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Article

A Knowledge-Driven Model to Assess Inherent Safety in Process Infrastructure

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Abstract: Process safety has drawn increasing attention in recent years and has been investigated from different perspectives, such as quantitative risk analysis, consequence modeling, and regulations. However, rare attempts have been made to focus on inherent safety design assessment, despite being the most cost-effective safety tactic and its vital role in sustainable development and safe operation of process infrastructure. Accordingly, the present research proposed a knowledge-driven model to assess inherent safety in process infrastructure under uncertainty. We first developed a holistic taxonomy of contributing factors into inherent safety design considering chemical, reaction, process, equipment, human factors, and organizational concerns associated with process plants. Then, we used subject matter experts, content validity ratio (CVR), and content validity index (CVI) to validate the taxonomy and data collection tools. We then employed a fuzzy inference system and the Extent Analysis (EA) method for knowledge acquisition under uncertainty. We tested the proposed model on a steam methane-reforming plant that produces hydrogen as renewable energy. The findings revealed the most contributing factors and indicators to improve the inherent safety design in the studied plant and effectively support the decision-making process to assign proper safety countermeasures.

Keywords: inherent safety; process infrastructures; fuzzy set theory; knowledge-driven model

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1. Introduction

With the advancement of complex systems in industries like oil, gas, and petrochemicals, and the development of new technologies, various products are produced and distributed in advanced and developing societies [1]. Major accidents such as Bhopal and Flixborough are the most prominent examples of these dimensions [2]. A Major Accident Reporting System (eMARS) study found 255 significant accidents between 2006 and 2016, of which about 20 percent were related to processing industries [3]. Meanwhile, CCPS reports reveal that process accidents are preventable in case of timely diagnosis and careful investigation of near misses [4]. Furthermore, chemical safety and crisis managers have sought appropriate and rational solutions to balance and reduce industry hazards [5]. Process safety prevents catastrophic events like fires and explosions [6]. Furthermore, managers in the industry are responsible for identifying and selecting the most effective ways to improve the working environment and prevent defects [7].

To secure a process, a four-part strategy is required consisting of procedural, active, passive, and inherently safe design [8]. Due to its preventive nature, "inherent safety" is a reasonable option to prevent loss of life and financial damage in risk management programs in complex systems [9]. Inherent safety refers primarily to designing equipment, processes, or systems without considering additional protective layers, which should be considered during the idea and design phases [10]. Moreover, according to eMARS statistics, procedural, active, and inactive strategies need to be more effective at minimizing and controlling risks despite their broad application. Therefore, the system's inherent safety should be the priority of management actions. This is without requiring multiple barriers to control and eliminate a wide range of risks [11]. Therefore, inherently safe design has been proposed as one of the main branches of process safety. This is because, in the design stages of the industry, it reduces risk and ultimately reduces the need for other control systems. This prominent feature has led to inherent safety approved by countries such as the United States, China, and the Council of Europe. This has helped to manage risk and prevent losses [11]. Inherent safety tries to improve the safety of industries, but its effectiveness varies based on the design stage. Its effectiveness decreases as we move from the initial to the final stages [12]. For example, it has high performance in concept design but could be more efficient in the Piping and Instrumentation Diagram (P&ID) [13].

In the early stages of system design (conceptual design and detailed design), it is critical to consider safety because, in these stages, the opportunity to address errors, challenges, deficiencies, and failures is at its highest level. At these stages, practically no cost has been paid for implementation and physical development, and all ideas and plans exist only on paper. As a result, in these stages, the system can be repeatedly designed based on process safety standards. So, the inherent safety analysis of the systems designed in these stages can demonstrate the weak points and strengths of the system well from the point of view of the process [14] characteristics and at a low cost. The findings of this assessment can lead to a new design with minor challenges and weaknesses. Therefore, the conceptual and detailed design stages best assess inherent safety. This approach can be the crucial active approach in risk management because its goal is to modify the system from the safety perspective in the most fundamental stages of the system's life cycle [15].

To apply inherent safety design principles in the industry, one of the biggest challenges is assessing the level of inherent safety. In order to mitigate residual risks, industry managers have used this assessment [16]. An appropriate and valid method should be applied to assess inherent safety. For this purpose, various methods, such as index-based methods [17], graphical methods [18], and optimization [19], have been proposed. One of the most widely used methods in this field is index-based. In addition to their flexibility, user-friendliness, ability to integrate with process simulation programs, and lack of technical and detailed process information, these methods are also highly effective [12]. Therefore, they can be used in the early stages of design. Index-based methods usually combine various risk factors such as chemicals, process conditions, and equipment parameters. Finally, index-based methods can provide a clear picture in the form of a numerical code [20]. It is possible to estimate this index accurately and use it to help industrial design engineers decide and select the most suitable inherent safety upgrade options. Index-based methods reduce the probability of process accidents [17].

Some researchers have conducted studies in this field in the past decades. The first index, the Prototype index of inherent safety (PIIS), was introduced by Edwards et al. (1993) [21] to rank the degree of inherent safety related to the process paths. Some other recently proposed IBMs include an index proposed by Athar et al. (2020) [22] entitled the equipment-based intrinsic safety index (EBISI), which is a new method for improving the computation of inherent safety using factors such as process aspects, chemicals, and equipment. Shariff et al. (2018) [23] introduced a new index-based method for the inherently safe design of distillation columns in the initial design stage, which included process and distillation indices in each group, considering different parameters. In another study by Wei et al. (2015) [24], an indicator was presented to assess the risk level of petrochemical plants by comparing the risks of toxicity, ignition, explosion, and chemical reactions based on inherent safety principles. Despite the valuable advantages of the presented indicators, there are still some remaining challenges, such as the need for a comprehensive method that considers all the influential factors, such as human and organizational factors, and thereby can assess and evaluate inherent safety in an application framework.

On the other hand, some scientific studies have been conducted to develop the criteria for these indicators so the accuracy and sensitivity of these methods could be more apparent. The variation in the indicators is due to the differences in the calculations of the indicators and how they are combined to obtain a general index so that a method can provide more realistic results if more indicators are considered [22].

Another minor drawback of the proposed indices is the inability to scale (in which physical or chemical properties are divided into ranges according to the mental judgment of individuals and assigned points) and discontinuities in boundaries that may cause unacceptable uncertainty in evaluations. Under these conditions, fuzzy set theory can interpret numerical and linguistic information in a mathematical framework because it can consider the middle ranges of parameters [25]. In addition, fuzzy sets can handle this uncertainty as one of the biggest challenges of safety assessment in process industries [26]. In this regard, Gentile et al. (2003) [27] have proposed a method for assessing the level of inherent safety to eliminate the effect of subjective scaling using a fuzzy hierarchical model. In addition, Alipour-Bashary et al. (2021) [28] presented a hybrid fuzzy hazard assessment framework to determine the construction demolition safety index. Also, in another study by Vázquez et al. (2019) [29], an index OFISI was presented based on fuzzy logic to assess the inherent safety of a piece of equipment or process.

The scientific gaps in the studies are the existence of uncertainty in calculating indicators from the point of view of epistemic uncertainty, the lack of comprehensiveness of existing approaches and their focus on process characters, and the failure to consider organizational and human factors as the two leading components of the man-machine system, the need for a calculation guide to evaluate computations and judge the status of process infrastructures, and the lack of weighting to factors to determine their priority in managerial-technical controls. Therefore, the present study has used fuzzy sets to handle epistemic uncertainty in calculations. Furthermore, the present study has tried to show their relative prioritization by considering process, human, and organizational factors and weighting them using Chang's fuzzy sets. In addition, developing a system based on Mamdani fuzzy sets to evaluate calculations and judge the status of process infrastructures is another innovation of the present study.

In the present study, all influencing factors related to inherent safety, including human and organizational factors and technical and process factors, were extracted in a comprehensive literature review. Then, using hybrid fuzzy sets, equations of positive and negative sides of inherent safety were developed, and their scores were calculated. Finally, in a case study, the value of the positive aspect of inherent safety was calculated to overcome the existing challenges. Based on that, control strategies were proposed to improve inherent safety. The innovation of the present study is:

(a) Presenting a scientific-applied computational approach to assessing inherent safety;
(b) Developing a computational framework for evaluating inherent safety;
(c) Considering all technical, process, human, and organizational factors.

Section 2.1 presents a taxonomy of inherent safety design assessments. This section identifies and extracts factors affecting inherent safety through a literature review. A comprehensive questionnaire was developed to assess inherent safety in process infrastructure. A fuzzy set-based knowledge-driven framework is proposed in Section 2.2. Section 2.2.1 calculates the weights of the experts using Mamdani fuzzy sets. Based on expert opinion and Chang fuzzy sets, Section 2.2.2 calculates the weight of the questionnaire factors. In addition, a system that relies on Mamdani fuzzy sets was designed in Section 2.2.3 to evaluate our results. Eventually, the developed framework was verified in a case study.

2. The Proposed Model

Figure 1 depicts the main steps of the proposed framework for quantifying the ISA of process infrastructure. A comprehensive literature review was used in the first step to identify contributing factors to inherent safety in process infrastructures. A systematic questionnaire for ISA in process infrastructures was developed, and the content validity ratio (CVR) and content validity index (CVI) were used to validate the tools. Fuzzy rule-based and Chang fuzzy sets [30] were applied to assess and evaluate inherent safety under uncertainty. A case study was conducted to test the model's efficiency in quantifying ISA in hydrogen infrastructure as one of the critical infrastructures regarding renewable energy.

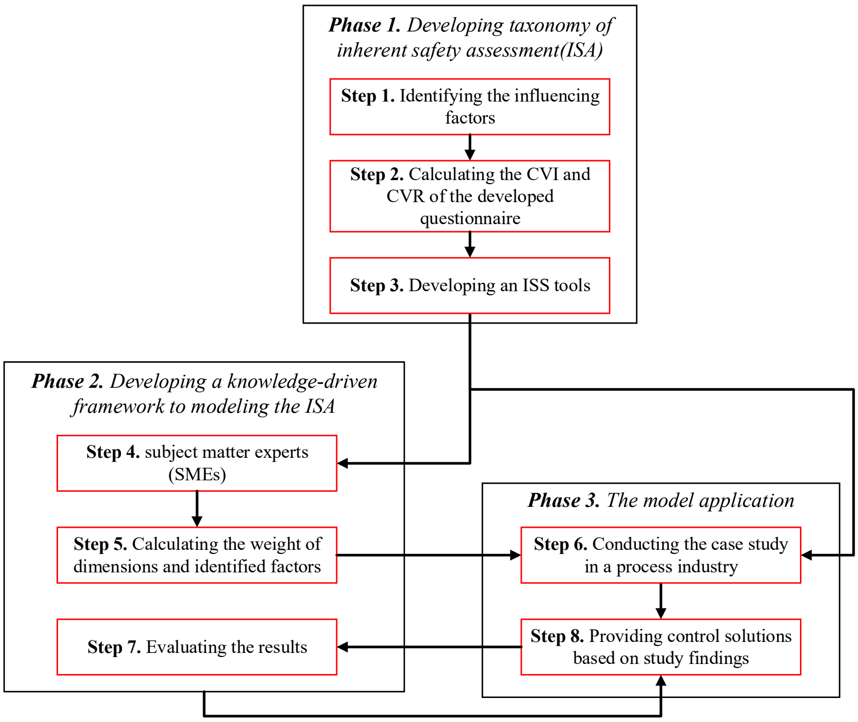

Figure 1. The main steps of the proposed framework.

2.1. Developing Taxonomy of Inherent Safety Assessment

A systematic literature review was used to determine and classify factors contributing to inherent safety design. Searches for keywords in the Scopus database included inherent safety, inherent safety index, inherent safety + influencing factors, inherent safety index + influencing factors, inherent process safety, inherent process safety index, and inherent process safety index. Papers were carefully reviewed, and 40 papers were selected for further analysis. After identifying the contributing factors, ten process safety experts reviewed and corrected the proposed taxonomy of inherent safety indicators. Lastly, the identified factors were divided into "positive" and "negative" groups based on their nature. The negative dimension consists of elements that have the potential to compromise inherent safety. The positive dimension consists of factors that strongly affect inherent safety. The extracted factors were then used to develop a specialized questionnaire. Ten process safety experts were asked to review a list of invoices for comprehensiveness. After adding other factors, the final list of elements was prepared in positive and negative categories. A numerical rating scale (NRS) was used to develop this questionnaire (see Figure 2). The NRS helped us do the study quantitatively and accurately. One of the numbers in Figure 2 had to be selected to answer each question. By dividing by ten digits (0 to 1), the calculations were more accurate, and the quantitative status of the system was more accurate. Scores represent specific system states. For example, NRS = 0 was considered if there was no evidence of a particular parameter in the industry.

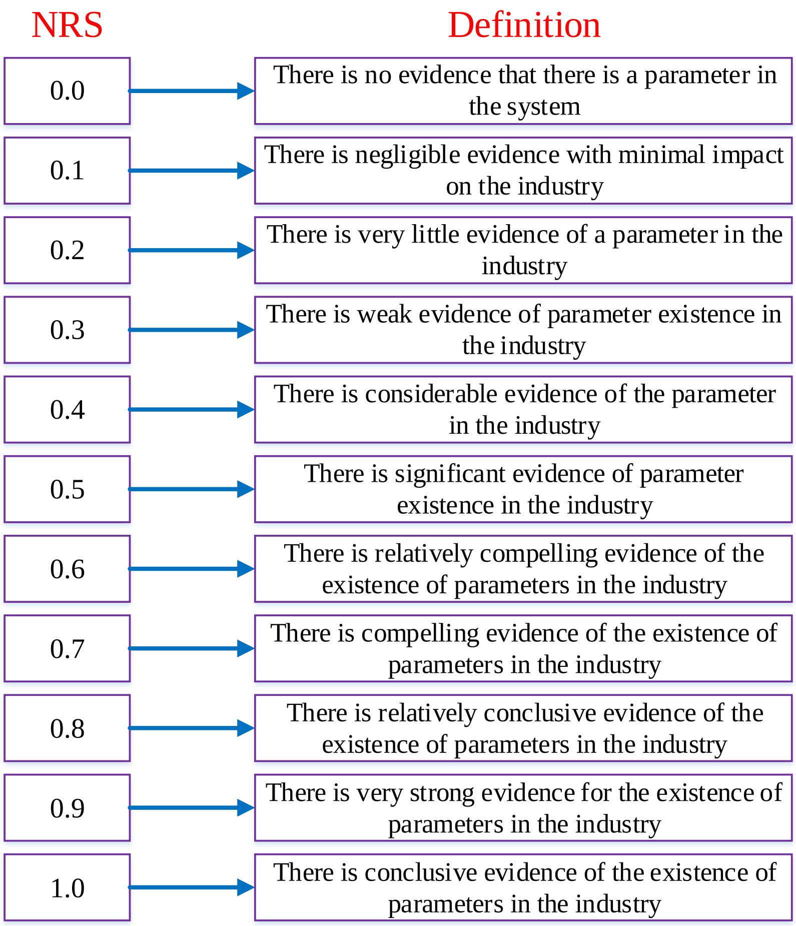

Figure 2. The numerical rating scale (NRS) was used in the questionnaire to determine the level of each factor.

As a new tool, the content validity of this questionnaire had to be examined and evaluated. For this purpose, the content validity ratio (*CVR*) and content validity index (*CVI*) were used. By examining the necessity and transparency of each question, these indicators provide a reliable numerical picture of the questionnaire's quality level. The checklist was sent to nine process safety experts in major process industries, and they were asked to determine the transparency and necessity of each question. Finally, the *CVR* and *CVI* indices were calculated using Equations (1) and (2).

$$CVR = \frac{n_e - N/2}{N/2} \tag{1}$$

$$CVI = \frac{n_c + n_r}{N} \tag{2}$$

where n_e represents the number of experts who answered "necessary", N represents the total number of experts, n_c represents the number of experts responding to "related", and nr represents the number of experts responding to "related but needed review". To determine whether the questionnaire's content was of high quality, the calculated indices were compared with the criteria. Notably, the minimum eligibility score was 0.78 (for nine experts). They were allowed to enter the questionnaire if their score exceeded 0.78. Otherwise, they were excluded.

2.2. Developing a Knowledge-Driven Framework

The most popular and practical approach to measuring safety concerns in knowledge engineering is utilizing subject matter experts' expertise (SME). This study proposes a knowledge-driven framework to quantify inherent safety parameters using fuzzy set theory. Insufficient information, vagueness, and fuzziness also contribute to subjective uncertainty. To better understand how to calculate Mamdani fuzzy sets, generalities were presented.

2.2.1. Mamdani Fuzzy Inference Sets

Mamdani fuzzy sets are sets with fuzzy inputs and fuzzy outputs. These sets consist of several IF-THEN rules [31]. The rule (listed with the k subtitle) may employ various fuzzy sets such as A_k and B_k [32]. Characters A and B illustrate linguistic terms modeled from the fuzzy sets specified on the input and output intermissions. A fuzzy set is depicted by a μA membership function that allocates the actual value of μA (x) between 0 and 1 to each x element at the input distance [32]. The value of μA (x) is the degree of membership of component x in fuzzy set A and can be decoded as the extent to which element x belongs to fuzzy set A. If fuzzy set A defines a specific concept, μA (x) can also be diagnosed as the value of proposition X is A whenever X = x. Correspondingly, fuzzy set B is characterized by a membership function μB, which allows the actual value of μB (y) between 0 and 1 to each actual value of y in the output range. This form is the most explicit fuzzy function with one input and output. Ancestors and results can also be propositions concerning rational AND, OR, or NOT associations. These associations are as defined in Equations (3)–(5) for OR, AND, and NOT connections, respectively [32]:

$$TruthValue(X\ is\ C\ OR\ X\ is\ D \mid X = x) = max(TruthValue(X\ is\ C \mid X = x),\ TruthValue(X\ is\ D \mid X = x)) = max(\mu_{C(x)}, \mu_{D(x)}) \quad (3)$$

$$TruthValue(X\ is\ C\ AND\ X\ is\ D \mid X = x) = min(TruthValue(X\ is\ C \mid X = x),\ TruthValue(X\ is\ D \mid X = x)) = min(\mu_{C(x)}, \mu_{D(x)}) \quad (4)$$

$$TruthValue(X\ is\ NOT\ A \mid X = x) = 1 - Truth\ Value(X\ is\ A \mid X = x) = 1 - \mu_{A(x)} \quad (5)$$

An algorithm in which a Mamdani sets uses an input number X = x to compute a numeric output y, according to a set of *If X is* A_k *then Y is* B_k rules, consists of the subsequent steps:

Step 1: Computing the degree of consistency between remarks (inputs) and the ancestors of each rule: At this step, the history observation of each IF-THEN rule for a given input is suspended. The degree of consistency between the input or observations of *X* = *x* and the prior *X is A* is just the degree of x membership in the fuzzy set A, for instance, μ_A (*x*). This stage estimates a μ_{Ak} (x) for each rule; *if X is* A_k, *then Y is* B_k (i.e., the degree of compatibility between the input and each rule). If $\mu_{Ak(x)} > 0$, the interconnected k rule is *fired* [32].

Step 2: Trim the existing fuzzy set in the result of each rule: The development of this step for each rule *if X is* A_k, *then Y is* B_k is the fuzzy set B_k shortened to the level $\mu_{Ak(x)}$, for sample, an output set $\mu_{output\ k \mid x}$ such as Equation (6) [32]:

$$\mu_{\ output\ k \mid x(y \mid x)} = min(\mu_{Bk(y)}, \mu_{Ak\ (x)}) \quad (6)$$

Step 3: Aggregation of all truncated fuzzy sets: In this step, the truncated fuzzy sets bonded to each inserted rule are counted up to a single fuzzy set $\mu_{Mamdani \mid x}$ as determined by the membership function as in Equation (7) [32]:

$$\mu_{Mamdani|x(y)} = \max_k \left[\mu_{output\ k|x(y)}\right] = \max_k [min\ \mu_{Bk}(y),\ \mu_{Ak}(x)] \quad (7)$$

Step 4: Defuzzification: Defuzzification of aggregated fuzzy set $\mu_{Mamddani\,|\,x}\,(y)$ transforms x to a precise number. Mamdani systems use the Center of Gravity (COG) caching method. This foretelling procedure returns the COG under the membership function $\mu_{Mamdani\,|\,x}$. This step is performed employing the fuzzy set integral calculation and is completed based on Equation (8) [33]:

$$z_{COG} = \frac{\int_z \mu_A(y)y\,dy}{\int_z \mu_A(y)\,dy} \tag{8}$$

where $\mu_{A(z)}$ is the aggregated output membership function, this is the most widely embraced defuzzification approach, reminiscent of the computation of anticipated values concerning the possibility distributions.

2.2.2. Calculating SMEs' Weight

Considering the SMEs profile (e.g., work experience, job position, and education level), each expert's opinion can have a different impact. Accordingly, the Mamdani fuzzy sets determined the assigned SMEs' importance level (weight). Omidvari et al. (2014) [34] considered experience, educational level, job title, and age parameters. Experience can also indicate the age of the specialist. As a result, the fourth factor, that is, the appropriateness of education and job title, was considered based on the opinion of the authors and experts because the alignment of academic education and job title can affect the weight of experts. Therefore, four criteria were considered: education level, work experience, job position, and degree-job ratio. For drawing essential decision rules, 48 "*IF* ... *THEN*" rules along with connectors "*OR*" or "*AND*" were developed. The triangular membership function was used for input and output ranging from 0 to 1. More information about linguistic terms and fuzzy numbers can be found in Figure 3. The center of gravity was also used in the defuzzification operation [35]. The employed procedure addresses experts' biases and uncertainties about the profile of SMEs.

2.2.3. Calculating the Importance Level of the Contributing Factors

An Extent Analysis (EA) method and Chang fuzzy sets were used in this step to determine the importance level of each identified contributing factor. Characteristics were compared to estimate their significance. SMEs were asked to determine the weight of each element relative to the other factors using Table 1. For instance, if Factor A was Very Important compared to Factor B, experts should assign the number 4. By setting fuzzy numbers to the variables and weighted numbers, fuzzy operations were performed on weighting the contributing factors. In Table 1, all factors related to each other were ranked based on expert opinions. Moreover, their fuzzy weights were entered into the Chang fuzzy sets.

The final weight of the factors was based on the low (expert opinion + %error), medium (+ %error), and high (expert opinion + %error) error limits in the experts' opinions. Interval values were used to characterize the potential uncertainty associated with knowledge elicitation. As a result, interval values can better describe the possible variation of findings and result in accurate discoveries in fuzzy mathematics, thus effectively addressing aleatory uncertainty [36].

Using the Chang relationship as presented in Equations (3)–(6), the Excel software was then used to estimate the mean of importance level [30]. The EA method was applied for each pair of contributing factors and dimensions [30]. The participants compiled and calculated the pairwise comparison matrix based on the set coefficients in this method [37]. The relative weights of the factors and options were then multiplied. Following these steps, the items selected were ranked. The study was modeled using three weights: low limit weight, medium limit weight, and high limit weight.

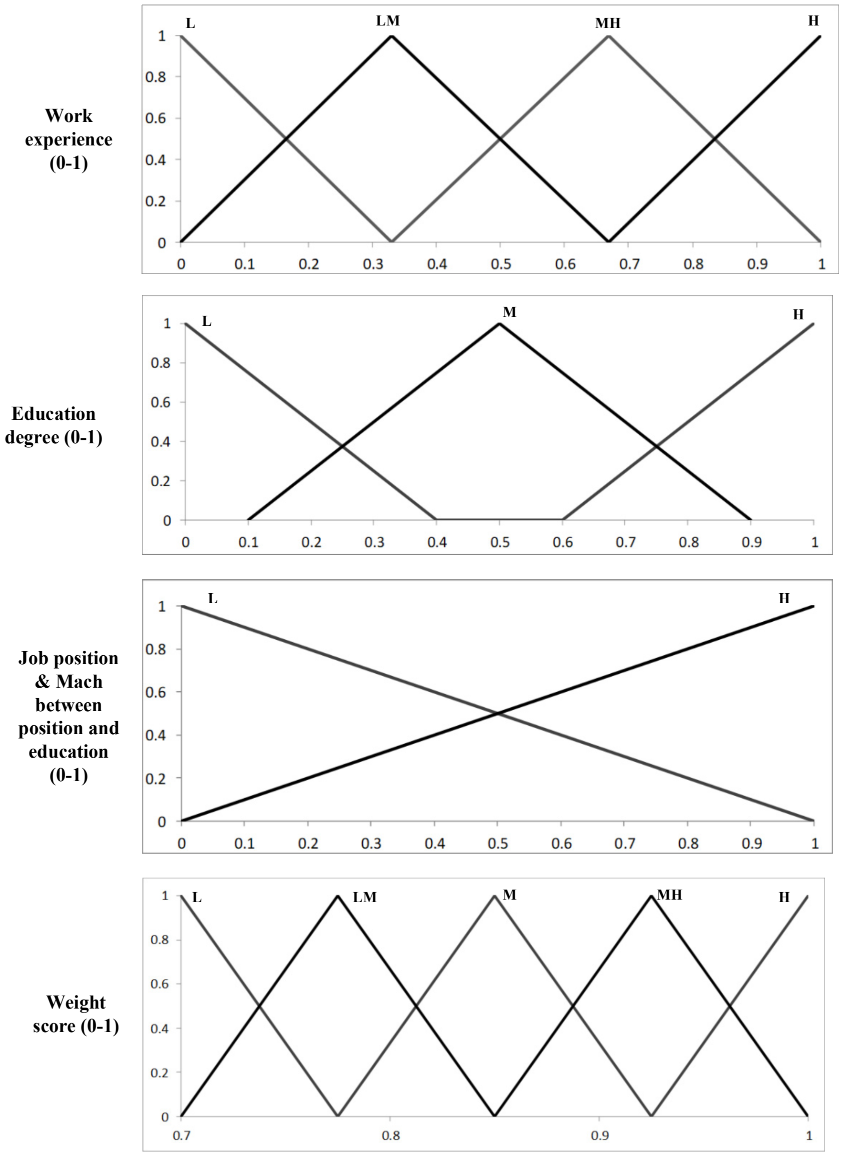

Figure 3. The membership functions of the fuzzy inference system for calculating the reliability of experts.

Chang's fuzzy sets are based on the EA method [30]. In the EA method, for each pair of comparisons matrix, the value of *Sk*, a triangular number, is calculated based on Equation (9) [30]. This computational was used to contribute factors and dimensions. The experts were asked to compare the contributing factors and dimensions.

$$S_k = \sum_{j=1}^{n} M_{g_k}^{j} \odot \left[\sum_{k=1}^{m} \sum_{j=1}^{n} M_{g_k}^{j} \right]^{-1} \tag{9}$$

where S_k is the fuzzy synthetic extent and $M_{g_k}^{j}$ (j = 1, 2, ... , n) are values of EA of the k_{th} object for n goals. After calculating the S_{ks} in this model, we should calculate their large degree compared to each other. In general, if *M1* and *M2* are two triangular fuzzy numbers, the pairwise comparison between *M1* and *M2* is achieved using Equation (10):

$$\begin{cases} V(\ M1\ \geq M2\ ) = 1 \text{ iff } m1\ \geq m2 \\ V(\ M2\ \geq M1\ ) = hgt(M1\ \cap M2) \text{ otherwise} \end{cases} \tag{10}$$

Then, we computed the weighting of the indices in the paired comparison matrix by Equation (11):

$$W'(xi) = Min\{V(S_i \geq Sk)\},\ k = 1, 2, \ldots, n\ ,\ k \neq i \quad (11)$$

Therefore, the weight vector of the indices will be in Equation (12):

$$W' = \left[W'(A_1),\ W'(A_2), \ldots, W'(A_n)\right]^T \quad (12)$$

That W' is the vector of fuzzy non-normal coefficients.

Table 1. Weight of the verbal expressions in the Chang method [37,38].

Verbal Expressions	Weight Definition	Fuzzy Numbers
Equal importance	1	[1, 1, 1]
A little more importance	2	[1, 1.5, 2]
Relatively more importance	3	[1.5, 2, 2.5]
Very importance	4	[2, 2.5, 3]
Most importance	5	[2.5, 3, 3.5]

2.2.4. Inherent Safety Situation Evaluation

There is a need for a system to evaluate the inherent safety status, as there is with other risk and safety assessment approaches. For this reason, Mamdani fuzzy sets were designed. This membership function is shown in Figure 4. It determines the required score of the positive dimension of ISA to overcome the negative dimension. There is no fixed mathematical relationship between these two dimensions, but the relationship varies based on interactions. For instance, to overcome a moderate (M) level on the negative dimension, a high (H) level of the positive dimension is needed based on experts' opinions. Accidents can still happen even in industries with the highest levels of safety. It identified process infrastructure weaknesses and provided control solutions based on the output of this system. A list of control solutions was compiled by prioritizing the factors with the lowest scores by weight.

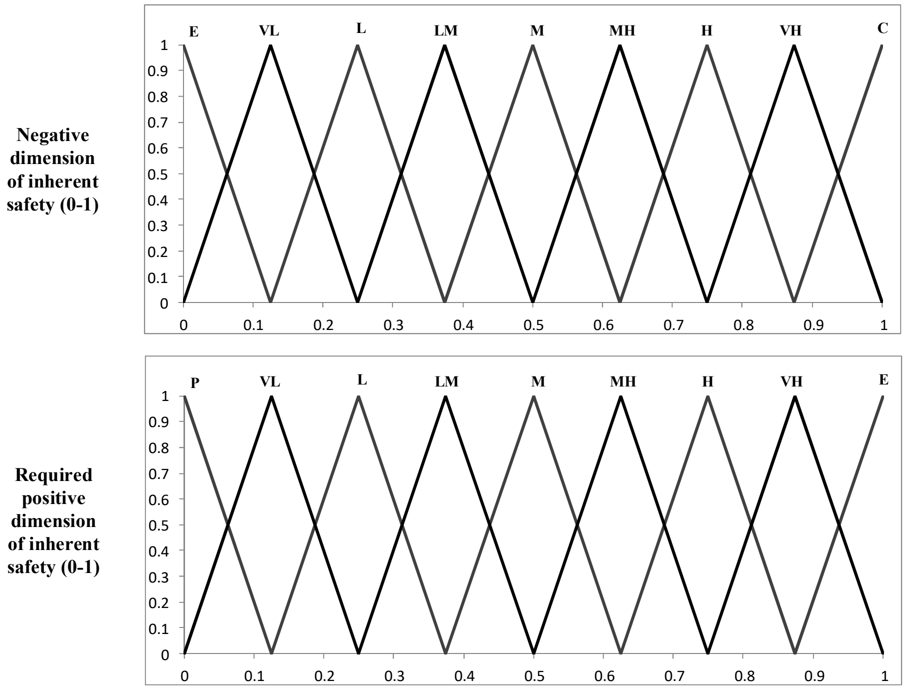

Figure 4. The membership function of fuzzy sets of the required positive side of the inherent safety situation.

3. Application of the Methodology

3.1. The Model Application: Steam Methane Reforming Plant to Produce Hydrogen

The proposed model was tested on a hydrogen production unit, one of the most critical units related to renewable energy, in the combined cycle power plant industry to quantify ISA. The present study conducted field and facility visits by a team of authors and technical and safety experts from the mentioned unit. A brainstorming process was used to fill out the final questionnaire. Figure 5 shows the process block diagram.

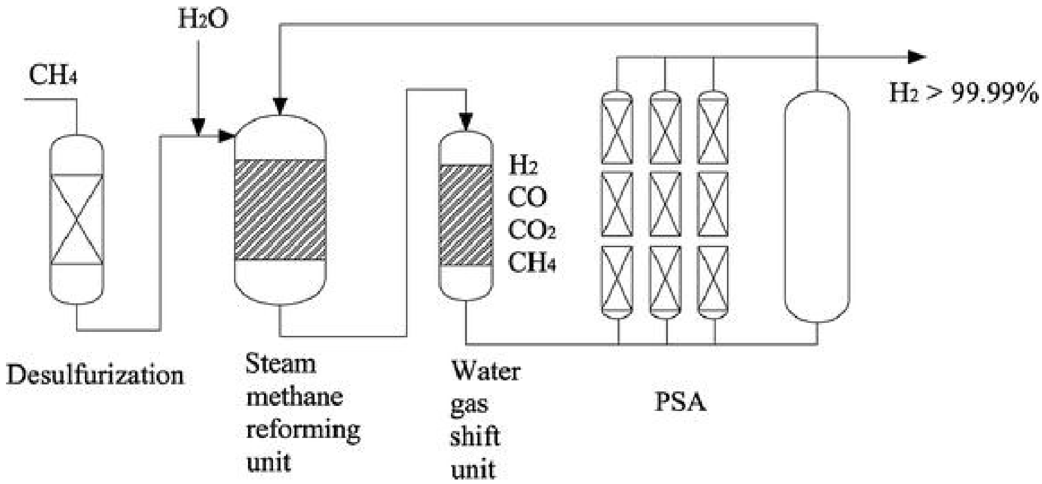

Figure 5. The block diagram of hydrogen generation by steam methane gas reforming [39].

A reforming tank mixes natural gas with steam from ionized water in the hydrogen generation machine. Steam methane gas reforming is a standard method of producing synthetic gas (CO + H_2). Chemical reactions occur at the top of the hydrogen generation machine (type: 2000 reactor) to convert methane and higher hydrocarbons into natural gas (Equation (13)). For methane gas, this reaction is described in Equation (14).

$$\mathrm{C_mH_n + mH_2O} \;-----> mCO + \left(\mathrm{m} + \frac{\mathrm{n}}{2}\right)\mathrm{H_2} \tag{13}$$

$$\mathrm{CH_4 + 2H_2O} \;-----> CO + \mathrm{3H_2}\ \Delta\mathrm{H}^{\circ}{}_{298} = 206.2\ \mathrm{KJ/mol} \tag{14}$$

The reactions typically occur at 800–1000 °C and 14–20 atm pressure over a nickel-based catalyst. Adding steam at a lower temperature to the *CO* obtained by the reform reaction produces more CO_2 and H_2 (Equation (15)). The reformed gas contains about 76% hydrogen per dry base. After cooling, the periodic pressure purification adsorption system (PSA) reduces impurities like CO_2, *CO*, CH_4, and N_2. Steam injected into the *PSA* contains hydrogen plus *CO* and combusted CH_4. This heat provides the energy needed for the overall reaction, which is endothermic [40].

$$\mathrm{CO + H_2O} ----- > \mathrm{CO_2 + H_2}\ \Delta\mathrm{H}^{\circ}{}_{298} = -41.2\ \mathrm{KJ/mol} \tag{15}$$

As a result of continuous control by operators, a significant volume of chemicals, high temperatures, and pressure, inherent safety is vital in this section because if an accident occurs, there may be domino effects in addition to system malfunctions. Hence, this unit was selected for the case study.

3.2. The Identified Contributing Factors

As shown in Table 2, a systematic review of the literature revealed 36 contributing factors to the inherent safety of process facilities. Three indicators comprise the negative element, including chemical (nine factors), process (five factors), and reaction (two factors). Conversely, the positive indicators include 21 factors in three leading indicators, including equipment (8 factors), human factors (5 factors), and organizational factors (7 factors). The questionnaire developed in the study is shown in Table 3, along with a proposed taxonomy of inherent safety dimensions and contributing factors. What was obtained in this step was the basis for developing a specialized questionnaire for the assessment of inherent safety in process infrastructures. The parameters were extracted, and each parameter was designed as a question.

Table 2. The proposed taxonomy of inherent safety dimensions, indicators, and contributing factors.

Negative Dimensions	Contributing Factor	Reference(s)	Positive Dimensions	Contributing Factor	Reference(s)
(A) Chemical	A1. Combustion enthalpy	[41]	(D) Equipment	D1. Equipment integrity	[22]
				D2. Materials quality	[42]
	A2. Combustibility	[43]		D3. Process structure	[44]
	A3. Explosiveness	[45]		D4. Control system	[18]
	A4. LEL/UEL	[46]		D5. Reliability	[47]
	A5. Boiling point	[48]		D6. Design	[41]
	A6. Stability class	[49]		D7. Security equipment	[10]
	A7. Toxicity	[11]		D8. Calibration	
	A8. Corrosively	[50]	(E) Human factors	E1. Education/training	[51]
	A9. Flashpoint	[52]		E2. Expert	[53]
(B) Process	B1. Flow rate	[54]		E3. Physical & Psychological situation	[55]
				E4. Job satisfaction	[56]
	B2. Volume	[41]		E5. Security guard	[57]
	B3. Temperature	[41]	(F) Organization	F1. Maintenance	[58]
	B4. Pressure	[59]		F2. Safety culture	[41]
	B5. System complexity	[60]		F3. Procedures	[61]
(C) Reaction	C1. Reaction enthalpy	[62]		F4. Monitoring system	[63]
				F5. Management involvement	[64]
	C2. Consequences modeling	[44]		F6. Emergency planning	[65]
				F7. Risk management system	[66,67]

The equation for calculating positive and negative dimensions' scores is presented in Equations (16) and (17), respectively, based on the findings.

$$Positive\ side\ score = \frac{W_A + W_B + W_C}{3} \tag{16}$$

$$Negative\ side\ score = \frac{W_D + W_E + W_F}{3} \tag{17}$$

A, *B*, and *C* denote the chemical, process, and reaction dimensions, while *D*, *E*, and *F* demonstrate the equipment, human, and organizational factors. In addition, *W* is each dimension's weight (importance level).

Table 3. The developed questionnaire to assess inherent safety in process infrastructure.

Number	Question	Score
1	What is the risk level of enthalpy combustion of chemicals used in the desired section? (A1)	
2	What is the level of combustion of the chemicals used in the desired section? (A2)	
3	What is the explosiveness of the chemicals used in the desired section? (A3)	
4	What is the risk level of the boiling temperature of the chemicals used in the desired section? (A5)	
5	What is the hazard level of the chemical stability class used in the desired section? (A6)	
6	What is the level of toxicity of the chemicals used in the desired section? (A7)	
7	What is the hazard of the flashpoint of the chemicals used in the desired section? (A9)	
8	What is the level of the corrosive chemicals used in the desired section? (A8)	
9	What is the hazard level of the chemicals used in the desired section between the upper and lower explosion limits (UEL-LEL)? (A4)	
10	What is the flow rate level in the pipelines in the desired section? (B1)	
11	What is the level of the volume of chemical storage tanks in the desired section? (B2)	
12	What is the storage (tanks) temperature level in the desired section? (B3)	
13	What is the level of pressure in the desired section? (B4)	
14	What is the level of complexity of the system in the desired section? (B5)	
15	What is the level of reaction enthalpy in the desired section? (C1)	
16	What is the consequence of the reaction deviation in the desired section? (C2)	
17	What is the level of equipment integrity in the sector? (D1)	
18	What is the level of safety quality of the materials used in the process structure in the desired section? (D2)	
19	What is the level of process control systems in the desired section? (D4)	
20	What is the level of integration of process structures in the desired section? (D3)	
21	What is the level of reliability of instrumentation equipment in the desired sector? (D5)	
22	What is the process's ergonomic design level in the desired section? (D6)	
23	What is the status of security systems (CCTV cameras, automatic alarms, and other security equipment) to prevent and eliminate sabotage in the desired section? (D7)	
24	What is the quantitative and qualitative equipment calibration level in the desired section? (D8)	
25	What is the level of education, compliance with job duties, and related personnel training in the department? (E1)	
26	What is the personnel's work experience in their field of work in the desired department? (E2)	
27	What is the level of compliance with the mental and physical conditions of the personnel to perform the assigned tasks in the desired section? (E3)	
28	What is the level of personnel's job satisfaction in the desired section? (E4)	
29	What is the level of coherence of the reactions of the security guards (human resources) to prevent and eliminate possible sabotage in the desired section? (E5)	
30	What is the level of coherence of the maintenance program of the desired section? (F1)	
31	What is the level of safety culture in the desired section? (F2)	
32	What is the level of accessibility to the instructions in the desired section? (F3)	
33	What is the level of coherence of the safety inspection program in the desired section? (F4)	
34	What is the level of management involvement in process safety issues in the desired section? (F5)	
35	What is the qualitative level of emergency response management in the desired section? (F6)	
36	What is the desired section's qualitative level of safety and health risk management programs? (F7)	

3.3. The SMEs Reliability Findings

Table 4 shows the weight of SMEs in the present study. Therefore, expert #6, with a weight of 0.982 (1.8% error), had the most significant impact, while expert #7, with a weight of 0.867 (13.3% error), had the most negligible impact. There were three levels of error percentages: low, medium, and high. Accordingly, if expert #7 considered a score = 4 in comparison to Chang's fuzzy sets, its low, medium, and high limits would be 3.468, 4, and 4.532. Experts' opinions were considered when determining the factors' final weight. Appendix A provides details of the mathematical calculations of expert weights. In this regard, Table A1 indicates the calculating related to the weight of the expert 2. What was obtained in this step was the basis of factor weighting calculations. Each expert had a weight that directly impacted the factors of his attitude, and this weight should be calculated. This step was one of the specific steps of handling epistemic uncertainty in weighting factors. Because the lack of expert knowledge was considered concerning the importance of the factors, and based on that, the upper and lower limits of the weights were estimated from a statistical point of view. This intermission is known as interval and has significant use in statistical studies.

Table 4. The findings of the employed SMEs' weight.

Number of Experts	Educational Degree	Type of Industry	Field of Education	Experience (Years)	Job Position	Relation between Degree and Position	Expert Weight (Error Percent)
1	Master	Gas refinery	Chemical engineering	6	Process safety expert	Yes	0.869 (±13.10)
2	Master	Petrochemical industry	Chemical engineering	8	HSE supervisor	No	0.907 (±0.9.30)
3	Master	Gas refinery	HSE management	15	HSE boss	Yes	0.915 (±8.05)
4	Master	Oil Company	Chemical engineering	15	HSE management	No	0.913 (±8.07)
5	Master	Oil Company	HSE management	16	HSE management	Yes	0.932 (±6.80)
6	PhD	Member of faculty	Environmental Protection	25	University faculty	Yes	0.982 (±1.80)
7	Bachelor	Petrochemical industry	Mechanical engineering	8	Senior engineer	No	0.867 (±13.30)
8	Master	Gas refinery	Chemical engineering	12	Process safety expert	Yes	0.945 (±5.50)
9	Master	Oil Company	Chemical engineering	16	Head of process safety management	Yes	0.967 (±3.30)

3.4. Dimensions and Contributing Factors' Importance Level

The weights for each contributing factor in the inherent safety design of the process plant are listed in Table 5. Interval values, including low, medium, and high limits, were used to characterize parameter uncertainty in the knowledge acquisition process. In the following steps, the average of three limits was used. Even though the medium limit does not represent the average, the average of all three limits has been calculated. Detailed mathematical calculations of the contributing factors' weights are provided in Appendix B, and among the factors associated with chemical properties, explosiveness and the lower explosive limit (LEL)/upper explosive limit (UEL) of chemicals significantly influenced inherent safety. In this regard, Table A2 indicates the importance relative to this factor. This factor can be considered the most influential character concerning the severity of the explosion. When combined with air, leakage of materials that produce explosive vapors can be very dangerous. Vapor cloud explosion (VCE) is the main consequence of LEL and UEL. In this explosion, the cloud of vapor created in the air can cause a catastrophic explosion if it is in the LEL–UEL range and comes in contact with delayed ignition sources [31].

Furthermore, flow rate and temperature were the most significant process-related factors. This finding aligns with previous process-oriented studies because they considered flow rate, pressure, and temperature as the main influencing parameters on process-oriented inherent safety [68]. Among the factors affecting reaction enthalpy, it received the highest score. Zhu et al. (2022) [69] also considered enthalpy the main factor in inherent safety measures. Among equipment-related factors, process structure and design were the most critical. In this regard, Tugnoli et al. (2012) [70] mentioned barriers' crucial role in inherent safety. They introduced the impact of the equipment structure and system design as the most apparent indicators of safety barriers. Human factors are also heavily influenced by experience and training. Gholamizadeh et al. (2022) [71] revealed a significant relationship between workers' experience and occupational accidents in Iran. Likewise, Gholamizadeh et al. (2022) [38] also calculated the average limit weight equal to 1 for experience and training in crisis management of process industries. Risk management and safety culture were also crucial organizational factors. Risk assessment is considered the most critical factor in safety management because the basis of all hazard and risk control procedures in industries are risk assessment outputs. Earlier studies had examined the contribution of equality to inherent safety factors, but the present study prioritized factors according to their weight.

Table 5. The estimated weight for each of the contributing factors.

Factors	Weight			Factors	Weight		
	Low Limit	Med Limit	High Limit		Low Limit	Med Limit	High Limit
Negative dimension				D2: Materials quality	0.4862	0.5460	0.9631
A1: Combustion enthalpy	0.5720	0.4440	0.6497	D3: Process structure	0.8494	0.8730	0.9788
A2: Combustibility	0.7114	0.9249	0.9629	D4: Control system	0.6418	0.6778	0.6798
A3: Explosiveness	1.0000	1.0000	1.0000	D5: Reliability	0.8088	0.8450	0.9936
A4: LEL/UEL	0.9015	0.8803	0.9318	D6: Design	0.9326	1.0000	1.0000
A5: Boiling Point	0.1766	0.2777	0.3304	D7: Security equipment	0.1638	0.2321	0.9932
A6: Stability Class	0.4619	0.5317	0.5680	D8: Calibration	0.0846	0.1797	0.9908
A7: Toxicity	0.2969	0.3605	0.4078	E1: Education/Training	0.7039	0.7276	0.7399
A8: Corrosively	0.1074	0.1172	0.1479	E2: Expert	1.0000	1.0000	1.0000
A9: Flash Point	0.3164	0.4017	0.5770	E3: Physical & Psychological situation	0.6842	0.7070	0.8167
B1: Flow rate	0.9665	1.0000	1.0000	E4: Job satisfaction	0.5400	0.6146	0.7759
B2: Volume	0.8586	0.9216	0.9433	E5: Security guard	0.1313	0.2499	0.4669
B3: Temperature	0.8673	0.9467	0.9993	F1: Maintenance	0.4753	0.4999	0.9450
B4: Pressure	0.8423	0.9600	1.0000	F2: Safety culture	0.9673	1.0000	1.0000
B5: System complexity	0.3849	0.5704	0.7326	F3: Procedures	0.4097	0.4506	0.9670
C1: Reaction enthalpy	0.7725	1.0000	1.0000	F4: Monitoring system	0.2664	0.2721	0.9648
C2: Consequence modeling	0.7617	1.0000	1.0000	F5: Management involvement	0.4843	0.5330	0.9873
Positive dimension				F6: Emergency planning	0.1361	0.1512	0.9782
D1: Equipment integrity	0.5857	1	0.9437	F7: Risk management system	0.3039	0.6180	1.0000

Table 6 also shows the estimated weights for ISA indicators. Expert opinions proved that the chemical property of the process facilities has a more significant impact on inherent safety than the process and reaction. Furthermore, process equipment was more effective than human and organizational factors.

Table 6. The estimated weight of the ISA indicators.

Dimension	Indicators	Weight
Negative	Chemical	0.5922
	Process	0.2391
	Reaction	0.1686
Positive	Equipment	0.5973
	Human factors	0.2371
	Organization	0.1654

These findings yield information to estimate the positive and negative dimensions' scores for inherent safety design. Accordingly, Equations (18) and (19) were proposed to assess the positive (P) and negative (N) dimensions' scores, respectively.

$$N = 0.5922A + 0.2391B + 0.1686C \tag{18}$$

$$P = 0.5973D + 0.2371E + 0.1654F \tag{19}$$

A, B, and C represent the chemical, process, and reaction indicators, while D, E, and F are the equipment, human, and organization.

Table 7 shows the NRS associated with the contributing factors in the case study. In contact with heat or electricity, hydrogen is a highly flammable gas. Hydrogen has a melting point of −259 °C and a boiling point of −253 °C. The LEL and UEL of hydrogen are 4% and 76% by air volume, respectively. Therefore, the hydrogen unit is inherently hazardous. This unit has a high risk of fire and explosion accidents in this unit if safety measures (positive aspects) are not considered.

Table 7. The results of the case study.

Contributing Factor	NRS	Contributing Factor	NRS
Negative dimension		D2. Materials quality	0.7
A1. Combustion enthalpy	0.9	D3. Process structure	0.6
A2. Combustibility	1	D4. Control system	0.7
A3. Explosiveness	1	D5. Reliability	0.6
A4. LEL/UEL	1	D6. Design	0.5
A5. Boiling point	0.6	D7. Security equipment	0.7
A6. Stability class	0.3	D8. Calibration	0.7
A7. Toxicity	1	E1. Education/training	0.6
A8. Corrosively	0.3	E2. Expert	0.7
A9. Flashpoint	0.8	E3. Physical & Psychological situation	0.5
B1. Flow rate	0.8	E4. Job satisfaction	0.4
B2. Volume	0.7	E5. Security guard	0.6
B3. Temperature	0.5	F1. Maintenance	0.6
B4. Pressure	0.8	F2. Safety culture	0.5
B5. System complexity	0.8	F3. Procedures	0.6
C1. Reaction enthalpy	0.5	F4. Monitoring system	0.6
C2. Consequence modeling	0.6	F6. Management involvement	0.5
Positive dimension		F7. Emergency planning	0.6
D1. Equipment integrity	0.6	F8. Risk management system	0.5

As can be deduced, all the steps up to this point were done for two purposes: (a) to use the questionnaire and (b) to have an equation to calculate the dimensions quantitatively. This way, the tools for assessing inherent safety in process infrastructures were provided. Let us assume that the calculated positive and negative dimensions equal 0.56 and 0.69, respectively. A fundamental challenge will arise at this point of the study: What do these findings indicate, and what should be done? Thus, what remained was to have an evaluation calculator capable of displaying the state of the infrastructure and showing us numerically what state the infrastructure is in now and what needs to be done. In Figure 6, each of ISA's contributing factors and dimensions is depicted. With a score of 0.8609, the "chemical" factor had the highest score among the negative dimensions. However, among the positive factors, the "equipment" factor had the highest score, with 0.6212. Appendix C details the calculations of the required positive dimension.

According to the Center for Chemical Process Safety (CCPS), inherent safety analysis can be performed at all stages of the plant life cycle. Still, process research, development, and plant design are the best ways. According to the CCPS, inherent safety can be assessed in basic technology, basic design, detailed plant design, delighted equipment design, and operation [72]. The present study has attempted to apply this analysis in the field of operation to provide a guide to minimize the weaknesses in creating the human-machine system in process infrastructure. For a safer design, one of four strategies: Substitute (use of less hazardous chemicals), Minimize (use the same chemical but with less volume), Moderate (reducing the severity of material leakage consequences), or Simplify (reduce system complexity with a more user-friendly design) could be employed [73]. This study does not consider the first two strategies (substitute and minimize) because they require advanced process engineering designs outside the safety and risk engineering scope. Still, the two strategies, Moderate and Simplify, were covered since they are unrelated to the chemical process and can be considered in safer redesigns.

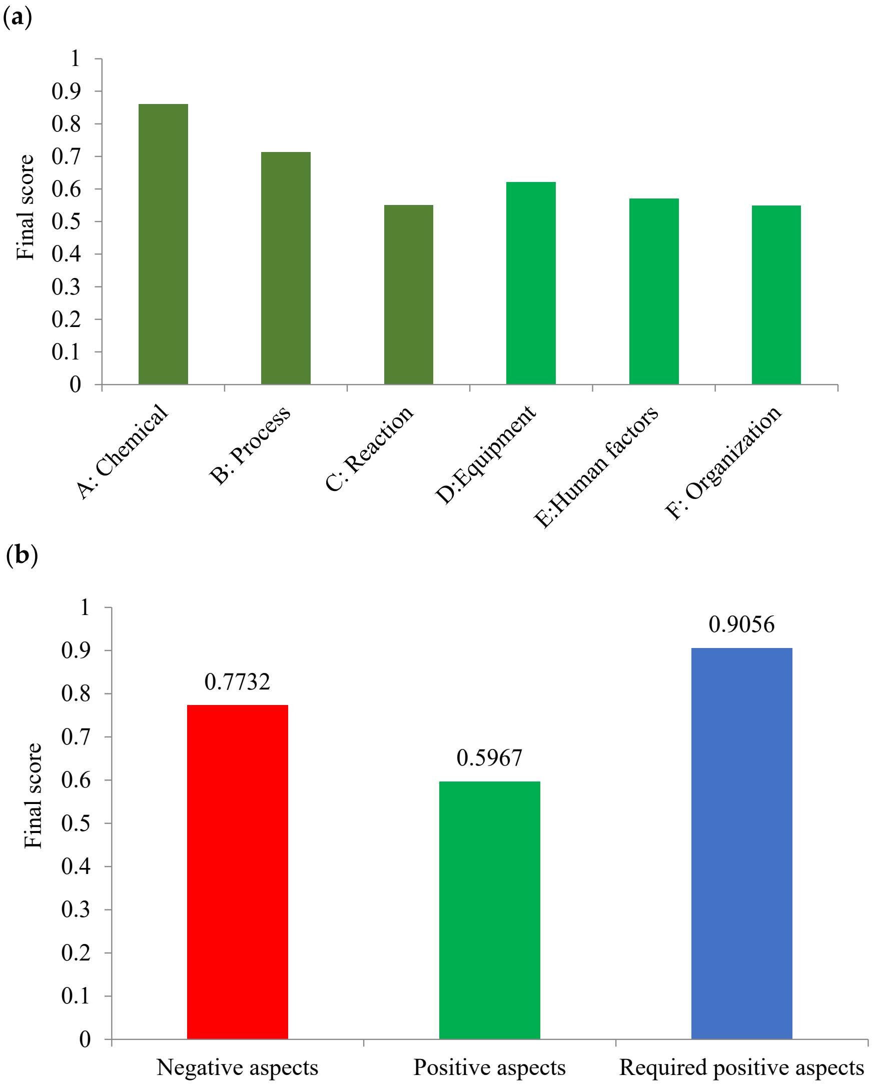

Figure 6. The estimated scores of (**a**) contributing factors and (**b**) dimensions of ISA in the hydrogen production unit.

According to the evaluation of fuzzy sets, the hydrogen production unit must have at least a 0.905 positive dimension score to overcome the negative dimension (with a score of 0.7732). Moreover, the score of the positive dimension of this unit was equal to 0.5967. Therefore, the hydrogen production unit does not provide the necessary positive measures (human factors, equipment, and organizational factors). Therefore, control solutions must be designed and implemented. The salient advantage of the proposed framework is that it provides a guide for identifying and prioritizing control measures. The necessary control measures can be identified and prioritized carefully using the questionnaire results and the calculated weights. Control measures are prioritized based on factors with the highest weight and lowest score [38].

Figure 7 shows the computed weight and NRS of contributing factors. Prioritizing control strategies is based on this figure. From an inherent safety perspective, all factors must score above 0.9 in the positive dimension to stabilize the hydrogen production unit. As shown in Figure 7, the factors E2 (expert), F2 (safety culture), D6 (design), D3 (process structure), D5 (reliability), and D1 (equipment integrity) had the highest impact weight. Thus, the management of the hydrogen production unit should prioritize control strategies accordingly.

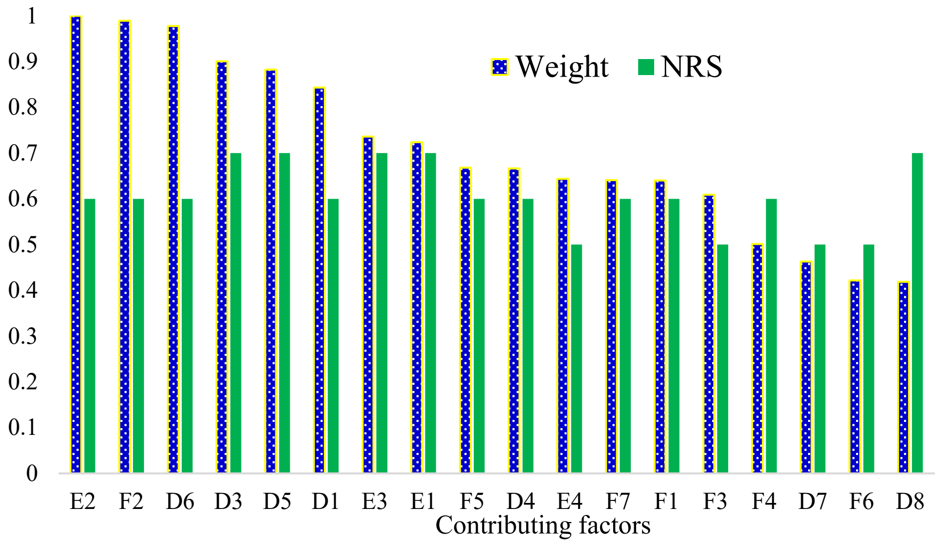

Figure 7. The computed weight and numerical rating scale for contributing factors.

The framework developed in the present study is in line with the mentioned four strategies and can help the decision-makers of the process industries choose the type of strategy and prioritize the control programs. As can be deduced, the study's findings determine the weight of the factors, provide a specialized questionnaire, provide the calculation equations to evaluate positive and negative dimensions and provide an evaluation calculator. According to the score of each item in the questionnaire, decision-makers can identify the weakness based on the filled questionnaire of their industry. On the other hand, the calculated weight of the factors allows decision-makers to identify and prioritize the critical factors based on their impact on the positive and negative dimensions. As a result, it is enough for the management to identify the items with the lowest obtained score and then rank them based on the weight of each factor (see Figure 7). In this way, they can identify the priority of control measures. For example, the authors suggest that the industry design the control programs to improve the level of factors E2 (expert), F2 (safety culture), D6 (design), D1 (equipment integrity), and F4 (monitoring system), respectively. Therefore, the following ways can be implemented, if possible, in the studied industry:

(a) Planning for the implementation of regular and documented educational programs (theoretical and operational) in the mentioned unit;
(b) Improving the level of the organization's safety culture through the cooperation of all organizational levels;
(c) Redesigning the hydrogen production unit from the point of view of safer material selection, better tank placement, more standardized piping arrangement, and more appropriate material selection;
(d) Designing timed monitoring systems to identify defects in time and fix them at the right time.

One of the essential concerns in the management of an organization is to lay the groundwork for creating a safe and accident-free work environment, which is achieved by implementing a safety culture [74]. Implementing a preventive (active) approach to maintain safety and health will not only help protect the workforce [75]. However, it can also be a factor for greater productivity and consequently reduce costs in the workplace. Safety and health have a significant role in reducing workplace accidents and diseases caused by the activities of employees in this environment. Therefore, safety culture is an approved method in this field, among other effective ways to create a healthy and safe environment [76]. Safety culture is the implementation of solid safety management and prioritizing health and safety in the workplace. Promoting the safety culture at work levels and creating a positive attitude in this area, along with the entire application of the rules and the collective participation of employees in issues related to this sector, can create a healthy and safe environment. Among the characteristics of an entirely positive safety culture is the total commitment of management levels to establish correct safety methods based on responsibility and honesty among all employees and management departments [77]. Developing and expanding a positive safety culture and creating a correct behavioral pattern for employees can significantly reduce accidents and errors caused by people's ignorance. Nevertheless, this is possible if all, or a large part, of a positive safety culture can be implemented. In order to achieve this goal, it is necessary to implement the following programs in organizations [78]:

A. Providing complete information about the safety and health of the workplace to all employees;
B. Collective participation and receiving suggestions and comments from employees and reviewing them from the management side;
C. Prioritizing safety under any circumstances, even at the cost of reducing or stopping production;
D. Frequent supervision of managers on the atmosphere of the work environment and consultation with personnel;
E. Updating information in the field of health and safety permanently;
F. Complete review and analysis of incidents and present the results of this review to all employees;
G. Allocation of sufficient funds to the health and safety department;
H. Providing necessary training to personnel suitable for each work environment;
I. Creating an atmosphere full of empathy and companionship among employees by providing honest safety policies.

Human-machine systems are affected by some parameters due to their nature. A primary chemical or mineral substance enters a chemical/physical process and produces one or more chemical compounds. Three aspects of this process are critical for hydrogen infrastructure. First is the input chemical, natural gas, or other chemical compounds. These compounds' physical, chemical, and toxicological properties can cause fires, explosions, and toxicological poisoning. Chemical leakage and release can also be significantly affected by the production process of primary and secondary compounds, depending on their complexity, length, and physical conditions. Thirdly, the reservoirs undergo chemical reactions. The temperature and pressure inside pipelines and storage tanks can rise to hazardous levels depending on the type of reaction. One example is the reaction between CH_4 and H_2O (Equation (14)). Temperature and pressure rise to 1000 °C and 20 atm in this reaction.

Moreover, flammable CH_4 enters the process, and combustible H_2 exits. A system of this kind must operate in a safe and controlled environment. In this case, the processing system must be inherently safe. On the other hand, the inherent safety analysis is one of this system's most critical safety management analyses.

This study compares the proposed model with seven quantitative models. From the perspective of risk analysis, these comparisons consider several specific criteria. The results are presented in Table 8.

In analyzing such a complex system, the present study has significant strengths. The present study covers all contributing factors related to chemical features, process nature, and reactive properties. Second, all these factors have been quantitatively prioritized in the present study. In addition, the current study considers the safety opportunities (or, in other words, the positive aspects) of hydrogen infrastructure processing systems. Two primary components of complex man-machine systems are human resources and equipment. The present study also covers the leading human resources and technical and equipment factors. Organizational factors also play a significant role in risk management and safety. These factors are also discussed in the present study.

Table 8. The comparison of eight different models to quantitative inherent safety analysis.

Different Study	P	C	O	H	HU	W	MM	A	E
Athar et al. [79]	✔	✔	-	-	-	-	-	✔	-
Xu et al. [20]	✔	✔	-	-	-	-	✔	✔	✔
Vázquez et al. [29]	✔	✔	-	-	✔	-	✔	✔	-
Abidin et al. [17]	✔	✔	-	-	-	-	✔	✔	-
Ahmad et al. [26]	✔	✔	-	-	-	-	✔	✔	✔
Ahmad et al. [80]	✔	✔	-	-	-	✔	✔	✔	✔
Einia et al. [81]	✔	✔	-	-	✔	-	✔	✔	✔
Present study	✔	✔	✔	✔	✔	✔	✔	✔	✔

P—Process factors; C—Chemical factors; O—Organizational factors; H—Human factors; HU—Handel the uncertainty; W—Weighting; MM—Mathematical modeling; A—Assessment; E—Evaluation.

Figure 8 depicts the overview of the application of study findings and their practical relevance. The present study is important from another aspect. Using fuzzy sets to quantify expert opinions when valid data is unavailable reduces uncertainty and provides quantitative values. By converting language variables into fuzzy numbers, Mamdani fuzzy sets work. In contrast, the COG defuzzification method [44], applied in previous studies, reliably converts fuzzy numbers to real numbers. Because Mamdani fuzzy sets must be compared in pairs to determine the weight, they cannot determine the exact weight of the factors despite their applicability in various computational aspects. The present study used Chang fuzzy sets to address this weakness. We assigned each expert's impact weights to minimize uncertainty in the present study. Calculating and considering this weight in calculating the weight of the factors made Chang's fuzzy calculations as accurate as possible. The applied innovation of the present study was the development of a quantitative questionnaire for inherent safety assessment in process infrastructures. We also presented the computational mathematical equations and the evaluation system for the analysis.

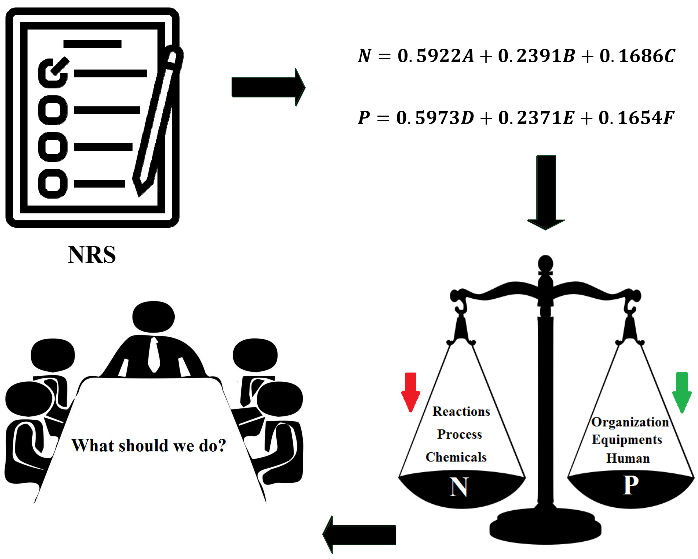

Figure 8. The overview of the application of study findings and their practical relevance.

4. Conclusions

An appropriate model to assess the inherent safety of process infrastructures is needed to fill the knowledge gap. This research provides a scientific and practical approach to identifying, assessing, evaluating, and controlling inherent safety hazards throughout the entire inherent safety design cycle. Improving structural integrity, safe and user-friendly design, and safety culture are the leading countermeasures to chemical, process, and reaction hazards in hydrogen production. Design factors were also more significant for overcoming the negative dimensions than human and organizational factors. We identified factors affecting ISA's positive and negative dimensions, while we have yet to model the intra-dependency among them. The findings of this study can be a practical guide for safety experts and decision-makers of process industries to evaluate inherent safety in the idea and design phase. The present study has also made contributions from a scientific point of view. (a) The developed approach deriving from Chang and Mamdani's fuzzy sets could handle epistemic uncertainty in collecting expert opinions and quantifying weights and calculations. (b) The factors identified in the taxonomy process can be a practical guide for researchers in the field of the inherent safety of process industries. They can use cause-effect analyses using fault tree analysis (FTA) or bow tie diagrams. (C) The findings related to the experts' opinion showed that a higher level of them is always needed in the positive dimension to control the negative dimension. (d) The ranking findings are a helpful guide for decision-makers to prioritize the shortcomings of their industries. On the other hand, the present study had some limitations. (A) Access to process industry data was limited, and studying a case in several units was impossible. (B) The community of experts in a higher volume could improve the accuracy of calculations to the maximum. (C) Weights calculated using Chang's fuzzy sets did not significantly show the difference in the weight of the factors. So, for future studies, it is suggested to employ valid methods such as the Decision-making trial and evaluation laboratory (DEMATEL) and the Analytic network process (ANP) to model dependency between them. In addition, the present study used Chang's fuzzy sets to weigh the factors that contributed to ISA. We recommend that future studies compare our findings with those of other Multi-Criteria Decision Making (MCDM) methods, such as VlseKriterijumska Optimizacija I Kompromisno Resenje (VICOR), fuzzy best worst, The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and The Simple Multi-Attribute Rating Technique (SMART). In the idea phase and initial design phases of the life cycle, the results of the present study can be utilized to develop inherent safety assessment models.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Calculating the Weight of the Expert 2

Table A1 indicates the calculating related to the weight of the expert 2. Using Equations (3)–(8), the weight of expert #2 was computed as Equations (A1) and (A2):

Table A1. Calculating the weight of the expert 2.

Number of Experts	Educational Degree	Type of Industry	Field of Education	Experience (Years)	Job Position	Relation between Degree and Position	Expert Weight
4	Master's	Oil company	Chemical engineering	15	HSE management	No	0.913

$$TruthValue(X \text{ is } A \text{ AND } X \text{ is } B \text{ AND } X \text{ is } C \text{ AND } X \text{ is } D \mid X = x) = min(TruthValue(X \text{ is } A \mid X = x), TruthValue(X \text{ is } B \mid X = x), (TruthValue(X \text{ is } C \mid X = x), (TruthValue(X \text{ is } D \mid X = x)) = min(\mu_{A(x)}, \mu_{Ak(x)}, \mu_{Bk(y)}, \mu_{Ck(y)}, \mu_{Dk(y)} = min\ (0.7, 0.89, 0.9, 0.88) = 0.36 \quad \text{(A1)}$$

$$TruthValue(X \text{ is } A \text{ AND } X \text{ is } B \text{ AND } X \text{ is } C \text{ AND } X \text{ is } D \mid X = x) = min(TruthValue(X \text{ is } A \mid X = x), TruthValue(X \text{ is } B \mid X = x), (TruthValue(X \text{ is } C \mid X = x), (TruthValue(X \text{ is } D \mid X = x)) = min(\mu_{A(x)}, \mu_{Ak(x)}, \mu_{Bk(y)}, \mu_{Ck(y)}, \mu_{Dk(y)} = min\ (0.7, 0.89, 0.9, 0.88) = 0.4 \quad \text{(A2)}$$

A, *B*, *C*, and *D* indicate experience, education, job position, and matching level. Expert 2 has a Master's degree and works in HSE management, a moderate-high level of experience, and a low level of matching between his field and his education. Based on Figure 3, there are two rules associated with this situation. Rule 31 and Rule 15. Therefore, there are two rules and four states in this respect wherein Equations (A3) and (A4) indicate the μ output of rule 31, and Equations (A5) and (A6) reveal the μ output of rule 15.

Rule number: 19 is: if X is MH, X is M, X is H, X is L then Y is MH

$$\mu_{output\ k \mid x(y \mid x)} = min(\mu_{Fk(y)}, \mu_{Ak\ (x)}, \mu_{Bk(y)}, \mu_{Ck(y)}, \mu_{Dk(y)}) = 0.89 \quad \text{(A3)}$$

$$\mu_{output\ k \mid x(y \mid x)} = min(\mu_{Fk(y)}, \mu_{Ak\ (x)}, \mu_{Bk(y)}, \mu_{Ck(y)}, \mu_{Dk(y)}) = 0.96 \quad \text{(A4)}$$

Rule number: 15 is: if X is LM, X is L, X is H, X is L then Y is LM

$$\mu_{output\ k \mid x(y \mid x)} = min(\mu_{Fk(y)}, \mu_{Ak\ (x)}, \mu_{Bk(y)}, \mu_{Ck(y)}, \mu_{Dk(y)}) = 0.89 \quad \text{(A5)}$$

$$\mu_{output\ k \mid x(y \mid x)} = min(\mu_{Fk(y)}, \mu_{Ak\ (x)}, \mu_{Bk(y)}, \mu_{Ck(y)}, \mu_{Dk(y)}) = 0.86 \quad \text{(A6)}$$

The membership function of the fuzzy set μMamdani | x is the Equation (A7):

$$\mu_{Mamdani|x(y)} = \substack{max \\ k}\left[\mu_{output\ k|x(y)}\right] = \substack{max \\ k}[min\ \mu Fk(y),\ \mu Ak\ (x),\ \mu Bk(y),\ \mu Ck(y),\ \mu Dk(y)] = 0.96 \quad \text{(A7)}$$

Eventually, we computed the COG's integral for calculating this area's center as 0.913 for expert 2.

Appendix B. Calculating the Weight of the A4: LEL/UEL

Foremost, for each set of sub-variables, a matrix $m \times n$ with $m = 1, \ldots, i$ and $n = \ldots, j$, we determined that each number M_{ij} was a characteristic of the matrix. In addition, we estimated Si for each row of the matrix as Equation (8):

$$s_i = \sum_{j=1}^{m} M_g^j [\sum_{i=1}^{n} \sum_{j=1}^{m} M_g^j]^{-1} \quad \text{(A8)}$$

After computing the Si, we had to estimate their importance relative to each other. If M1 and M2 are two fuzzy triangular numbers, the extent of the importance of M1 over M2, represented by V (M1 ≥ M2), is determined by Equations (A9)–(A13):

$$M_1 = (1_1, m_1, u_1)\ and\ M_2 = (1_2, m_2, u_2) \quad \text{(A9)}$$

$$\begin{cases} V(\ M1\ \geq M2\ ) = 1 \text{ if } m1\ \geq m2 \\ V(\ M1\ \geq M2\ ) = hgt(M1\ \cap M2) \text{ otherwise} \end{cases} \quad \text{(A10)}$$

$$V\ (M_1 \geq M_2) = \substack{sup \\ x\ z\ y}[\min(\mu_{M1}\ (x),\ \mu_{M2}\ (y))] \quad \text{(A11)}$$

$$V\ (M_1 \geq M_2) = hgt\ (M_1 \cap M_2) = \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} \quad \text{(A12)}$$

$$M_g^j\ : M_g^1,\ M_g^2, M_g^3, \ldots, M_g^m\ i = 1,\ \ldots, n\ j = 1, \ldots, m \quad \text{(A13)}$$

Therefore, each expert finished a pairwise comparison matrix for each set of variables. We averaged the experts' opinions. Eventually, for each sub-variables, a matrix comparison was constructed, which was the average of the views of the nine experts. Each expert delivers specified an array of matrices in the form of fuzzy triangular numbers ($l1$, $m1$, $u1$) $M1$ and $M2$ ($l2$, $m2$, $u2$) to $M6$ ($l6$, $m6$, $u6$). In this step, we multiplied the weight of each expert in the corresponding matrix. We calculated the average opinions of experts for each contributing factor of the pairwise comparison matrix as Equation (A14):

$$M_M = ((l_1 + l_2 + \ldots + l_6)/6, (m_1 + m_2 + \ldots + m_6)/6, (u_1 + u_2 + \ldots + u_6)/6)) \quad \text{(A14)}$$

Preferably, we added the first elements of all the parts and separated them by the number of experts (M = 9) and the first component's average details. Hence, we added the second components of all parts, divided them by 9, and did the same for the third component. We computed the average of the experts' views for the upper triangle of the matrix. We obtained the lower triangle values of the matrix by switching the upper triangle to Equations (A15) and (A16).

$$M_{12} = (l, m, u) \quad \text{(A15)}$$

$$M_{21} = \left(\frac{1}{u}, \frac{1}{m}, \frac{1}{l}\right) = M_{12}^{-1} \quad \text{(A16)}$$

We performed this operation for all seven matrices, and finally, we obtained seven averages. We completed the following steps to calculate the weight of each influence by the EA method for each matrix. For instance, we computed the low, medium, and high limit weight of the LEL/UEL (A4) factor employing the overhead equations. Table A2 indicates the importance relative to this factor.

Table A2. The importance relative of A4: LEL/UEL.

Low Limit		Medium Limit		High Limit	
V(S4 > S6)	0/962	V(S4 > S6)	0/977	V(S4 > S6)	0/985
V(S1 > S6)	1/059	V(S1 > S6)	1/023	V(S1 > S6)	1/008
V(S2 > S6)	1/057	V(S2 > S6)	1/027	V(S2 > S6)	1/014
V(S3 > S6)	1/106	V(S3 > S6)	1/095	V(S3 > S6)	1/077
V(S5 > S6)	0/896	V(S5 > S6)	0/881	V(S5 > S6)	0/903
V(S7 > S6)	1/048	V(S7 > S6)	1/059	V(S7 > S6)	1/052

Ultimately, we computed the importance of a triangular fuzzy number from K of another triangular fuzzy number (Mi (i = 1 … k)) as Equations (A17)–(A19) for low, medium, and high limits, respectively.

$$V(M_1 \geq M_2, M_3, \ldots, M_k) = min((M_1 \geq M_2), (M_1 \geq M_3), \ldots, (M_1 \geq M_k))$$

$$\textit{Low limit: } V\ (S6 < S1, S2, S3, S4, S5, S7,) = min\ (1/059, 1/057, 1/06, 0/962, 0/896, 1/048) = 0/896 \quad \text{(A17)}$$

$$\textit{Medium limit: } V\ (S6 < S1, S2, S3, S4, S5, S7,) = min\ (1/023, 1/027, 1/095, 0/977, 1/059, 0/881) = 0/881 \quad \text{(A18)}$$

$$\textit{High limit: } V\ (S6 < S1, S2, S3, S4, S5, S7,) = min\ (1/008, 1/014, 1/077, 0/958, 0/903, 1/052) = 0/903 \quad \text{(A19)}$$

Appendix C. Calculating the Required Positive Dimension

In this respect, employing Equations (3)–(8) in the text, we computed the required positive dimension score as below. First, we calculated the actual value utilizing Equation (A20).

$$TruthValue(X\ is\ A \mid X = x) = min\ (TruthValue(X\ is\ A \mid X = x) = 0.23 \quad \text{(A20)}$$

where A presents the computed negative dimension score, based on Table 2 and Figure 3, two rules are associated with this condition. Rule #8 and rule #9. Therefore, there are two rules and two states in this regard and Equations (A21) and (A22) illustrate the μ output of rules 8 and 9, respectively.

Rule number: 8 is: if X is MH then Y is E

$$\mu_{\ output\ k\,|\,x(y\,|\,x)} = min(\mu_{Ek(y)}, \mu_{Ak\ (x)}) = 0.92 \tag{A21}$$

Rule number: 9 is if X is C then Y is E

$$\mu_{\ output\ k\,|\,x(y\,|\,x)} = min(\mu_{Ek(y)}, \mu_{Ak\ (x)}) = 0.81 \tag{A22}$$

The membership function of the fuzzy set μMamdani | x is Equation (A23):

$$\mu_{Mamdani|x(y)} = {}^{max}_{k}\left[\mu_{output\ k|x(y)}\right] = {}^{max}_{k}[min\ \mu Fk(y),\ \mu Ak\ (x),\ \mu Bk(y),\ \mu Ck(y),\ \mu Dk(y)] = 0.92 \tag{A23}$$

Ultimately, we calculated the integral of COG as 0.905 for the studied hydrogen production facility.

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