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Differences in perception of the importance of process safety indicators between experts in Iran and the West

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A B S T R A C T

Introduction: The importance of safety in high-risk industries such as oil and gas facilities has been reported previously. Process safety performance indicators can provide insight into improving the safety of process industries. This paper aims to rank the process safety indicators (metrics) by Fuzzy Best-Worst Method (FBWM) using the data gathered through a survey. *Method:* The study uses a structured approach considering the UK Health and Safety Executive (HSE), the Center for Chemical Process Safety (CCPS), and the IOGP (International Association of Oil and Gas Producers) recommendations and guidelines to generate an aggregate set of indicators. It calculates the level of importance of each indicator based on the opinions of experts from Iran and some Western countries. *Results:* The findings of the study demonstrate that some lagging indicators such as the number of times processes do not proceed as planned due to insufficient staff competence and the number of unexpected disruptions of the process due to failure in instrumentation and alarms are important in process industries in both Iran and Western countries. Western experts identified process safety incident severity rate as an important lagging indicator, whereas Iranian experts considered this as relatively unimportant. In addition, leading indicators such as sufficient process safety training and competency, the desired function of instrumentation and alarms, and proper management of fatigue risk play an important role in enhancing the safety performance of process industries. Experts in Iran viewed permit to work as an important leading indicator, while experts in the West focused on fatigue risk management. *Practical Applications:* The methodology used in the current study gives a good view to managers and safety professionals in regard to the most important indicators of process safety and allows them to focus more on important process safety indicators.

1. Introduction

1.1. Background

The importance of safety in high-risk industries such as oil and gas facilities has been reported previously (Askarian et al., 2018; Moradi Hanifi et al., 2019; Omidi et al., 2021; Omidi et al., 2018). Process safety and risk analysis are generally considered to be of paramount significance in preventing fatalities and asset loss due to accidents (Amin et al., 2019). In order to monitor and improve the safety in process facilities and to provide ongoing assurance that major hazard risks are adequately controlled (HSE, 2006), process safety performance indicators (metrics) are applied (Khan et al., 2010).

Process safety performance indicators and the information they provide are required to create a safer process industry. Aggregating existing process safety indicators, sorting them into specific elements, determining their relative importance, and providing a risk score for each may not only help to reduce an over-abundance of indicators but also further reduce losses and improve safety. Reviewing existing indicators to define a small but effective number of indicators can reduce the effort required to collect necessary information (Pasman & Rogers, 2014). Simple and easy-to-use metrics and a small number of the best predictive indicators can improve the effectiveness of the safety management system (Khan et al., 2010; Sultana et al., 2019). In addition, implementing practical and actionable safety metrics in key areas can lead to improvements in performance outcomes and provide important information about the level of safety within the organization (Øien

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et al., 2011; Stough, 2012). The development of process safety indicators can give early warnings and may help prevent major accidents in process industries (Sultana et al., 2019). However, the type of safety performance indicators used and their number vary heavily across industries and between countries.

The levels of safety, accepted levels of risks, and safety regulations are different between countries. Furthermore, the levels of safety culture in high-hazard industries in Western (industrialized) countries are different from the cultural contexts of developing countries. These differences may lead to different risk perceptions and the use of different safety indicators in high-hazard industries in developed and developing countries (Manzey & Marold, 2009).

1.2. Lagging and leading indicators

Two types of process safety indicators (lagging and leading) are identified in the literature (Sultana et al., 2019; Swuste et al., 2016). Lagging indicators are a form of reactive monitoring based on measures of undesired outcomes such as injuries, accidents, near misses, and process safety incidents (CCPS, 2011; HSE, 2006; Louvar, 2010). Lagging indicators need to be monitored but these indicators do not provide adequate forewarning for preventing accidents (Louvar, 2010).

In contrast, leading indicators are a form of active monitoring based on the routine systematic checking of key actions or activities within the risk control systems. They can be considered as measures essential to deliver the desired safety outcome (HSE, 2006). Leading indicators focus on the performance of key work processes, operating discipline, or layers of protection that prevent incidents (CCPS, 2011). These indicators provide an early warning to prevent process accidents (Louvar, 2010). The key characteristics of leading indicators offered in the literature include simplicity with a close connection to outcomes, readily interpretable by different groups in the same way, objectively and reliably measurable, easily and accurately communicated, and broadly applicable across company operations (Sinelnikov et al., 2015; Stough, 2012).

Both leading and lagging indicators provide insights into the level of safety of a system. Leading indicators are associated with potential barrier failures and are proxies for hazards, while lagging indicators are associated with failures after an incident and are proxies of the events (Sultana et al., 2019; Swuste et al., 2016). The development of process safety indicators is an effective strategy to provide early warnings for major accidents and to measure how safety is managed within installations (Sultana et al., 2019).

1.3. Process safety in developing and developed countries

Process safety can affect chemical and manufacturing industries in both developing and developed countries. Major process safety incidents that occurred between the 1970s and the 1990s led to the development of process safety management in developed countries (Besserman & Mentzer, 2017). Developing countries have also addressed and promoted process safety, but more recently. Typically, developed countries have better reporting procedures, process safety metrics, and more developed process regulations, such as the process safety management regulations established by the U.S. Occupational Safety and Health Administration (OSHA, 1992), for preventing and mitigating loss incidents. In contrast, new process safety regulations in developing countries are based on previous regulations in developed countries. These help developing countries use learnings from developed countries to protect workers, the public, and the environment. Moreover, developed countries have better emergency response, infrastructure, more enforcement of regulations, and lower fatality rates than developing countries. The reported job fatality rate per region by the International Labor Organization (ILO) in 2001 for the United Kingdom was 0.84 per 100,000 workers and for India and China was 9.97 and 12.31, respectively (Besserman & Mentzer, 2017). It appears from major hazard incidents records in 2007 that the consequences of major incidents (such as the probability of lethality) are significantly higher in developing countries than in developed countries (Hemmatian et al., 2014). More incident reports in developed countries are due to better reporting procedures. Therefore, developed regions and developing countries are at different points in the evolution of process safety, which provides a basis for comparison (Besserman & Mentzer, 2017).

1.4. Guidelines and recommended practices on process safety indicators

Following the Texas City explosion and fire at the BP site, several organizations such as the UK Health & Safety Executive (UK HSE), the Center for Chemical Process Safety (CCPS), the American Petroleum Institute (API), and the Organization for Economic Cooperation and Development (the OECD) have developed recommendations or guidelines on process safety indicators (Zhen et al., 2019). The UK HSE (2006) framework considers the two types of indicators to provide dual assurance to confirm that the risk control system is operating as intended or process safety risks are being effectively managed. In the CCPS (2008 and 2011) guidelines, three types of process safety performance metrics are described (i.e., lagging metrics, leading metrics, and near-miss metrics). The CCPS (2011) metric recommendations are consistent with the API documents and contain examples of leading metrics and related quantifiable parameters (Swuste et al., 2016; Zhen et al., 2019).

OECD published guidelines on safety performance indicators in two versions; one for industry and the other for public authorities and communities. In these documents, developed by a group of experts, safety metrics are defined and classified into result indicators (reactive or lagging indicators) and activity indicators (proactive or leading indicators) (OECD, 2008a, 2008b).

A recommended practice (RP) for the refining and petrochemical industries was issued by the API (ANSI/API, 2010, 2016). Process safety indicators in the RP are categorized into four tiers. Tiers 1 and 2 (corresponding to lagging indicators) are intended for process safety events and public reporting, and tiers 3 and 4 (corresponding to leading indicators) are related to challenges to safety systems and operating discipline and management system performance for internal use within individual facilities.

The International Association of Oil & Gas Producers (IOGP) provided further guidance on key performance indicators (OGP report no. 456) to support the applicability of the API RP 754 and to reduce and eliminate process risks (IOGP, 2016a; Zhen et al., 2019). Leading indicators in the report are linked to preventive barriers and the lagging indicators are linked to de-escalating barriers. The report provides further guidance on the HSE framework and the ANSI/API RP754 (Swuste et al., 2016; Zhen et al., 2019).

1.5. Prioritization and weighting method

Safety professionals in process industries have different perspectives on safety performance indicators. These lead them to attach different levels of importance to each indicator and to assign different weights to measurements. Assigning different weights to different indicators allows managers and safety professionals to formulate different strategies for improving process safety. The factors considered to be more influential may vary by country, encouraging the adoption of different process safety management strategies.

To accommodate this variation between perspectives, multi-criteria decision-making (MCDM) may be used (Salimi & Rezaei, 2018). During the past decade, MCDM methods have increasingly been used for dealing with uncertainties and solving engineering problems (Antucheviciene et al., 2015). MCDM methods are appropriate where there is uncertainty, for example through vagueness (due to the lack of complete information) or ambiguity (arising from the qualitative judgment of decision-makers) (Guo & Zhao, 2017). Consequently, they are helpful for tackling real-world issues that share these characteristics (Wang & Lee, 2009). The best-worst multi-criteria decision-making method (BWM), as a new MCDM method, was proposed by Rezaei (2015). Unlike other MCDM methods, the BWM obtains the weights of criteria and alternatives with respect to different criteria by using least pairwise comparisons. Extending BWM to the fuzzy environment (fuzzy BWM or FBWM) and the employment of fuzzy information may be a more appropriate way for tackling convoluted decision-making problems under an uncertain environment (Guo & Zhao, 2017; Hafezalkotob & Hafezalkotob, 2017). It is noteworthy that the BWM procedure seems to be much easier, more accurate, and less redundant than the conventional MCDM procedures because the method does not require secondary comparisons (Guo & Zhao, 2017; Rezaei, 2015).

1.6. Research purpose

The aim of this paper is to demonstrate the difference in ranking of process safety indicators between experts in Iran and in the West using FBWM and based on fuzzy preference comparisons. Specifically, the paper will:

i. use a structured approach considering the UK HSE, the CCPS, and the IOGP recommendations and guidelines to aggregate the indicators and to identify a reduced number of suitable indicators for process safety;
ii. capture perceived importance of process safety indicators from experts in Iran and the West;
iii. describe and apply FBWM to evaluate two sets of indicators including lagging and leading indicators;
iv. account for differences in expert perceptions between Iran and the West.

Experts' subjective evaluations of process safety indicators are anticipated to reflect the focus and the level of process safety and related indicators in Iran and Western countries, permitting comparison.

2. Method

The importance of process safety indicators has been addressed in scientific literature and in the reports of national and international organizations (Swuste et al., 2016). This study is based on the UK HSE guideline, the CCPS recommendations, and the IOGP guideline. These guidelines and recommendations consist of process safety indicators that are scientifically designed to consider process sensitivity, measurable values, and monitorable parameters, and contain easy-to-use metrics (Khan et al., 2010).

Process safety indicators classified into leading and lagging indicators were ranked by experts. The experts were experienced staff within the field of process safety and involved in the process industries in Iran (as a developing country) and Western countries (Western Europe and the United States) (as developed countries). Fig. 1 presents the safety practitioners' working experience. Almost 50% of the Iranian respondents had more than 10 years of work experience. Among the Western experts, 60% had more than 25 years of experience.

2.1. The basis for the study of lagging and leading indicators

Definitions for lagging and leading indicators were drawn from the UK HSE, the CPPS, and the IOGP (Fig. 2). In this study, some indicators from the HSE guide such as the number of incidents or unexpected disruption of process due to deficiencies in plant change and permit to work were considered as lagging indicators and the percentage of successful process implementation due to the appropriate inspection/maintenance and the appropriate level of staff competence were regarded as leading indicators (HSE, 2006). Process Safety Total Incident Rate (PSTIR) and Process Safety Incident Severity Rate (PSISR) were considered as lagging metrics in CCPS recommendations (CCPS, 2011), and used here. In addition, three safety performance indicators including fatal accident rate (FAR), total recordable injury rate (TRIR), and lost time injury frequency (LTIF) from the IOGP were considered as other lagging indicators (Fig. 2) (IOGP, 2016b, 2019).

2.2. Procedure

After determining the indicators from related guidelines, these were weighted by experts who have worked in the oil and gas industries in Iran or Western countries, in a comparative study was conducted to weight the indicators by experts who have had

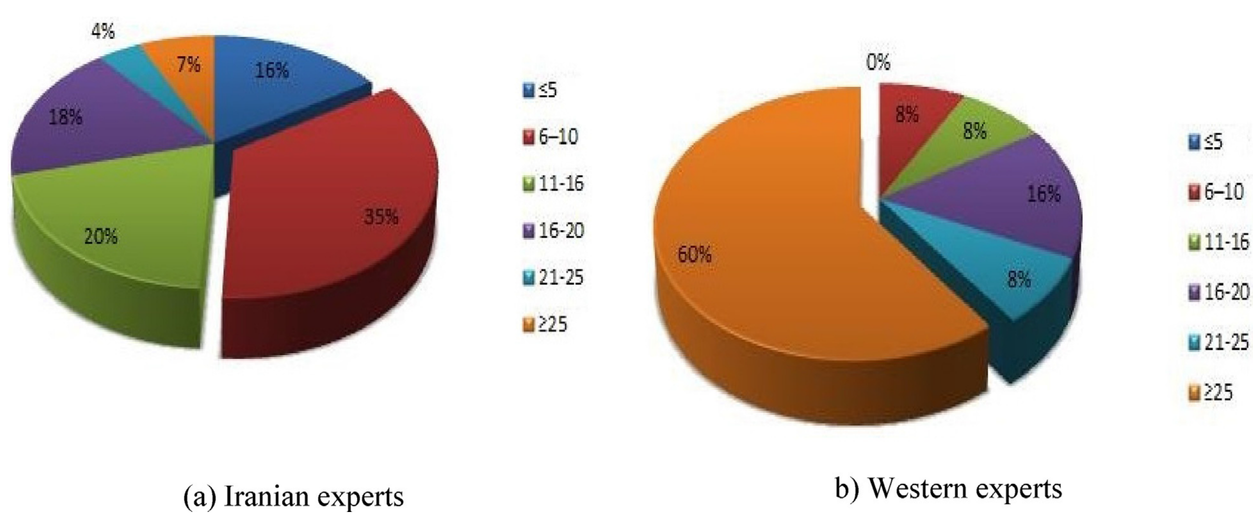


Fig. 1. Distribution of experts based on their work experience.

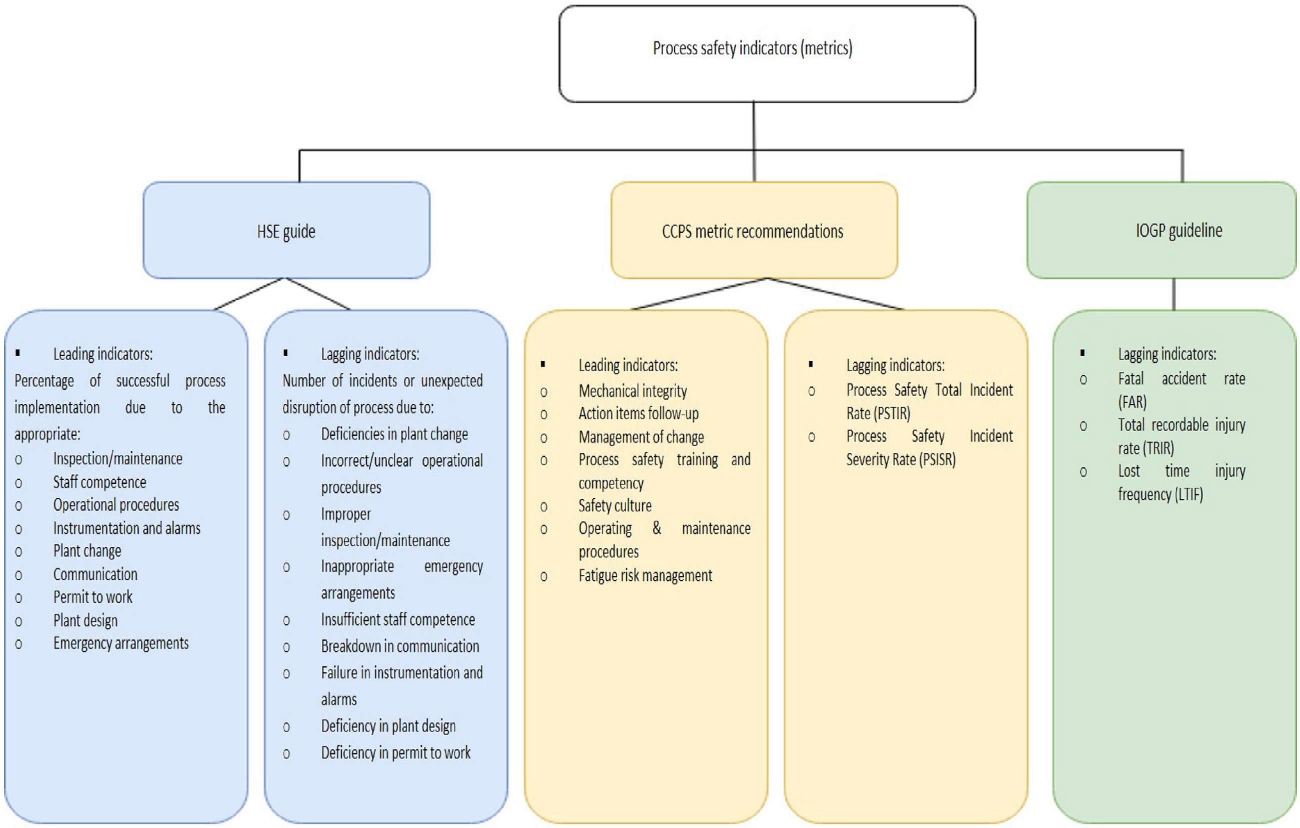


Fig. 2. Process safety indicators incorporated in the survey questionnaire.

either past or current work experience in the context of oil and gas industries in Iran and in Western countries. A questionnaire was developed to gather data in relation to each indicator. The questionnaire was sent by email to respondents. A total of 35 questionnaires were sent to Iranian industrial practitioners, and 32 questionnaires were returned (response rate = 91%). The questionnaire was sent to 23 Western industrial practitioners, and 13 questionnaires were returned (response rate = 56%). Fig. 3 shows the workflow of the approach used in the current study.

2.2.1. Determination of the importance of indicators

FBWM as a pairwise comparison-based method was applied to determine the fuzzy weights of indicators. The procedure of FBWM can be described in a series of steps (Guo & Zhao, 2017; Hafezalkotob & Hafezalkotob, 2017; Rezaei et al., 2017; Rezaei, 2015):

1. Determine the decision criteria system. In the first step, the criteria {C1, C2,..., Cn}that should be used for decision making are considered. In this work, these are process safety indicators.
2. Determine the best (B) and the worst (W) criteria. The best (most important) and the worst (least important) criteria are identified by decision-makers (respondents).
3. Execute the fuzzy preference comparisons for the best criterion. The fuzzy preference of the best criterion over all the other criteria is determined. The linguistic terms of preferences (Table 1) are used to determine the fuzzy preference of the most important (best) criterion over all the criteria. Then, the transformation of obtained fuzzy preference to triangular fuzzy numbers (TFNs) ($a_{Bj} = (a^L_{Bj}, a^M_{Bj}, a^U_{Bj})$) is done according to the transformation rules. The resulting fuzzy Best-to-Others vector would be:

$$A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn})$$

where A_B indicates the fuzzy Best-to-Others vector; a_{Bj} indicates the fuzzy preference of the best criterion c_B over criterion j, $j = 1, 2, \ldots, n$. Since each criterion is equally important in comparison with itself then the fuzzy preference of the best criterion over itself would be $a_{BB} = (1, 1, 1)$.

4. Execute the fuzzy preference comparisons for the worst criterion. The fuzzy preferences of all the criteria over the worst criterion are extracted using the linguistic variables. The fuzzy preferences of all the criteria over the worst criterion are determined, and the obtained fuzzy preferences are transformed to TFNs ($a_{Bj} = (a^L_{jW}, a^M_{jW}, a^U_{jW})$) according to the transformation rules. The resulting fuzzy Others-to-Worst vector would be:

$$A_W = (a_{1W}, a_{2W}, \ldots, a_{nW})$$

where A_W indicates the fuzzy Others-to-Worst vector; a_{iW} indicates the fuzzy preference of criterion i over the worst criterion c_W, $i = 1, 2, \ldots, n$. Since in the comparison process the worst criterion is equally important in comparison with itself then the fuzzy preference of the worst criterion to itself is $a_{WW} = (1, 1, 1)$.

5. Find the optimal weights $(w^*_1, w^*_2, \ldots, w^*_n)$. The optimal weight for the criterion j (w_j) is the one where for each fuzzy pair of w_B/w_j and w_j/w_W, we have $w_B/w_j = a_{Bj}$ and $w_j/w_W = a_{jW}$. Where w_B indicates the weight of the best criterion and w_j is the weight of the worst criterion. To satisfy these conditions for all j, a solution should be determined where the maximum absolute differences $\left|\frac{w_B}{w_j} - a_{Bj}\right|$ and $\left|\frac{w_j}{w_W} - a_{jW}\right|$ for all j is minimized. The optimization problem for determining the optimal fuzzy weights $(w^*_1, w^*_2, \ldots, w^*_n)$ can be determined as follows.

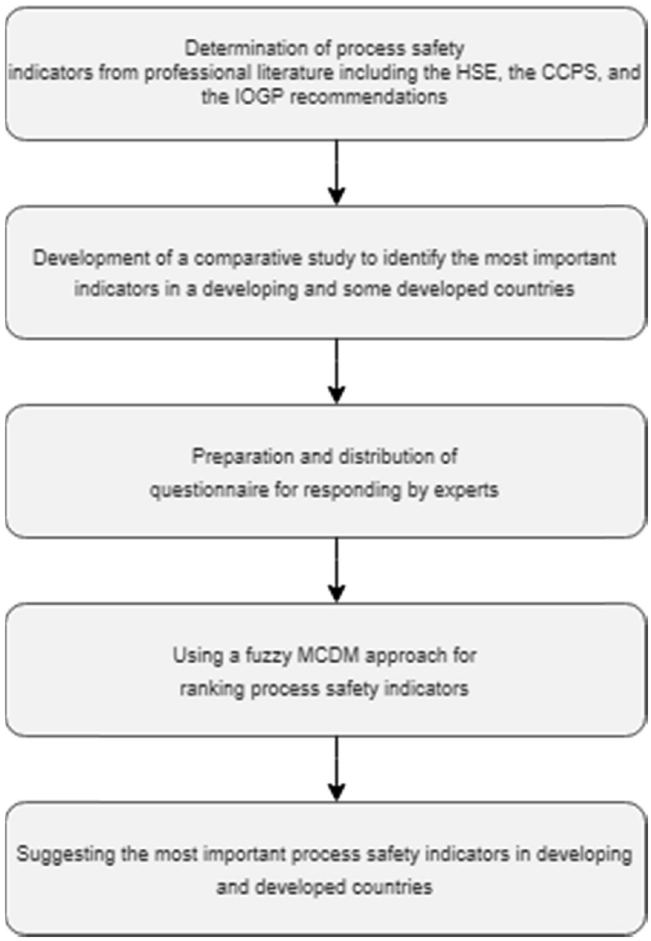


Fig. 3. The workflow of the study comparing the expert opinions regarding lagging and leading indicators.

Table 1
Linguistics variables for evaluating the factors.

Linguistics terms	Membership function
Equally important (EI)	(1,1,1)
Weakly important (WI)	(0.666,1,1.5)
Fairly important (FI)	(1.5,2,2.5)
Very important (VI)	(2.5,3,3.5)
Absolutely important (AI)	(3.5,4,4.5)

$$\min \quad \varepsilon,$$

$$s.t.$$

$$w_B - \varepsilon \lesssim a_{Bj} w_j, \quad \text{for all } j,$$

$$w_B + \varepsilon \gtrsim a_{Bj} w_j, \quad \text{for all } j,$$

$$w_j - \varepsilon \lesssim a_{jW} w_W, \quad \text{for all } j,$$

$$w_j + \varepsilon \gtrsim a_{jW} w_W, \quad \text{for all } j,$$

$$\sum_j w_j = 1,$$

$$w_j \geq 0, \quad \text{for all } j$$

In the above problem, the symbol $\lesssim$ refers to "almost lesser than" which is used to consider fuzzy values in the model. Transferring the fuzzy constraints to the crisp equivalents would lead to the following problem:

$$\min \quad \varepsilon,$$

$$s.t.$$

$$w_B - \varepsilon \leq \left[a_{Bj}^M + (1-\alpha)a_{Bj}^U\right] w_j \quad \text{for all } j,$$

$$w_B + \varepsilon \leq \left[a_{Bj}^M - (1-\alpha)a_{Bj}^L\right] w_j \quad \text{for all } j,$$

$$w_j - \varepsilon \leq \left[a_{jW}^M + (1-\alpha)a_{jW}^U\right] w_W \quad \text{for all } j,$$

$$w_j + \varepsilon \leq \left[a_{jW}^M - (1-\alpha)a_{jW}^L\right] w_W \quad \text{for all } j,$$

$$\sum_j w_j = 1,$$

$$w_j \geq 0, \quad \text{for all } j$$

where, $\alpha (0 \leq \alpha \leq 1)$ indicates a possibility level defined by the decision maker, while a_{Bj}^U, a_{Bj}^M and a_{Bj}^L respectively stand for upper bound, middle value, and lower bound of the triangular fuzzy number describing the fuzzy preference of the best criterion over criterion j. Similarly, a_{jW}^U, a_{jW}^M , a_{jW}^L represent the upper bound, middle value, and lower bound of the triangular fuzzy number describing the fuzzy preference of criterion j over the worst criterion. The optimal fuzzy weights $(w_1^*, w_2^*, \ldots, w_n^*)$, can be determined by solving the problem.

In addition, in the current study, a hierarchical structure was developed to determine the weight of each leading indicator. For this purpose, three criteria (levels or aspects) consisting of organizational, human, and technical were considered for leading indicators, each of which included sub-criteria (sub-aspects). Organizational criteria included mechanical integrity, action items follow-up, management of change (plant change), safety culture, operating & maintenance procedures (operational procedures), emergency arrangements, and inspection/maintenance. Human criteria included process safety training and competency, fatigue risk management, and communication. Technical criteria included instrumentation and alarms, plant design, and permit to work.

2.2.2. Actionability of the process safety indicators

The actionability (practicability) of each lagging/leading indicator was examined as well. For determining the actionability of each indicator, respondents were requested to determine the actionability of each study indicator based on the available information on the companies or publicly available databases of process industries in their countries. The respondents rated the actionability of each indicator on a five-point scale from very low to very high.

The possible values for actionability (practicability) were described based on the linguistic variables (terms) of decision-makers. The linguistic evaluations were transformed to fuzzy numbers (represented by TFNs). The process of fuzzification and defuzzification were applied to determine the actionability of each indicator in relation to applications in process industries and to compute the score for each indicator based on experts' evaluation. Table 2 presents the description of linguistic variables of actionability.

Table 2
Linguistics variables for actionability.

Linguistics terms	Membership function
Very low	(0,1,1.5)
Low	(0.5,1.5,2.5)
Moderate	(1.5,2.5,3.5)
High	(2.5,3.5,4.5)
Very high	(4.5,5,5)

Table 3
Linguistics variables for the perceived probability.

Linguistics terms	Membership function
Very low	(0,0,0.3)
Low	(0.1,0.3,0.5)
Moderate	(0.3,0.5,0.7)
High	(0.5,0.7,0.9)
Very high	(0.9,1,1)

2.2.3. The score of indicators

The safety score of each indicator was calculated from the perceived importance of the indicator, the perceived probability of incident occurrence due to failure to observe the indicators, and the perceived compliance status of the indicator (Tang et al., 2018b). The perceived importance of indicators was determined using FBWM. The respondents were asked to rate the perceived probability of incident occurrence due to failure to observe the indicators on a five-point scale. The higher the perceived rating of each indicator, the higher level of perceived probability. The perceived compliance status of each indicator was determined based on a numbering system adapted from the traffic light system proposed by the HSE in its Asset Integrity Key Program where red, amber, and green indicate non-compliance, partial compliance (the desired status has not been met), and compliance, respectively (HSE, 2008; Tang et al., 2018a). In the numbering system, "0" was assigned for indicators without data, and "1," "2," and "3" were assigned for non-compliance, partial compliance, and compliance, respectively. The comparison of indicators' performance by the respective performance targets or standards was applied to determine the compliance status.

The weight of each indicator (W_i) was calculated by multiplying the perceived importance of the indicator (I_i) with the perceived probability of incident occurrence due to failure to observe the indicator (P_i) and the safety score of an indicator (a) was obtained by multiplying the number assigned to the compliance level of an indicator (C_i) with the weight of the indicator (W_i), as follows:

$$W_i = I_i \times P_i$$

$$\text{Score of each indicator}, \quad a = W_i \times C_i$$

A higher score represents greater compliance with performance targets.

The possible values for each of the variables related to the perceived probability of incident occurrence due to failure to observe the indicators and the perceived compliance status were described based on the linguistic variables (terms) of decision-makers.

The linguistic evaluations were transformed into fuzzy numbers (represented by TFNs). The process of fuzzification and defuzzification were applied to compute the score for each indicator based on experts' evaluations. Table 3 and Table 4 show the descriptions of linguistic variables of perceived probability and compliance status specified by mathematical explanations (fuzzy membership function). In this work, the average method was applied for the defuzzification of fuzzy outputs.

2.2.4. Fuzzy risk assessment for leading indicators

For leading indicators, the perceived risk level was determined. The level of perceived risk was determined based on experts' judgment. Experts were safety practitioners from Iran and Western countries. Good risk understanding, adequate expertise, and subjective (knowledge-based) judgments about risk based on probabilities are required for risk assessment (Aven & Krohn, 2014; Aven et al., 2011). The comparison arises because perceptions of risk are different between countries (Keown, 1989) and levels of safety are different in the process sectors of Iran and the West.

Table 4
Linguistics variables for the compliance status.

Linguistics terms	Membership function
Without data "0"	(0,0,1.5)
Non-compliance "1"	(0.5,1.5,2.5)
Partial compliance "2"	(1.5,2.5,3.5)
Compliance "3"	(3.5,4,4)

The perceived risk value of the indicator (R_i) is the product of severity (S_i) and likelihood of occurrence (or probability) (P_i) as: $R_i = S_i \times P_i$ (Gul & Guneri, 2016). In the current study, the perceived risk of the indicator was calculated by multiplying the perceived severity of consequences (or outcomes) due to failure to observe the indicator with the perceived probability of incident occurrence due to failure to observe the indicator. Measurement of this perceived probability was done using a five-point scale from 1 = rare to 5 = almost certain. For determining the perceived severity of consequences (or outcomes) due to failure to observe the indicator, the respondents were requested to indicate the perceived severity on a five-point scale from 1 = insignificant to 5 = catastrophic. The acceptability level of the perceived risks was determined based on the risk assessment matrix provided by Gul and Guneri (2016) (Table 5).

In process risk analysis, due to the number of uncertainties, real situations are very often not crisp and deterministic. In these circumstances, a fuzzy logic system (FLS) can be employed (Markowski & Mannan, 2008) to develop a fuzzy risk assessment. This was used here because the categorization of probability and severity in a traditional approach is imprecise and vague and can lead to major uncertainties concerning the risk category.

The steps of FLS, used to assess the perceived risks, are as follows (Markowski & Mannan, 2008, 2009; Yen & Langari, 1999):

1. The fuzzifier transforms crisp inputs into fuzzy inputs. In the fuzzification process, the mapping of the linguistic variables of each risk matrix component including probability, severity, and risk into fuzzy sets is performed in order to activate rules. Input variables for developing fuzzy risk assessment and their domain in a number of fuzzy sets are shown in Table 6. Different forms of a membership function can be used based on the type of input and output variables.
2. Inference engine of the FLS maps input fuzzy sets into fuzzy output sets by a set of rules. It handles the way in which rules are combined. The set of rules for risk assessment is created based on the logic of the traditional risk matrix. IF $\bar{p}_n$ is probability AND $\bar{s}_m$ is severity of consequences THEN risk is $\bar{r}_z$. $\bar{p}_n$, $\bar{s}_m$, and $\bar{r}_z$ represent the fuzzy sets in relation to probability, severity, and risk in a universe of discourse, respectively. The set of 25 knowledge rules (e.g., **IF** Probability is "Possible" and Severity of Consequence is "Moderate" **THEN** Risk Category (Level) is "Intermediate Risk") was generated using the risk matrix consisting of 5 categories of probability, 5 categories of severity, and 5 categories of risk. The Mamdani fuzzy inference system was applied to convert the qualitative rules into quantitative

Table 5
The risk assessment matrix.

	Perceived probability				
Perceived severity	Rare (1)	Unlikely (2)	Possible (3)	Likely (4)	Almost certain (5)
Insignificant (1)	Insignificant risks	Acceptable risks	Acceptable risks	Acceptable risks	Acceptable risks
Minor (2)	Acceptable risks	Acceptable risks	Acceptable risks	Intermediate risks	Intermediate risks
Moderate (3)	Acceptable risks	Acceptable risks	Intermediate risks	Intermediate risks	Significant risks
Major (4)	Acceptable risks	Intermediate risks	Intermediate risks	Significant risks	Significant risks
Catastrophic (5)	Acceptable risks	Intermediate risks	Significant risks	Significant risks	Unacceptable risks

Table 6
Fuzzy sets for risk value in a comparison of expert opinions between Iran and Western countries.

Linguistic variables	Linguistic term (fuzzy set)	Descriptive range	Universe of discourse
Probability	Rare	$0 \le L \le 0.3$	$L \in (0, 1)$
	Unlikely	$0.1 \le L \le 0.5$	
	Possible	$0.3 \le L \le 0.7$	
	Likely	$0.5 \le L \le 0.9$	
	Almost certain	$0.7 \le L \le 1$	
Severity of consequences	Insignificant	$0 \le S \le 1.5$	$S \in (0, 5)$
	Minor	$0.5 \le S \le 2.5$	
	Moderate	$1.5 \le S \le 3.5$	
	Major	$2.5 \le S \le 4.5$	
	Catastrophic	$3.5 \le S \le 5$	
Risk category	Insignificant	$0 \le R \le 0.45$	$R \in (0, 5)$
	Acceptable	$0 \le R \le 1.75$	
	Intermediate	$0.25 \le R \le 3.15$	
	Significant	$1.05 \le R \le 5$	
	Intolerable	$2.45 \le R \le 5$	

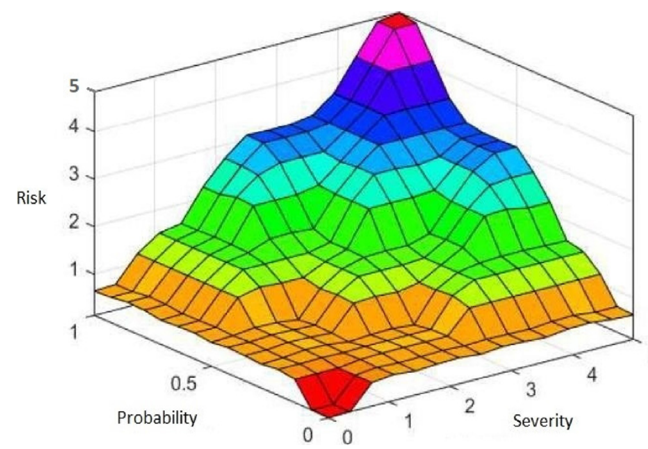


Fig. 4. Risk surface in the current study.

results (Mamdani & Assilian, 1975; Yen & Langari, 1999). After evaluating the rules, the aggregation of the output of different rules was performed. The aggregated output membership function is expressed as follows:

$$\mu_{R^-}(r) = \max_k \{min\mu^k_{P^-}(p_n), \mu^k_s, \mu^k_{R^-}(r_Z)\}$$

where k, n, m, and z are the number of rules, the number of fuzzy probability sets, the number of fuzzy severity sets, and the number of fuzzy risk sets, respectively.

3. Defuzzification is the process of the conversion of the final fuzzy set into a crisp number. In the process, weighting and averaging the outputs from all of the individual fuzzy rules into a crisp numerical output value are carried out. There are various methods for defuzzification. In the current study, the center of area (COA) or the centroid method was used for defuzzification. The defuzzified output applying COA defuzzification method for the risk category (level) can be expressed by the following formula:

$$r_{crisp} = \frac{\int \mu_{\bar{R}}(r) r dr}{\int \mu_{\bar{R}}(r) dr}$$

where r is the output variable (risk category), r_{crisp} denotes the crisp quantity of the output variable and $\int \mu_{\bar{R}}(r)$ indicates the aggregated membership function.

The mapping from two input parameters (probability and severity) to one output parameter (risk) provides a basis from which the relationship between probability, severity, and risk can be illustrated by a three-dimensional plot (fuzzy risk surface). The risk surface (Fig. 4) was illustrated based on input parameters and different regions of risk (Markowski & Mannan, 2008).

3. Results

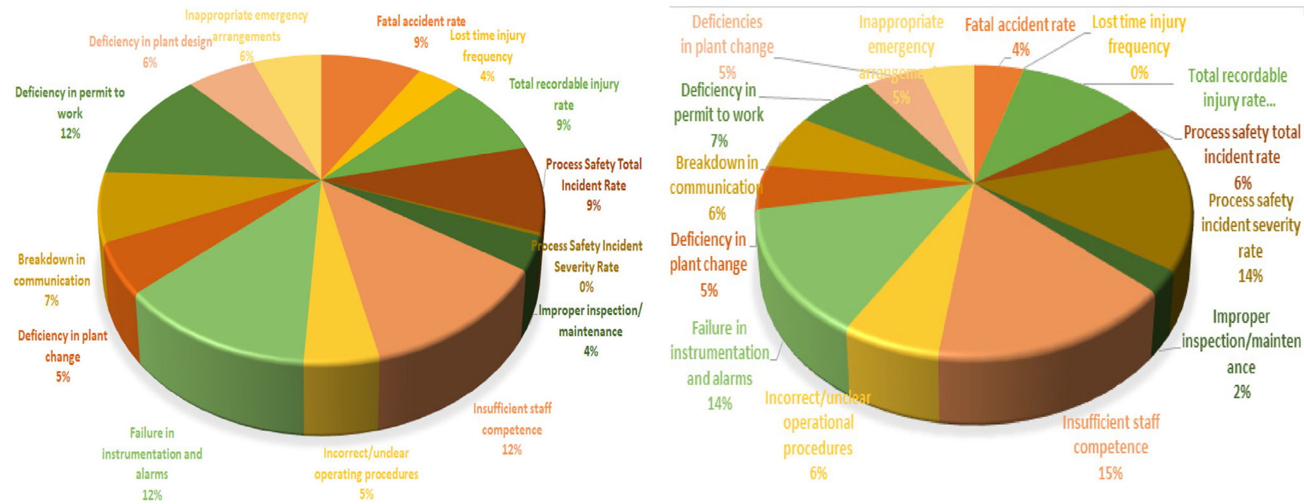
3.1. Lagging indicators

Lagging indicators that are based on incidents and events were defined based on the HSE guide, the CCPS recommendation, and the IOGP guideline. For each lagging indicator, the perceived importance, the actionability, and the score of the indicator from Iranian and Western experts' viewpoints were determined.

As can be seen from Fig. 5, based on the results obtained using FBWM, two important lagging indicators that were consistent between Iranian and Western experts were the failure in instrumentation and alarms and insufficient staff competence. Notably, Western experts identified PSISR as an important lagging indicator, whereas Iranian experts considered this to be the least important lagging indicator. All experts agreed that LTIF and the number of incidents or unexpected disruptions of process due to improper inspection/maintenance were the least important lagging indicators. Experts from the West also considered FAR to be less important.

In addition, deficiency in the permit to work and LTIF were some of the more important actionable lagging indicators in both contexts. LTIF was considered to be less important but actionable in both study contexts (Table 7). Experts from Iran also identified the number of times processes do not proceed as planned due to incorrect/unclear operational procedures and the number of unexpected disruption of process due to failure in instrumentation and alarms as the other important actionable lagging indicators. Those experts from the West noted FAR and inappropriate emergency arrangements as the other important actionable lagging indicators (Table 7).

In terms of the safety scores of lagging indicators, LTIF and PSTIR had low compliance with safety standards in the West and



(a) Iran (b) Western countries

Fig. 5. Perceived relative importance of the lagging indicators for process industries in Iran and Western countries.

Table 7
Actionability and safety scores for lagging indicators in Iran and the West.

Lagging indicator	Iran		Western countries	
	Actionability	Score of lagging indicator	Actionability	Score of lagging indicator
Fatal accident rate (FAR)	2.384	0.037	3.861	0.023
Lost time injury frequency (LTIF)	2.909	0.012	3.667	0.0002
Total recordable injury rate (TRIR)	2.586	0.030	3.472	0.049
Process safety total incident rate (PSTIR)	2.036	0.019	3.125	0.021
Process safety incident severity rate (PSISR)	1.552	0.0004	2.875	0.050
Number of incidents or unexpected disruption of process due to:				
Deficiencies in plant change	2.111	0.020	3.153	0.024
Incorrect/unclear operational procedures	2.788	0.023	3.208	0.030
Improper inspection/maintenance	2.596	0.035	3.639	0.013
Inappropriate emergency arrangements	2.545	0.031	3.681	0.027
Insufficient staff competence	2.313	0.045	3.139	0.064
Breakdown in communication	1.929	0.025	3.139	0.027
Failure in instrumentation and alarms	2.737	0.069	3.361	0.072
Deficiency in plant design	2.510	0.023	3.028	0.020
Deficiency in permit to work	3.152	0.079	3.486	0.040

Iran, respectively. Also, deficiencies in plant change and plant design were similarly rated by both sets of experts as lagging indicators that had low compliance, suggesting that they are universally important contributory factors in process safety incidents. For any lagging indicator, low safety scores indicate that incidents and disruptions associated with that indicator are more likely. Western experts gave improper inspection/maintenance a low score suggesting its importance as a cause of incidents in process industries (Table 7).

3.2. Leading indicators

The local and global weights of each leading indicator from Iranian and Western experts' viewpoints are shown in Table 8. In the current study, a hierarchical structure was developed to determine the weight of each leading indicator. Three criteria consisting of organizational, human, and technical were considered for leading indicators, each of which included sub-criteria. The optimal fuzzy weight was obtained for each leading indicator in the defined criteria.

In both contexts, organizational and human criteria had higher weights than technical criteria. Western experts weighted organizational and human criteria equally (weight = 0.400), whereas Iranian experts considered organizational criteria (weight = 0.424) as the most important criterion. Experts from Iran identified emergency arrangements and management of change (plant change) as the most important sub-criteria of the organizational criterion, while those in the West noted operational procedures and action items follow-up as the most important sub-criteria of the organizational criterion (Table 8).

The global weights of the sub-criteria were used to compare the actual weights of all sub-criteria. For this purpose, the relative weights were multiplied by the weights of the main criteria (Rezaei et al., 2015). In both settings, the appropriate process safety training and competency was the most important leading indicator. This was followed by instrumentation and alarms. Experts in Iran also viewed permit to work as an important leading indicator, while experts in the West focused on fatigue risk management. Overall the least important indicator appeared to be inspection/-maintenance. Some other indicators showed large variation between settings, for example plant design and action items

Table 8
Results of FBWM-weights of criteria and sub-criteria related to leading indicators.

Criteria	Iran	Western countries	Sub-criteria	Iran			Western countries		
	Criteria weights	Criteria weights		Sub-criteria weights	Global weights	Rank	Sub-criteria weights	Global weights	Rank
Organizational	0.424	0.400	Mechanical integrity	0.091	0.028	13	0.143	0.038	8
			Action items follow-up	0.111	0.034	12	0.179	0.048	6
			Management of change (plant change)	0.176	0.053	6	0.143	0.038	9
			Safety culture	0.158	0.048	8	0.143	0.038	10
			Operating & maintenance procedures (operational procedures)	0.148	0.045	9	0.179	0.048	7
			Inspection/maintenance	0.116	0.035	11	0.071	0.019	13
			Emergency arrangements	0.199	0.060	5	0.143	0.038	11
Human	0.294	0.400	Process safety training and competency	0.403	0.085	1	0.445	0.119	1
			Fatigue risk management	0.359	0.075	4	0.364	0.097	2
			Communication	0.238	0.050	7	0.182	0.049	5
Technical	0.282	0.200	Instrumentation and alarms	0.400	0.081	3	0.400	0.053	3
			Plant design	0.200	0.040	10	0.400	0.053	4
			Permit to work	0.400	0.081	2	0.200	0.027	12

Table 9
Actionability, safety scores, and risk values for leading indicators in Iran and the West.

Leading indicators	Iran			Western countries		
	Actionability	Score of leading indicator	Risk value	Actionability	Score of leading indicator	Risk value
Percentage of successful process implementation due to the appropriate:						
Mechanical integrity	1.879	0.018	2.960	3.056	0.084	3.700
Action items follow-up	1.626	0.052	2.930	3.056	0.087	3.170
Management of change (plant change)	2.273	0.082	2.930	3.194	0.070	3.190
Safety culture	1.586	0.028	2.880	2.083	0.056	3.040
Operating & maintenance procedures (operational procedures)	3.150	0.077	2.870	3.028	0.089	3.140
Inspection/maintenance	2.045	0.049	3.040	3.278	0.040	3.300
Emergency arrangements	2.636	0.115	3.110	3.444	0.088	3.480
Process safety training and competency	3.242	0.151	3.010	2.889	0.187	2.930
Fatigue risk management	2.056	0.030	2.860	2.083	0.132	3.840
Communication	2.141	0.037	2.900	2.556	0.076	2.930
Instrumentation and alarms	2.297	0.060	2.990	3.000	0.115	3.540
Plant design	2.364	0.058	3.030	2.500	0.092	3.320
Permit to work	2.893	0.156	3.100	3.139	0.059	3.270

follow-up were rated highly by experts in the West but not in Iran. Conversely, permit to work and emergency arrangements were rated highly by experts in Iran but not in the West.

Furthermore, as shown in Table 9, scores for actionability of leading indicators generally were greater in the reports of Western experts than those from Iran. Western experts identified emergency arrangements, inspection/maintenance, and management of change (plant change) as the three most actionable leading indicators, whereas Iranian experts considered process safety training and competency, operating and maintenance procedures (operational procedures), and permit to work as the three most actionable leading indicators. The least actionable indicator in both settings was safety culture because it is difficult to manage and manipulate.

In terms of the safety scores, while the leading indicator with the greatest weight by both sets of experts was process safety training and competence, the other most highly ranked indicators differed. These were permit to work and emergency arrangements for Iranian experts and fatigue risk management and instrumentation and alarm for Western experts. In terms of safety score, fatigue risk management obtained a relatively lower weight than other indicators in Iran compared with its relative score in the West, and permit to work obtained relatively lower weight in the West than other indicators compared with the situation in Iran (Table 9).

The perceived risk values for leading indicators were different between experts from Iran and the West (Table 9). In Iran, experts considered the three greatest risks associated with emergency arrangements, permit to work, and inspection/maintenance. In contrast, Western experts rated fatigue risk management, mechanical integrity, and instrumentation and alarms as the three greatest risks. Notably, the risk level related to fatigue risk management was perceived highest by the Western experts but lowest by those from Iran. Safety-related communication was not rated as a high risk in either setting, suggesting that this is well covered in practice.

4. Discussion

Safety indicators in process facilities are used as a predictive signal for major accidents. These indicators report the performance of the installation reflecting the effectiveness of the safety management system and differences in risk levels. Process safety indicators have been developed in different industries and at different time periods based on safety level and company goals (Swuste et al., 2016). In addition, the application of process safety indicators differs between countries, so a comparison of process safety indicators may show similarities or differences between developing and developed countries and thus may help to enhance the safety performance in process facilities of both sets of countries (Besserman & Mentzer, 2017; Swuste et al., 2016).

This study showed some similarities and some clear differences in the lagging indicators believed to be the more important ones by experts in Iran and the West. Failure in instrumentation and alarms and insufficient staff competence were important in both settings. Deficiencies in permit to work processes were considered important in Iran, whereas PSISR was considered to be important in the West. Failure in complying with permit to work processes is identified as a reason for some accidents such as HSE, 2005. Establishing an appropriate and effective permit to work system in process industries can help prevent and reduce process accidents (HSE, 2005; Jahangiri et al., 2016). In addition, process industries in Iran need to attend to the severity of process incidents (Soltanzadeh et al., 2019). The contributory effects of failure of work permit procedures in accidents, the importance of instrumentation and alarm systems in the safety analysis and in mitigating an abnormal state and major-accident conditions, and the effective role of training and competence on major accidents are reported in other studies (Do Koo et al., 2019; Hemmatian et al., 2014; Keown, 1989; Kim et al., 2019). The greater importance attached to PSISR in the West than in Iran perhaps suggests that there is a need for developing countries to attend to some specific process safety indicators and rate-based process safety metrics (such as PSISR) for measuring process safety performance and improving safety (CCPS, 2011).

With regards to leading indicators, this study shows that some leading indicators such as process safety training and competency, instrumentation and alarms, and fatigue risk management are important in both Iran and the West. The importance and the current status of process safety training and competency in the process industries is clearly critical and is considered an essential leading indicator (Sultana et al., 2019). Both operator fatigue and failed and insufficient instrumentation can lead to major accidents in the process industries (Knegtering & Pasman, 2009), so the proper functioning of instrumentation and alarms and the proper management of fatigue risk are considered important indicators for executing the processes safely and preventing process safety incidents. Experts in this study confirmed this. An important difference between the data obtained from experts in developing and developed countries was related to plant design. Plant design (compliance of safety critical items of plant with current design standards or codes) was identified as another important leading indicator in the West, whereas it had lower importance in Iran. Ensuring safety critical items of plant or equipment are compliant with the relevant standard is essential for the continued delivery of safe outcomes (HSE, 2006).

Perceptions of risk for leading indicators, as indicated by fuzzy risk assessments, were higher in the opinion of Western experts compared to those in Iran. This may be a function of the relatively greater age and experience of the respondents from the West compared with those from Iran. Experience of decision-making in critical operational situations could influence the expert's subjective judgments (Aven & Krohn, 2014). Past experience and the experience of negative safety outcomes can also influence the level of perceived risk and people's perception of hazards (Keller et al., 2006). In addition, the difference may also be a function of cultural background. Perception and evaluation processes are different between different societies having different cultural values and risk components, and this can affect individual's perception of risks (De Camprieu et al., 2007).

The higher values of perceived risks by experts in Western countries may lead to greater efforts to improve process safety, enhance compliance with safety rules and procedures, and may create a greater desire for participation in process safety-related issues. Fuzzy risk assessments for leading indicators revealed that emergency arrangements and permit to work were perceived to be the greatest risk by experts from Iran, whereas experts in the West considered fatigue risk management and mechanical integrity to be the greatest risks. Higher risk perceptions can result in more protective behavior (Xia et al., 2017).

In addition, FBWM used in the current work, as a recently developed method, gives managers and process safety practitioners in both developing and developed countries the opportunity to establish effective strategies for enhancing process safety by identifying the most influential factors and indicating where attention and effort should be placed. In comparison to existing MCDM approaches, FBWM needs less data and a full pairwise comparison matrix is not needed. The structured pairwise comparison system in the Best Worst Method produces more consistent results (Guo & Zhao, 2017; Salimi & Rezaei, 2018).

This study has a number of limitations. Only the experts' opinions and judgments about process safety indicators were considered and the actual data from specific facilities were not taken into account. Future work could compare site-specific information and process safety indicators in actual facilities from both developing and developed countries to show differences and similarities in the application of process safety indicators in actual facilities. Furthermore, the data in relation to developing countries were gathered only from Iran. Therefore, the representativeness of data is insufficient and the generalizability of the conclusions to other developing countries may be limited. Further studies in other developing countries can increase the generalizability of the results (e.g., future research might compare Southeast Asia or South America where risk perceptions differ).

4.1. Practical implications

The results suggest that some lagging indicators such as the number of incidents or unexpected disruption of process due to insufficient staff competence and failure in instrumentation and alarms are important from the perspectives of process safety experts of both developing and developed countries. So, continued attention needs to be given to these lagging indicators to prevent future incidents and adverse events.

In terms of leading indicators, the study has yielded some interesting results. Important leading indicators common to both contexts were safety training and competency, and instrumentation and alarms. Attention should continue to be given to these indicators irrespective of location. Experts in the two settings also identified other important leading indicators, but these differed. Experts in the West identified fatigue risk management, while those in Iran noted permit to work. One explanation for this difference might be in the evolution of indicators of process safety. As some indicators, evidently more proximal to the specific task or process, are routinely taken care of, others might become more salient. In this way permit to work precede fatigue risk management in the evolution of leading safety indicators in process industries.

Assigning different weights to different process safety indicators helps to identify the most important process safety indicators and to define a small and effective number of indicators for process facilities in both developing and developed countries. This gives opportunities for managers and safety professionals in process industries to have a good view of effective indicators and allows them to focus on more important ones (Salimi & Rezaei, 2018). Fuzzy Best Worst Method as the methodology used in the current study can help determine the weight and importance of process safety indicators. Identifying the most important process safety indicators is essential for organizations in developed and developing countries to define effective indicators to improve process safety performance, create a safer process industry, and prevent losses and process safety incidents.

5. Conclusion

Besserman and Mentzer (2017) pointed out that developing and developed countries occupy different stages in the application of process safety indicators and have areas of improvement in process safety that could help to enhance the safety performance in process facilities globally. In process industries, for improvement of process safety performance, the challenge is to define a small and effective number of process safety indicators (lagging and leading indicators). Developing a framework that differentiates the importance of process safety indicators based on the opinions of safety professionals helps to identify the most important process safety indicators. This can also be used to highlight the difference in perception between developing and developed regions and provides a basis to define an effective number of process safety indicators based on their importance (weight). This can lead to safety improvements in process facilities globally. FBWM was used to identify universally important lagging and leading indicators. In both settings, these are the number of times processes do not proceed as planned due to insufficient staff competence and failure in instrumentation and alarms (lagging indicators), and the percentage of successful process implementation due to appropriate process safety training and competency and instrumentation and alarms (leading indicators). This method has also shown differences in opinion between experts in Iran and the West. In terms of leading indicators, the most obvious of these are the percentage of successful process implementation due to plant design, action items follow-up, permit to work, and emergency arrangements. We suggest that these differences may be due to the experience and cultural background of the respondents, but also to the level of maturity/stage of evolution of the process industries in these countries, respectively.

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Declaration of Competing Interest

The authors declare that they have no competing interests.

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