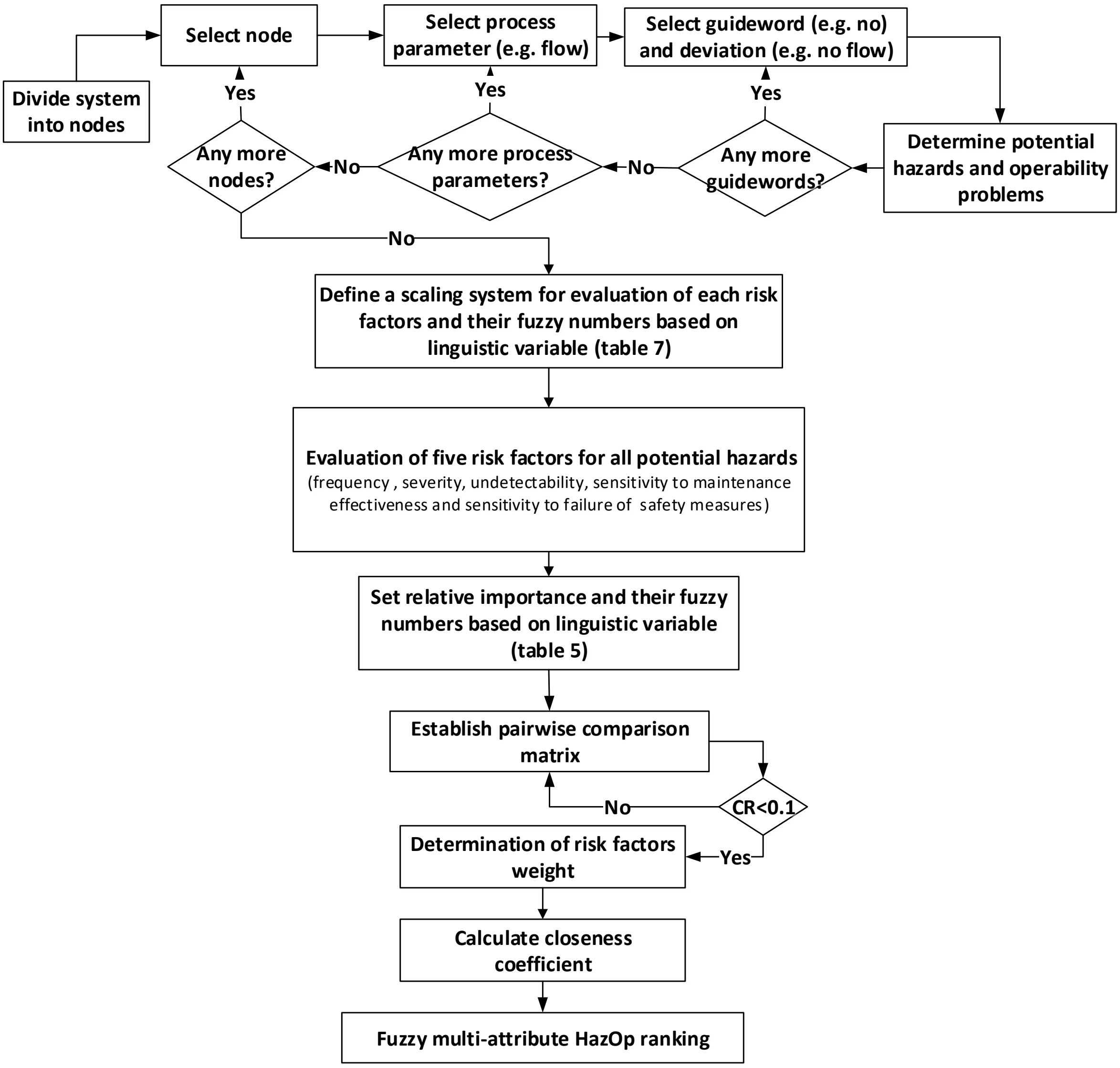

**Fig. 2.** Flowchart of FMA-HAZOP.

### 3.1. HAZOP Analysis

In HAZOP analysis, if the system or process under study deviates from its design limits, accidents may occur. Relevant documents such as process description, process flow diagram, and P&ID along with subject matter experts' opinion are used to identify design limits of the system, possible deviations, and potential consequences. The system is then broken down into simpler sections each of which being treated as a node in the HAZOP analysis. Based on the process intent, the relevant process parameters (flow, temperature, pressure, etc.) are defined. By combining the HAZOP guide words (no, more, less, etc.) with the identified process parameters, possible deviations from the design intent can be identified. As an example, the deviation "high pressure" can be identified by applying the guide word "high" to the process parameter "pressure". Potential causes of the defined deviations and their potential consequences should also be considered. Potential causes may be equipment or operational failures. All meaningful deviations related to each node should be considered. Table 1 exemplifies the guide words used in the HAZOP analysis (IEC:61882 2001).

**Table 1:** Guide words used in HAZOP and their meaning (IEC:61882 2001).

| Guide word | Definitions |
|---|---|
| No/not | Complete negation of the design intent |
| More | Quantitative increase |
| Less | Quantitative decrease |
| As well as | Qualitative modification/increase |
| Part of | Qualitative modification/decrease |
| Other than | Complete substitution |

In the conventional HAZOP, based on qualitative evaluation of the frequency (Table 2) and the severity of consequences (Table 3), a risk matrix (Fig. 3) is used to rank the risks (Table 4).

**Table 2:** Frequency evaluation of consequences in HAZOP (IEC:61882 2001)

| Category | Description |
|---|---|
| 1 | Not expected to occur during the facility lifetime |
| 2 | Expected to occur no more than once during the facility lifetime |
| 3 | Expected to occur several times during the facility lifetime |
| 4 | Expected to occur more than once in a year |

**Table 3:** Severity evaluation of consequence in HAZOP (IEC:61882 2001)

| Category | Description |
|---|---|
| 1 | No injury/ less than one week of production loss/ less than 0.1 millions of dollars equipment damage |
| 2 | Minor injury/ between one week and one month of production loss/ between 0.1 and 1 millions of dollars equipment damage |
| 3 | Injury/ between one and six months of production loss/ between 1 and 10 millions of dollars equipment damage |
| 4 | Death or severe health effects/ more than six months of production loss/ above 10 millions of dollars equipment damage |

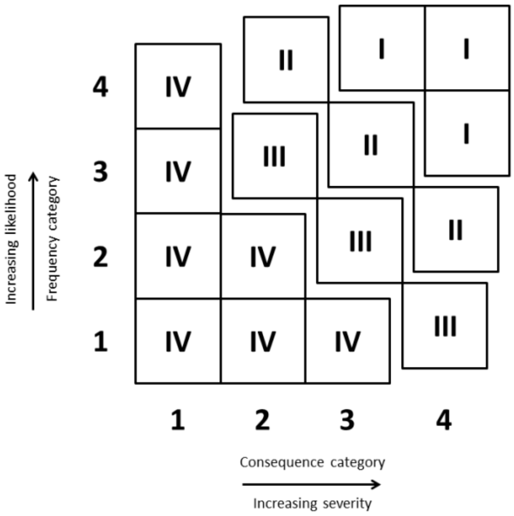

**Fig. 3.** Risk matrix (CCPS, 2010)

**Table 4:** Risk ranking of consequences in HAZOP (IEC:61882 2001)

| Number | Category | Description |
|---|---|---|
| I | Unacceptable | Should be mitigated with engineering and/or administrative controls to a risk ranking of III or less within a specified time period (e.g., 6 months). |
| II | Undesirable | Should be mitigated with engineering and/or administrative controls to a risk ranking of III or less within a specified time period (e.g., 12 months). |
| III | Acceptable with controls | Should be verified that procedures or controls are in place |
| IV | Acceptable as is | No mitigation required |

### 3.2. Definition of Risk Factors

In the present study, five risk factors are taken into account: frequency (F), severity of consequences (S), un-detectability (U), the sensitivity to maintenance effectiveness (SM), and the sensitivity to failure of safety measures (SSM). The definitions of risk factors in this study are:

- Frequency (*F*)

This factor considers the frequency by which a specific consequence of the hazard would appear. Failure of safety measures and imperfect maintenance can affect the frequency of certain consequences; in this step, for evaluation of this factor, we assume that all the safety measures are operational, and scheduled maintenance activities have been conducted.

- Severity (S)

The severity of the resulting consequences such as injuries and fatalities, damage to the equipment, the environmental impact and business interruption are considered in the evaluation of this factor. In this step, the possibility and the effect of safety measures failure and imperfect maintenance are taken into account in order to consider the highest level of severity.

- Un-detectability (U)

Detectability measures the possibility of failures being foreseen/detected before the accident occurs so that the accident can be prevented or mitigated; un-detectability implies the opposite.

- Sensitivity to maintenance effectiveness (SM)

Maintenance has previously been considered in some studies as a risk factor (Grassi et al. 2009, Biyikli and Aydogan 2016). Besides, inefficient maintenance has resulted in some major accidents (Okoh and Haugen 2013). Imperfect maintenance of equipment can increase both the frequency and the severity of hazards. Sensitivity to maintenance (SM) is an indication of such increase (Grassi et al. 2009). Thus, hazards with a higher sensitivity to quality of maintenance activity have a higher risk.

- Sensitivity to failure of safety measures (SSM)

The failure of safety measures – both physical and non-physical – in process facilities has contributed to many catastrophic accidents (Lees, 2012). Some researchers have considered the physical presence of safety measures (Hatami-Marbini et al. 2013; Pinto 2014) and safety-measure-related factors such as the "current safety level" (Gürcanli and Müngen 2009), and the "adequacy of the existing protection measures" (Murè and Demichela 2009) as risk factors. To measure this factor, the analyst should estimate the impact of failure of all related safety measures on the risk of the hazards.

### 3.3. Fuzzy logic

A fuzzy set (or number) $\widetilde{M}$ in a universe of discourse $x$ is characterized by a membership function $\mu_{\widetilde{M}}(x)$ which assigns a real number in the interval [0, 1] to each element $x$ of $X$ to indicate the grade of membership of $x$ in $\widetilde{M}$. A triangular fuzzy number $\widetilde{M}$ can be identified as a triplet $(l, m, u)$ as presented in Fig. 4 and Eq. (1) (Zimmermann 2011), where *l*, *m* and $u$ are the lower, the middle and the upper bounds of $\widetilde{M}$, respectively. A comparison between a crisp set and a fuzzy set is also depicted in Fig. 5.

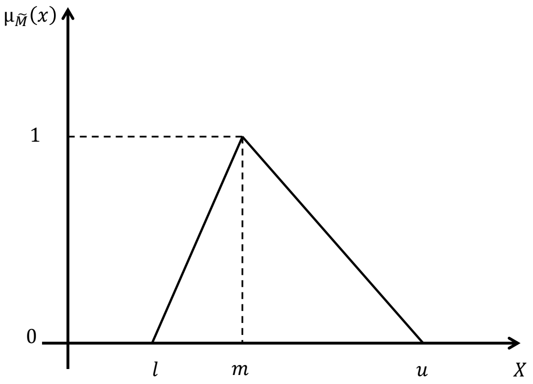

**Fig. 4.** Schematic of a triangular fuzzy number (Zimmermann 2011).

$$\mu_{\widetilde{M}}(x) = \begin{cases} 0 & x \leqslant l \\ \frac{x-l}{m-l} & l \leqslant x \leqslant m \\ \frac{u-x}{u-m} & m \leqslant x \leqslant u \\ 0 & x \geqslant u \end{cases} \tag{1}$$

Considering the two triangular fuzzy numbers $\widetilde{M}_1 = (l_1,\ m_1,\ u_1)$ and $\widetilde{M}_2 = (l_2,\ m_2,\ u_2)$, the operational laws are defined as (Chen 2000, Zimmermann 2011):

$$(l_1,\ m_1,\ u_1) \oplus (l_2,\ m_2,\ u_2) = (l_1 + l_2,\ m_1 + m_2,\ u_1 + u_2) \tag{2}$$

$$(l_1,\ m_1,\ u_1) \odot (l_2,\ m_2,\ u_2) \approx (l_1 l_2,\ m_1 m_2,\ u_1 u_2) \tag{3}$$

$$(\lambda,\ \lambda,\ \lambda) \odot (l_1,\ m_1,\ u_1) = (\lambda l_1,\ \lambda m_1,\ \lambda u_1);\ \lambda > 0,\ \ \lambda \in R\ , \lambda\ is\ a\ crisp\ number \tag{4}$$

$$(l_1,\ m_1,\ u_1)^{-1} = \left({}^{1}\!/_{u_1},\ {}^{1}\!/_{m_1},\ {}^{1}\!/_{l_1}\right) \tag{5}$$

The distance between $\widetilde{M}_1$ and $\widetilde{M}_2$ is calculated as:

$$d\left(\widetilde{M}_1, \widetilde{M}_2\right) = \sqrt{\frac{1}{3}\left[(l_1 - l_2)^2 + (m_1 - m_2)^2 + (u_1 - u_2)^2\right]} \tag{6}$$

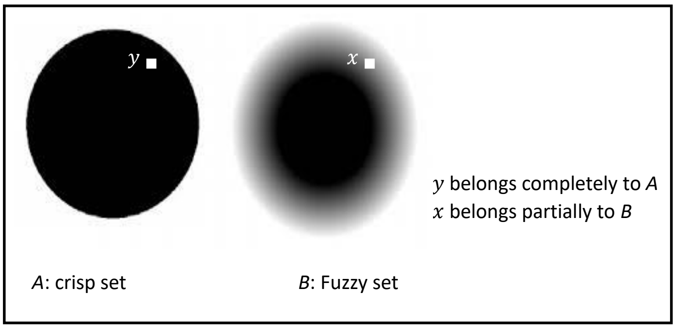

**Fig. 5.** Presentation of crisp and fuzzy sets (Zimmermann 2011).

### 3.4. Weighing risk factors via fuzzy AHP

In this step, weight of the risk factors is determined using the fuzzy AHP (Chang 1996). The triangular fuzzy scales of relative importance used in pairwise comparison are presented in Table 5.

**Table 5:** Fuzzy numbers of relative importance in pairwise comparison.

| Description | Triangular fuzzy number |
|---|---|
| Complete and utter importance | $(\frac{5}{2}, 3, \frac{7}{2})$ |
| Much stronger importance | $(2, \frac{5}{2}, 3)$ |
| Stronger importance | $(\frac{3}{2}, 2, \frac{5}{2})$ |
| Low importance | $(1, \frac{3}{2}, 2)$ |
| Approximately equal importance | $(\frac{1}{2}, 1, \frac{3}{2})$ |
| Exactly equal importance | (1,1,1,) |

All the elements on the main diagonal of the pairwise comparison matrix are (1, 1, 1) while the element on the $i^{\text{th}}$ row and the $j^{\text{th}}$ column is:

$$\widetilde{M}_{gi}^{j} = (l_{ij}, m_{ij}, u_{ij}) \tag{7}$$

Accordingly, the element on the j<sup>th</sup> row and the i<sup>th</sup> column can be determined as:

$$\widetilde{M}_{gj}^{i} = \left(\widetilde{M}_{gi}^{j}\right)^{-1} = \left(l_{ij}, m_{ij}, u_{ij}\right)^{-1} = \left(\frac{1}{u_{ij}}, \frac{1}{m_{ij}}, \frac{1}{l_{ij}}\right) \tag{8}$$

The consistency of the comparison matrix established this way can be checked using the consistency ratio (CR). To do so, pairwise fuzzy numbers should be converted to crisp numbers via a defuzzification process. In this study, the graded mean integration approach (Zimmermann 2011) is used for defuzzification of the fuzzy numbers of the comparison matrix. The fuzzy number $\widetilde{M} = (l,\ m,\ u)$ is transformed into a crisp number M as:

$$P(\widetilde{M}) = M = \frac{l+4m+u}{6} \tag{9}$$

After deffuzification of each fuzzy number of the comparison matrix, the consistency ratio (CR) of the matrix can be calculated as the ratio of the consistency index (CI) and the random consistency index (RI) (Saaty 1980):

$$CR = \frac{CI}{RI} \tag{10}$$

CI and RI can be identified using Eq. (11) and Table 6, respectively.

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{11}$$

where $\lambda_{max}$ is the largest eigenvalue, and $n$ is the number of factors being compared in the matrix. If CR is lower than 0.1, the assigned weight amounts are consistent, which otherwise should be reassigned.

**Table 6:** Random consistency index (Saaty 1980).

| **n** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Random consistency index (RI) | 0 | 0 | 0.52 | 0.89 | 1.11 | 1.25 | 1.35 | 1.40 | 1.45 | 1.49 |

Assume that $X = \{x_1, x_2, x_3, \ldots, x_n\}$ is an object set, and that $U = \{u_1, u_2, u_3, \ldots, u_m\}$ is a goal set. For each object-goal pair, the extent analysis should be performed (Chang 1996), resulting in $m$ extent analysis values for each object:

$$\widetilde{M}_{g_1}^{1}, \widetilde{M}_{g_2}^{2} \ldots, \widetilde{M}_{g_n}^{m} \tag{12}$$

where $\widetilde{M}_{g_i}^{j}$\{ i= 1, 2, ..., n and j = 1, 2, . . . , $m$\} are triangular fuzzy numbers. The value of fuzzy synthetic extent with respect to the $i^{\text{th}}$ object is itself a triangular fuzzy number which can be defined as:

$$\tilde{S}_i = \sum_{j=1}^{m} \widetilde{M}_{g_i}^{j} \odot \left[\sum_{i=1}^{n} \sum_{j=1}^{m} \widetilde{M}_{g_i}^{j}\right]^{-1} \tag{13}$$

For $\widetilde{M}_1 = (l_1, m_1, u_1)$ and $\widetilde{M}_2 = (l_2, m_2, u_2)$, the possibility degree of $\widetilde{M}_1 \geq \widetilde{M}_2$, denoted as $V(\widetilde{M}_1 \geq \widetilde{M}_2)$, is given as:

$$V\left(\widetilde{M}_2 \geq \widetilde{M}_1\right) = \begin{cases} 1 & if\ m_2 \geq m_1 \\ 0 & if\ l_1 \geq u_2 \\ \mu_{\widetilde{M}_1}(d) = \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & otherwise \end{cases} \tag{14}$$

where $d$ is the horizontal coordinate of the highest intersection point $D$ of $\mu_{\widetilde{M}_1}$ and $\mu_{\widetilde{M}_2}$ (Fig. 6). Similarly, the possibility degree of $\widetilde{M} \geq \widetilde{M}_1, \widetilde{M}_2, \widetilde{M}_3, \ldots, \widetilde{M}_k$ is given by:

$$V\left(\widetilde{M} \geq \widetilde{M}_1, \widetilde{M}_2, \widetilde{M}_3, \ldots, \widetilde{M}_k\right) = \min V\left(\widetilde{M} \geq \widetilde{M}_i\right), \quad i = 1, 2, \ldots, \mathrm{k}, \tag{15}$$

The weight of factors in the comparison matrix can be calculated as:

$$d'(A_i) = \min V\left(\tilde{S}_i \geq \tilde{S}_k\right) k = 1, 2, \ldots, \mathrm{n}; k \neq i \tag{16}$$

Having the weight vector $W' = (d'(A_1), d'(A_2), \ldots, d'(A_n))^T$, the normalized weight vector $W$ can be calculated as:

$$W = (d(A_1), d(A_2), \ldots, d(A_n))^T \tag{17}$$

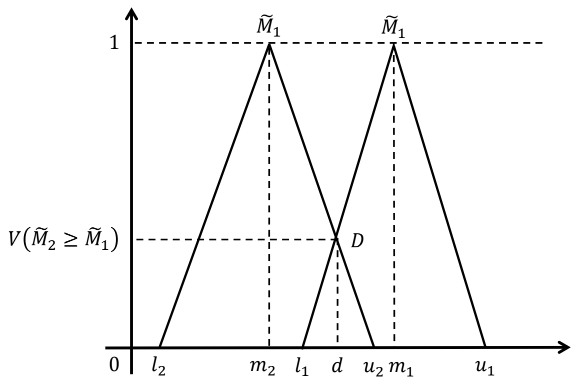

**Fig. 6.** The intersection between two triangular fuzzy numbers $\widetilde{M}_2$ and $\widetilde{M}_1$ (Chang 1996).

### 3.5. Ranking hazards using fuzzy TOPSIS

The fuzzy TOPSIS is a technique for multi-attribute decision making under uncertainty particularly when the number of alternatives to consider (hazards in the present study) is large (Grassi et al. 2009). In this technique, an optimal alternative should have the shortest and the farthest distances, respectively, from the positive and negative ideal solutions. The linguistic variables and the corresponding triangular fuzzy numbers used in the fuzzy TOPSIS for evaluation of risk factors are shown in Table 7.

**Table 7:** Linguistic variables and the corresponding fuzzy numbers in fuzzy TOPSIS.

| linguistic variable | Symbol | Triangular fuzzy number |
|---|---|---|
| Negligible | NE | (0,0,1) |
| Very low | VL | (0,1,2) |
| Low | LO | (1,2,3) |
| Medium low | ML | (2,3,4) |
| Fair | FA | (3,4,5) |
| Medium high | MH | (4,5,6) |
| High | HI | (5,6,7) |
| Very high | VH | (6,7,8) |
| Absolutely high | AH | (7,8,9) |
| Maximum | MA | (8,9,9) |

Assume that the fuzzy rating of the decision maker about the $i^{\text{th}}$ alternative $A_i$ based on the $j^{\text{th}}$ criterion $C_j$ can be presented as $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$, where the weight of the criterion $C_j$ is calculated from Eq. (17) as $\widetilde{w}_j = (w_{j1}, w_{j2}, w_{j3})$. The problem can be expressed in a matrix form as:

$$\widetilde{D} = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_i \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccccc} C_1 & C_2 & \cdots & C_j & \cdots & C_n \end{array} \\ \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1j} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2j} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \tilde{x}_{i1} & \tilde{x}_{i2} & \cdots & \tilde{x}_{ij} & \cdots & \tilde{x}_{in} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mj} & \cdots & \tilde{x}_{mn} \end{bmatrix} \end{array} \tag{18}$$

$$\widetilde{W} = [\widetilde{w}_1, \widetilde{w}_2, \cdots, \widetilde{w}_j \cdots, \widetilde{w}_n] \tag{19}$$

where $A_i$ are possible alternatives (hazards in this study), and $C_j$ are the criteria (risk factors in this study). The decision matrix $D$ needs to be normalized. The normalized matrix $\tilde{R}$ is defined as:

$$\tilde{R} = [\tilde{r}_{ij}]_{m\times n} \tag{20}$$

where:

$$\tilde{r}_{ij} = \begin{cases} \left(\frac{a_{\mathrm{ij}}}{c_j{}^{+}}, \frac{b_{ij}}{c_j{}^{+}}, \frac{\mathrm{c_{ij}}}{c_j{}^{+}}\right) & j \in B; \\ \left(\frac{a_j{}^{-}}{\mathrm{c_{ij}}}, \frac{a_j{}^{-}}{b_{ij}}, \frac{a_j{}^{-}}{a_{\mathrm{ij}}}\right) & j \in C; \end{cases} \tag{21}$$

$B$ and $C$ are the set of benefit and cost criteria, respectively. $c_j{}^{+} = \max\limits_i c_{ij}$ if $j \in B$, and $a_j{}^{-} = \min\limits_i a_{ij}$ if $j \in C$.

Considering the different importance of each criterion, the weighted normalized fuzzy decision matrix can be constructed as:

$$\tilde{V} = \left[\tilde{v}_{ij}\right]_{m\times n,} i = 1, 2, \ldots, m, j = 1, 2, \ldots, n; \tag{22}$$

where $\tilde{v}_{ij} = \tilde{r}_{ij}.\widetilde{w}_j$.

We can define the fuzzy positive-ideal solution $\mathrm{A}^{+} = (\tilde{v}_1{}^{+}, \tilde{v}_2{}^{+}, \ldots, \tilde{v}_j{}^{+} \ldots, \tilde{v}_n{}^{+})$ and fuzzy negative-ideal solution $A^{-} = (\tilde{v}_1{}^{-}, \tilde{v}_2{}^{-}, \ldots, \tilde{v}_j{}^{-}, \ldots, \tilde{v}_n{}^{-})$ where $\tilde{v}_j{}^{+} = (1, 1, 1)$ and $\tilde{v}_j{}^{-} = (0, 0, 0)$ for $j = 1, 2, \ldots, n$.

Distance of each alternative from $\mathrm{A}^{+}$ and $A^{-}$ can be calculated as:

$$d_i{}^{+} = \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_j{}^{+}\right), \ i = 1, 2, \ldots, m, \tag{23}$$

$$d_i{}^{-} = \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_j{}^{-}\right), \ i = 1, 2, \ldots, \mathrm{m}, \tag{24}$$

The closeness coefficient (CC) can be used to determine the rank order of the alternatives:

$$CC_i = \frac{d_i{}^{-}}{d_i{}^{+} + d_i{}^{-}}, \quad i = 1, 2, \ldots, \mathrm{m}, \tag{25}$$

## 4. Results and discussions

### 4.1. HAZOP analysis

To perform the HAZOP study, the P&ID of the gas wellhead facility (Fig. 1) is divided into five sections or nodes as listed in Table 8. For each node, several meaningful deviations, i.e., the ones with credible causes and consequences, can be considered. Disregarding unlikely deviations such as the "low temperature" which does not occur according to the site's geographical location, the meaningful deviations along with their causes and potential consequences have been listed in Table 9.

**Table 8:** List of nodes for HAZOP analysis of gas wellhead facility.

| Node | Title |
|---|---|
| 1 | Wellhead and flow line |
| 2 | Corrosion inhibitor injection facilities |
| 3 | Flare and burn pit facilities |
| 4 | Pig receiver facilities |
| 5 | Header and trunk Line |

**Table 9:** Results of HAZOP analysis.

| Hazard No. | Node | guideword | Parameter | Deviation | Causes | Consequences |
|---|---|---|---|---|---|---|
| 1 | 1 | No/less | Flow | No/less flow of gas | Closure of SSSV, failure of hydraulic panel system (e.g., leakage in tubing, power failure, pump failure, and transmitter failure) | Loss of production |
| 2 | 1 | No/less | Flow | No/less flow of gas | Closure of SSV, failure of hydraulic panel system (e.g., leakage in tubing, power failure, pump failure, and transmitter failure) | Loss of production |
| 3 | 1 | No/less | Flow | No/less flow of gas | Closure of manual valve (e.g., production valve, LMV, and UMV) on Christmas Tree | Loss of production |
| 4 | 1 | No/less | Flow | No/less flow of gas | Closure of adjustable choke valve and or plugging of fixed/adjustable choke valve by debris/grit | Loss of production |
| 5 | 1 | No/less | Flow | No/less flow of gas | Failure of FCV 244 or failure of any elements of the control system to close more | Loss of production |
| 6 | 1 | No/less | Flow | No/less flow of gas | Closure of MOV 224 | Loss of production |
| 7 | 1 | No/less | Flow | No/less flow of gas | Closure of MOV 254 | Increase pressure upstream of the valve and possibility of damage to line due to over pressure |
| 8 | 1 | No/less | Flow | No/less flow of gas | Plugging of Grit Trap | Loss of production |
| 9 | 1 | High | Level | High level in the separator | Failure of LCV 138 under the separator or any elements of the control system to close more | Sour liquid carry over to downstream and thus increasing the rate of corrosion, increasing liquid hold-up in flow lines, gradual increasing of the back pressure |
| 10 | 1 | High | Level | High level in the separator | Closure of any manual drain valve downstream of LCV 138 | Sour liquid carry over to downstream and thus increasing rate of corrosion, increasing liquid hold-up in flow lines, gradual increasing of the back pressure |
| 11 | 1 | Low | Level | Low level in separator | Failure of LCV 138 under the separator or any elements of the control system to open more | Toxic gas blow-by to burn pit leading to loss of gas |
| 12 | 1 | High | Pressure | High Pressure | Fire case | Possibility of damage to the separator due to over pressure |
| 13 | 1 | More | Flow | More flow of gas | Failure of FCV 244 or any elements of the control system to open more and or more opening of adjustable choke valve | Possibility of damage to the flow lines and downstream equipment due to over pressure |
| 14 | 1 | As well as | Flow | Leakage/rupture | Corrosion, erosion, aging, gasket failure, ring failure, insulating joint failure, thermal tension, etc. | Toxic gas release, risk of personnel injury, loss of material, the environmental pollution and loss of production |
| 15 | 1 | As well as | Flow | Leakage/rupture | Corrosion, erosion, aging, gasket failure, ring failure, insulating joint failure, TPD, thermal tension, etc. | Risk of reverse flow |
| 16 | 1 | Other than | Operation | Fire case | Ignition of released gas | Damage to facilities |
| 17 | 1 | Other than | Operation | Well blowout | Failure of Christmas Tree due to any reason. | Toxic gas release to atmosphere. |
| 18 | 2 | No/less | Flow | No/less flow of the corrosion inhibitor | Closure of manual valve on pump discharge by error | Damage to pump and thus the environmental pollution |
| 19 | 2 | High | Level | High level | More filing of tank by error or failure of LG | Overfilling of inhibitor, and thus the environmental pollution |
| 20 | 2 | Low | Level | Low level | Consumption and not refilling by failure | Possibility of damage to pump and also flow cut off in the flow lines |
| 21 | 3 | High | Pressure | High pressure | Failure of PCV 350 on burn pit ignition system to open more | Improper ratio of fuel/air, leading to not burning of the pilot |
| 22 | 3 | High | Pressure | High pressure | Failure of PCV 330 on flare ignition system to open more | Improper ratio of fuel/air, leading to not burning of the pilot |
| 23 | 3 | High | Pressure | High pressure | Failure of PCV 334 on flare/ burn pit pilot gas to open more | Loss of gas |
| 24 | 3 | High | Level | High level | Not draining liquids in proper time by error or by failure of level indication system (level control system in flare K.O Drum has been changed from automatic to manual). | Accumulation of liquid, overflow to flare header and damage to flare stack, flaming rain, and the risk of the environmental pollution and personnel injury |
| 25 | 3 | Low | Level | Low level | Operator failure to close drain valve in proper time | Possibility of purge gas/sour gas blow-by to burn pit and thus uncontrolled burning and toxic dispersion |
| 26 | 3 | Other than | Operation | Loss of performance | Failure of PCV 334 on flare/burn pit pilot gas to close more | Loss of pilot gas and possibility of venting of unburned relief gas and dispersion of flammable and toxic gas |
| 27 | 3 | Other than | Operation | Loss of performance | Flame out condition due to any reason | Loss of pilot gas and possibility of venting of unburned relief gas and dispersion of flammable and toxic gas to area |

| Hazard No. | Node | guideword | Parameter | Deviation | Causes | Consequences |
|---|---|---|---|---|---|---|
| 28 | 3 | Other than | Operation | Loss of performance | Failure of PCV 330 on flare ignition system to close more | Delay in ignition |
| 29 | 3 | Other than | Operation | Loss of performance | Failure of PCV 350 on burn pit ignition system to close | Delay in ignition |
| 30 | 3 | Other than | Operation | Loss of performance | Failure of flame front ignitor system | Delay in ignition |
| 31 | 3 | Other than | Operation | Corrosion | Corrosive environment in K.O drum | Damage to K.O Drum and risk of fire, the environment pollution, toxic gas release and risk of personnel injury |
| 32 | 4 | High | Pressure | High pressure | Thermal expansion during box-up or fire case | Damage to pig barrels and facilities due to over pressure |
| 33 | 4 | Other than | Operation | Pig receiver problems | Failure of PCV 283 to open more. (In current condition, the PCV 283 is used as a manually operated valve). | Regarding to PCV 283 is fully open during pigging operation so no major issue of concern is identified |
| 34 | 4 | Other than | Operation | Pig receiver problems | Failure of PCV 283 to close more | Stopping pigging operation |
| 35 | 4 | Other than | Operation | Pig receiver problems | Failure of PCV 283 to close more | During emergency shutdown, flow lines will not depressurize properly (while MOV 256 and MOV 255A open simultaneously) |
| 36 | 4 | Other than | Operation | Pig receiver problems | Opening of Pig Receiver door when it is pressurized | Possibility of personnel injury due to toxic gas release |
| 37 | 4 | Other than | Operation | Pig receiver problems | Opening of Pig Receiver door when it is pressurized | Fire |
| 38 | 4 | Other than | Operation | Corrosion | Corrosive environment in Barrel | Damage to Barrel and the risk of fire, the environment pollution, toxic gas release and risk of personnel injury |
| 39 | 4 | Other than | Operation | Isolation | Any lines that are out of service | Risk of fire, the environment pollution, toxic gas release and risk of personnel injury |
| 40 | 5 | No/Less | Flow | No/less flow of gas | Decreased/cut-off of flow from upstream | Loss of production |
| 41 | 5 | No/Less | Flow | No/less flow of gas | Closure of MOV 208 and or Closure of MOV 221/222 by error | Loss of production |
| 42 | 5 | No/Less | Flow | No/less flow of gas | Closure of MOV 208 and or Closure of MOV 221/222 by error | Increase pressure upstream of the valve and possibility of damage to relevant well flowline due to over pressure and the risk of relevant well trip. |
| 43 | 5 | No/Less | Flow | No/less flow of gas | Closure of MOV 317/417 by error | Loss of production |
| 44 | 5 | No/Less | Flow | No/less flow of gas | Closure of MOV 317/417 by error | Increased pressure upstream of the valve and possibility of damage to the flow lines due to over pressure and risk of well trips |
| 45 | 5 | No/Less | Flow | No/less flow of gas | Not receiving in downstream | Loss of production |
| 46 | 5 | No/Less | Flow | No/less flow of gas | Not receiving in downstream | Increased pressure and possibility of damage to relevant facility |
| 47 | 5 | High | Pressure | High pressure | Thermal expansion during box-up or fire case | Possibility of damage to line and equipment due to over pressure |
| 48 | 5 | High | Pressure | High pressure | Hold-up in pipeline | Back pressure for upstream facility and wellhead |
| 49 | 5 | Other than | Operation | Leakage/rupture | Corrosion, erosion, aging, gasket failure, ring failure, insulating joint failure, TPD, thermal tension, etc. | Toxic gas release, risk of personnel injury, loss of material, the environmental pollution and loss of production |
| 50 | 5 | Other than | Operation | Fire case | Ignition of released gas | Damage to facilities |

Using Tables 2 and 3 to determine the frequency and the severity of the hazards in the conventional HAZOP, the risks ranked by the risk matrix in Fig. 3 are listed in Table 10.

**Table 10:** Risks ranked using the risk matrix in conventional HAZOP.

| Hazard No. | Judgment | | Risk category | Rank No. |
|---|---|---|---|---|
| | F | S | | |
| 1 | 3 | 1 | IV | 15 |
| 2 | 3 | 1 | IV | 15 |
| 3 | 1 | 1 | IV | 15 |
| 4 | 1 | 1 | IV | 15 |
| 5 | 3 | 1 | IV | 15 |
| 6 | 3 | 1 | IV | 15 |
| 7 | 1 | 4 | III | 4 |
| 8 | 1 | 1 | IV | 15 |
| 9 | 3 | 1 | IV | 15 |
| 10 | 1 | 1 | IV | 15 |
| 11 | 2 | 2 | IV | 15 |
| 12 | 1 | 4 | III | 4 |
| 13 | 1 | 1 | IV | 15 |
| 14 | 2 | 2 | IV | 15 |
| 15 | 1 | 4 | III | 4 |
| 16 | 1 | 4 | III | 4 |
| 17 | 1 | 4 | III | 4 |
| 18 | 1 | 1 | IV | 15 |
| 19 | 2 | 1 | IV | 15 |
| 20 | 2 | 1 | IV | 15 |
| 21 | 3 | 1 | IV | 15 |
| 22 | 3 | 1 | IV | 15 |
| 23 | 3 | 1 | IV | 15 |
| 24 | 2 | 2 | IV | 15 |
| 25 | 2 | 2 | IV | 15 |
| 26 | 2 | 2 | IV | 15 |
| 27 | 2 | 2 | IV | 15 |
| 28 | 2 | 1 | IV | 15 |
| 29 | 2 | 1 | IV | 15 |
| 30 | 2 | 1 | IV | 15 |
| 31 | 2 | 2 | IV | 15 |
| 32 | 1 | 1 | IV | 15 |
| 33 | 2 | 1 | IV | 15 |
| 34 | 2 | 1 | IV | 15 |
| 35 | 2 | 1 | IV | 15 |
| 36 | 2 | 4 | II | 1 |
| 37 | 1 | 4 | III | 4 |
| 38 | 2 | 4 | II | 1 |
| 39 | 1 | 2 | IV | 15 |
| 40 | 2 | 1 | IV | 15 |
| 41 | 2 | 1 | IV | 15 |
| 42 | 1 | 4 | III | 4 |
| 43 | 2 | 1 | IV | 15 |
| 44 | 1 | 4 | III | 4 |
| 45 | 2 | 1 | IV | 15 |
| 46 | 1 | 4 | III | 4 |
| 47 | 1 | 4 | III | 4 |
| 48 | 3 | 1 | IV | 15 |
| 49 | 2 | 4 | II | 1 |

| Hazard No. | Judgment | | Risk category | Rank No. |
|---|---|---|---|---|
| | F | S | | |
| 50 | 1 | 4 | III | 4 |

### 4.2. FMA-HAZOP analysis

To rank the identified hazards by FMA-HAZOP, Table 5 is first used to develop the comparison matrix to determine the weight of the risk factors. Table 11 shows the results of pairwise comparison of the risk factors, with a CR = 0.017 which is way below the maximum threshold of 0.1. Table 12 presents the relative weight of the risk factors calculated by the fuzzy AHP. Table 7 is used for evaluation of risk factors in the FMA-HAZOP. As can be seen from Table 12, for the case study of interest, the frequency and the severity have the largest impact whereas the sensitivity to maintenance has the smallest impact on the risk. The identified hazards can be ranked as in Table 13 based on the calculated closeness coefficients by fuzzy TOPSIS.

**Table 11:** Pairwise comparisons matrix for risk factors.

| Risk factors | F | S | U | SSM | SM |
|---|---|---|---|---|---|
| F | $(1,1,1)$ | $(1,1,1)$ | $(\frac{3}{2},2,\frac{5}{2})$ | $(\frac{3}{2},2,\frac{5}{2})$ | $\boldsymbol{(\frac{5}{2},3,\frac{7}{2})}$ |
| S | $(1,1,1)$ | $(1,1,1)$ | $(\frac{3}{2},2,\frac{5}{2})$ | $(\frac{3}{2},2,\frac{5}{2})$ | $\boldsymbol{(\frac{5}{2},3,\frac{7}{2})}$ |
| U | $(\frac{2}{5},\frac{1}{2},\frac{2}{3})$ | $(\frac{2}{5},\frac{1}{2},\frac{2}{3})$ | $(1,1,1)$ | $(1,1,1)$ | $\boldsymbol{(1,\frac{3}{2},2)}$ |
| SSM | $(\frac{2}{5},\frac{1}{2},\frac{2}{3})$ | $(\frac{2}{5},\frac{1}{2},\frac{2}{3})$ | $(1,1,1)$ | $(1,1,1)$ | $\boldsymbol{(1,\frac{3}{2},2)}$ |
| SM | $(\frac{2}{7},\frac{1}{3},\frac{2}{5})$ | $(\frac{2}{7},\frac{1}{3},\frac{2}{5})$ | $(\frac{1}{2},\frac{2}{3},1)$ | $(\frac{1}{2},\frac{2}{3},1)$ | $\boldsymbol{(1,1,1)}$ |

**Table 12:** Relative weight of risk factors.

| Risk factors | F | S | U | SSM | SM |
|---|---|---|---|---|---|
| Weight | 0.2599 | 0.2599 | 0.1785 | 0.1785 | 0.1231 |

**Table 13:** Risk ranking by FMA-HAZOP.

| Hazard No. | Judgment | | | | | Closeness coefficient ($cc_i$) | Rank No. |
|---|---|---|---|---|---|---|---|
| | F | S | U | SSM | SM | | |
| 1 | MH | VL | FA | FA | HI | 0.1004 | 24 |
| 2 | HI | VL | FA | FA | MH | 0.1047 | 22 |
| 3 | NE | VL | FA | NE | VL | 0.0386 | 50 |
| 4 | VL | VL | FA | VL | LO | 0.0493 | 48 |
| 5 | MH | VL | ML | FA | HI | 0.0954 | 25 |
| 6 | FA | VL | ML | ML | FA | 0.0782 | 33 |
| 7 | LO | VH | FA | MH | FA | 0.1099 | 17 |

| Hazard No. | Judgment | | | | | Closeness coefficient ($cc_i$) | Rank No. |
|---|---|---|---|---|---|---|---|
| | F | S | U | SSM | SM | | |
| 8 | NE | NE | HI | NE | VL | 0.0445 | 49 |
| 9 | HI | LO | FA | ML | HI | 0.1090 | 19 |
| 10 | VL | LO | FA | ML | LO | 0.0616 | 45 |
| 11 | ML | FA | FA | FA | HI | 0.1021 | 23 |
| 12 | VL | AH | HI | HI | LO | 0.1172 | 11 |
| 13 | VL | VL | FA | MH | HI | 0.0762 | 36 |
| 14 | FA | FA | HI | VH | VH | 0.1342 | 4 |
| 15 | VL | VH | HI | ML | VH | 0.1148 | 14 |
| 16 | LO | VH | HI | HI | VH | 0.1330 | 5 |
| 17 | VL | MA | FA | MA | VH | 0.1363 | 3 |
| 18 | VL | ML | FA | MH | ML | 0.0777 | 34 |
| 19 | ML | LO | LO | FA | FA | 0.0751 | 37 |
| 20 | ML | ML | FA | MH | FA | 0.0943 | 27 |
| 21 | MH | NE | FA | VL | HI | 0.0852 | 30 |
| 22 | MH | VL | FA | VL | HI | 0.0893 | 29 |
| 23 | MH | VL | FA | LO | HI | 0.0928 | 28 |
| 24 | FA | FA | MH | MH | ML | 0.1092 | 18 |
| 25 | FA | ML | MH | VH | VL | 0.1057 | 20 |
| 26 | ML | FA | HI | MH | HI | 0.1160 | 12 |
| 27 | ML | FA | HI | MH | FA | 0.1100 | 16 |
| 28 | LO | VL | FA | LO | HI | 0.0712 | 41 |
| 29 | ML | VL | FA | ML | HI | 0.0820 | 31 |
| 30 | LO | VL | FA | LO | FA | 0.0652 | 44 |
| 31 | FA | FA | HI | MH | VH | 0.1263 | 8 |
| 32 | VL | LO | FA | MH | ML | 0.0722 | 39 |
| 33 | LO | NE | FA | VL | LO | 0.0517 | 46 |
| 34 | LO | NE | FA | VL | LO | 0.0517 | 46 |
| 35 | LO | LO | FA | ML | LO | 0.0681 | 43 |
| 36 | FA | VH | FA | HI | MH | 0.1312 | 6 |
| 37 | LO | VH | FA | ML | MH | 0.1052 | 21 |
| 38 | ML | VH | FA | HI | VH | 0.1301 | 7 |
| 39 | VL | FA | FA | MH | VL | 0.0777 | 35 |
| 40 | ML | VL | FA | LO | FA | 0.0722 | 40 |
| 41 | ML | VL | FA | FA | FA | 0.0798 | 32 |
| 42 | LO | VH | ML | VH | MH | 0.1158 | 13 |
| 43 | ML | LO | ML | LO | FA | 0.0723 | 38 |
| 44 | LO | AH | ML | VH | MH | 0.1216 | 10 |
| 45 | ML | LO | ML | VL | FA | 0.0688 | 42 |
| 46 | LO | AH | ML | HI | FA | 0.1146 | 15 |
| 47 | VL | AH | HI | VH | ML | 0.1240 | 9 |
| 48 | MH | LO | ML | MH | ML | 0.0954 | 26 |
| 49 | FA | AH | HI | AH | VH | 0.1610 | 1 |
| 50 | LO | AH | HI | HI | VH | 0.1388 | 2 |

### 4.3. Comparison between HAZOP and FMA-HAZOP

50 hazards were identified using the conventional HAZOP analysis for the gas wellhead facility (Table 9). Safety is very critical for gas wellhead facilities, and thus, as expected, there is no hazard in Category I and only 6% of the hazards in Category II that should be mitigated to the lower categories (hazard numbers 49, 36, 38). Likewise, 22% of the hazards are in Category III, which require controlling procedures and mitigating actions, and 72% of the hazards are in Category IV with no need for further prevention or

mitigation measures. Hazards rankings identified using both the conventional HAZOP and FMA-HAZOP are shown in Fig. 5. As can be noted, compared to the conventional HAZOP, FMA-HAZOP has resulted in more distinguished ranks for the hazards, which in turn facilitates the allocation of risk-reduction measures under limited resources (budget, time, etc.).

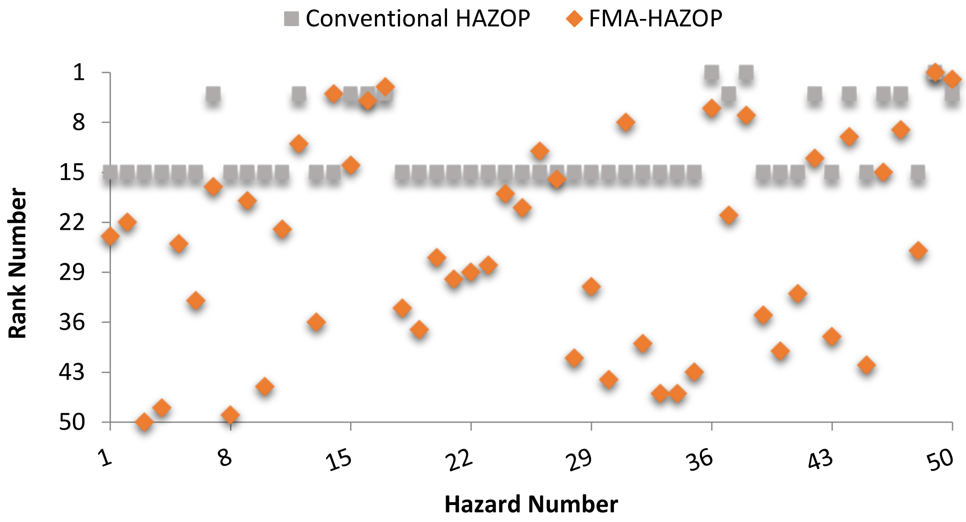

**Fig. 7.** Hazards ranking in conventional HAZOP and FMA-HAZOP.

Release of toxic chemicals is one of the frequent hazards in the process facilities as in the Seveso and Bhopal disasters (Lees 2012). Comparing the results of conventional HAZAOP and FMA-HAZOP (Tables 10 and 12), the hazards 36, 38 and 49 are ranked as the top three hazards using conventional HAZOP whereas when using FMA-HAZOP the top three hazards are identified as the hazards 49, 50, and 17. Hazard 49, release of toxic gas in header and trunk line, which can be actualized by using low-grade gaskets, poor inspection of pipelines coating, and insufficient repair with proper coating, has a “fair” frequency and an “absolutely high” severity. Due to some reasons such as the absence of hydrogen sulfide gas detector, the un-detectability of this hazard is “high”. This hazard is also “very highly” sensitive to the regular inspection and maintenance the failure of which could increase the frequency of release of toxic gas. The failure of respective safety measures such as cathodic protection, PSL, corrosion inhibitor injection due to poor safety management, inadequate training, and poor safety culture could highly impact the frequency of this hazard, resulting in a “absolutely high" SSM.

Explosion and fire caused by the ignition of released flammable chemicals is one of the significant hazards in the process plants(Lees 2012). Hazard 50, the ignition of released flammable gas in header and trunk line, is the 2nd top hazard according to the results of FMA-HAZOP whereas according to the results of HAZOP this hazard along with nine other hazards are ranked in the fourth place. In other words, using the three additional risk factors U, SM and SSM in FMA-HAZOP has helped differentiate among the hazards.

Hazard 17, i.e., the third top hazard in FMA-HAZOP and the forth top hazard in HAZOP is the well blowout. Well blowout is one of the most undesired and expensive accident in the oil and gas facilities(Khakzad et al., 2013 ), and extremely sensitive to the failure of safety measures such as SSSV, training and annulus pressure management (Zhang et al. 2018).

Thus, in FMA-HAZOP, hazards with higher sensitivity to failure of safety measures (e.g., hazards 14, 16, 17 and 50) take higher ranks compared to those in the conventional HAZOP. Likewise, hazards with higher sensitivity to maintenance (e.g., hazards14, 16, 17 and 50) take higher ranks compared to those in the conventional HAZOP.

## 5. Conclusions

In the present study, we developed FMA-HAZOP to alleviate the limitations of the conventional HAZOP by (i) incorporating more risk factors, that is, un-detectability, sensitivity to failure of safety measures, and sensitivity to maintenance effectiveness, than just the frequency and the severity of hazards, (ii) dealing with uncertainty about the degree of the risk factors via fuzzy set theory, and (iii) differentiating among the importance of the risk factors via multi-attribute decision making techniques such as AHP and TOPSIS.

Applying both the conventional HAZOP and FMA-HAZOP to a gas wellhead facility, it was demonstrated that FMA-HAZOP outperforms the conventional HAZOP although it is more time-consuming. FMA-HAZOP provides more information to safety managers about the hazards and their rankings, and thus facilitates the layout of more effective safety management strategies by narrowing the number of critical hazards.

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