Development of an Inherent Safety Index Based on Fuzzy Logic

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During the past several years, researchers in the U.S. and Europe have developed measurement techniques and analysis tools to estimate the inherent safety of a plant or a processing unit. These tools are based on traditional Boolean mathematical methodologies that are limited by the uncertain and subjective nature of the information analyzed. Preliminary results reported here are on the development of an inherent safety index based on fuzzy logic theory that is an extension of the Boolean theory. The basic ideas of fuzzy logic theory and its application are presented by the inherent safety evaluation of a storage tank. The inherent safety index developed by Heikkila is taken as a base and is compared with the results of the proposed prototype index. It shows the benefits of using fuzzy logic. Strengths and limitations of the proposed methodology are also presented.

Introduction

The main purpose of inherently safer design (ISD) is opposite to the purpose of the traditional concept of safety. While the former aims to eliminate or to reduce the hazards present in a process facility, the latter aims to reduce the consequences of a possible accident by using add-on barriers. In this case the hazard is still present and "safety" depends upon the reliability of the protective barriers. Inherent safety is based on principles that were formalized by Trevor Kletz (1991). Other authors analyze the benefits and problems associated to both ISD and the traditional approach (Lutz, 1997) while Zwetsloot and Askounes-Ashford (1999) present cases where ISD has proven to be not only technologically feasible, but also economically attractive even for productive chemical facilities. Examples and analysis of ISD are presented by Hendershot (1995, 1997a,b) and Gowland (1996).

The inherent safety principles represent "simple and good engineering practices" and they are well known by most safety practitioners, but the application is problematic for design and process engineers. Recently, Gupta and Edwards (Gupta et al., 2002) published the results of an extensive survey on the status of ISD in industrial, academic, and regulatory activities. Lack of knowledge and willingness to change, along with the lack of reliable and simple methodologies, are cited as causes of the slow acceptance and implementation of ISD.

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Similar results are presented by Kletz (1996) and Moore (1999), while Gowland (1996) summarized the problems into two fundamental questions:

- How can the effects of the changes (to inherently safer process or equipment in the plant) be measured?
- How to know if the plant follows the inherent safety principles or not?

Several techniques and tools have been developed to overcome this problem. However, these techniques analyze specific aspects of the factors that affect the inherent safety level. Also, it is difficult to integrate all the results under one unique evaluation.

Inherent safety measurement

In the early 1990s the European Union started the INSIDE Project (http://www.aeat-safety-and-risk.com/html/inside.html) with the objective of promoting inherent safety, health, and environmental protection within the European industry. Another main objective was the development of a toolkit, INSET (http://www.aeat-safety-and-risk.com/html/inside.html - inset) to identify inherently safer alternatives for any stage of the life cycle of a plant. However, the project did not focus on the development of a methodology to evaluate an overall inherent safety index (Mansfield, 1997).

Cave and Edwards (1997) developed an index for chemical route selection, while the first overall inherent safety index applied to process synthesis was developed by Heikkila et al. (1996) to be applied to the earlier stages of the life cycle of a plant (conceptual design and process synthesis) when it is easier to modify the process and/or the chemicals (the application of the principles is more effective). However, the amount of information available is limited and some of the principles cannot be evaluated. Heikkila's index is based on the evaluation of 12 parameters, which are carefully selected based on well-accepted engineering knowledge. The parameters are organized into two main indices called the Chemical Inherent Safety Index and the Process Inherent Safety Index. The Chemical Inherent Safety Index is divided into two sub-indices, one for reaction hazards (that analyze heats of reaction for the main and side reactions, and chemical interaction between substances), and one for hazardous substances (that analyze flammability, explosivity, toxicity, and corrosivity). The Process Inherent Safety Index is divided into two sub-indices, one for process conditions (analyzing inventory process temperatures and pressures), and another one for a process system (that analyzes equipment and process structures). The sub-indices are multiplied by weighting factors that can be chosen by the designer to emphasize some aspects above others and are then added together to obtain the value of the main indices. Then, these two main index values are added to get the value of the Overall Inherent Safety Index. For each one of the selected parameters, a possible range of variation is selected and divided into several sub-ranges. Each sub-range receives a score between zero and six according to its contribution to hazardous conditions (that is, the higher the score, the more hazardous the situation) (Heikkila et al., 1996).

The Heikkila index is based on Boolean mathematics, and each sub-range can be seen as a set with sharp boundaries. Also, an element can belong only to one set at a time. However, when an element is very close to the limits of the range, a small change in the value of the element will produce a "jump" to the adjacent sub-range, or set. This behavior produces two significant effects:

(1) Excessive sensitivity in regions close to the limits of each sub-range.

(2) Insufficient sensitivity within each sub-range.

In the first case, a small variation in the value of the parameter will cause a sudden shift of the index value. This border fluctuation effect is typical of methodologies based on intervals. As an example of this behavior, a change of two degrees, from 150 to 148°C when the interval is defined from 150 to 300°C, shifts the temperature into the lower subrange to obtain a score that suggests a safer process. The second effect is more serious because of the efforts to reduce the value of one parameter (that is, a temperature reduction from 290 to 160°C), and have no bearing on the analysis if they are not enough to jump to the lower sub-range.

Choosing larger numbers of narrower sub-intervals can solve these problems, but the complexity of the resulting system increases. Another solution is suggested by fuzzy logic theory where the transition from one interval to the next is smooth. Since an element can belong at the same time to more than one fuzzy set, data with uncertainty, caused by the measurement method or subjective evaluation, can be analyzed in a better way. These two characteristics (smooth transition and ability to work with uncertain data) of fuzzy systems solve both problems presented by the traditional interval approach. Furthermore, fuzzy logic presents an additional advantage because it can "compute with words," which is a very useful property when safety evaluations are based on subjective judgment and uncertain data. This concept is elaborated in the following examples.

Engineers work comfortably with crisp limits, but these values are used as fuzzy numbers. The flammability range of a substance demonstrates this. The range is limited by the upper and lower flammability limits (5% to 20%), which are crisp numbers. The measurement of gas concentration is a uniform reading assumed to be valid for the entire cloud (since it is not possible to know the concentration in each point). However, an explosive vapor cloud does not have a homogeneous concentration due to diffusion and turbulence effects that produce regions of higher and lower explosivity. When the concentration value is lower, but around the lower flammability limit, strictly speaking, an explosion should not occur. However, we know, as humans, or can assume that the explosion is very possible. This linguistic knowledge (that is, when the gas concentration is "around" the flammability limit, an explosion is highly possible) can be modeled by using the flammability limits as a fuzzy number (that is, around 5%).

Methodology

Fuzzy logic approach

Fuzzy logic is the general name of "fuzzy set analysis" and "possibility theory"; it can deal with uncertainty and imprecision, and it is an efficient tool to work with problems where no sharp boundaries (or problem definitions) are possible. Fuzzy logic could be confused with the traditional probability theory, however. While the former can measure the degree of membership in a set, the latter only measures the likelihood of an event to be in that set (Yen and Langari, 1999). The difference, as shown in Figure 1, is that, while in a Boolean Set, an element can only be inside or outside the set, the element in Fuzzy Logic can be partially or totally inside or outside.

The position of the element is described by the membership function (μ) that has a value of one ($\mu = 1$), if the element belongs completely to the set; a value of zero ($\mu = 0$), if the element does not belong to the fuzzy set; and any value between zero ($0 < \mu < 1$) and one, when the element belongs partially to the fuzzy set. Figure 2 shows an example of membership function of the flammable limits for the mixture

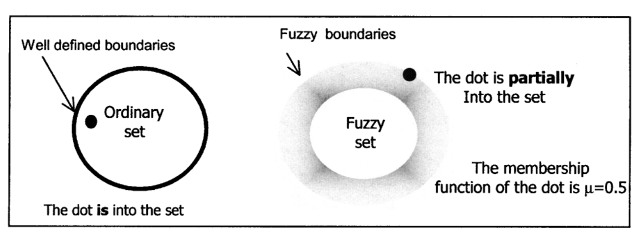

Figure 1. Difference between an ordinary set and a fuzzy set.

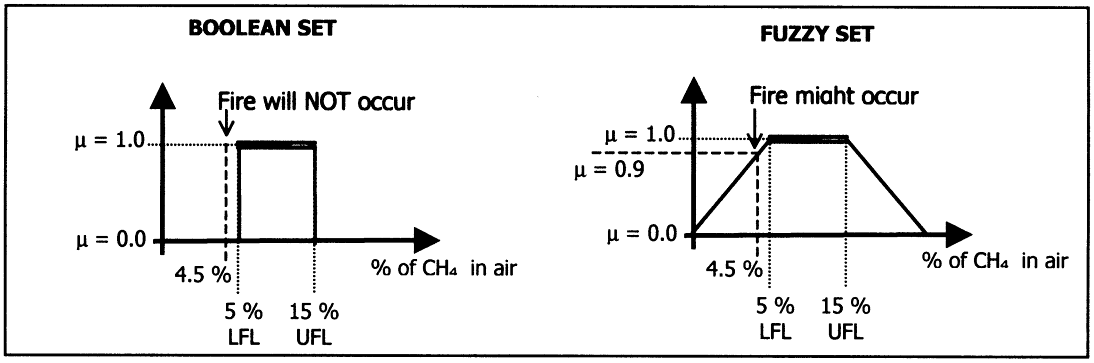

Figure 2. Flammability limits described by a Boolean Set and a fuzzy Set.

methane-air at standard conditions. Under these conditions, the lower flammable limit (LFL) and upper flammable limit (UFL) are, respectively, 5% and 15%. When the concentration of CH_4 is lower than 5% or larger than 15%, it is not possible for a fire to occur, even with an ignition source. According to the traditional mathematical approach, the probability of fire occurrence is 0, even if the concentration of CH_4 is 4.5% (very close to the LFL). According to the Fuzzy Logic approach, the possibility of fire, represented by the "flammability" membership function, will increase (according to a predefined function, that here is assumed linear) as the concentration moves toward the LFL. The function reaches its maximum value when the concentration of CH_4 is between the LFL and the UFL, and will decrease proportionally to the gas concentration after the UFL. By using the fuzzy set approach, it is possible to take into account the heuristic knowledge that, as the CH_4 concentration gets closer to the flammability limits, the possibility of a fire increases. This also takes into account the uncertainty associated with heterogeneous mixing of the gas cloud due to turbulence effects and uncertainty associated with the measuring sensor.

In Fuzzy Logic the variables are known as Linguistic Variables. In Figure 2, the linguistic variable is the concentration of methane. This variable is divided into sub-ranges, or fuzzy sets, whose main characteristic is that the extremes overlap at least with the adjacent sets. This overlap allows an element to belong to more than one fuzzy set at the same time, and the degree of membership into each set indicates how much the element belongs to each fuzzy set. Each fuzzy set is defined by the membership function whose shape and range of possible values describe the physical behavior of the set. The range of the membership function where its value is larger than zero is known as the support of the fuzzy set described by that function.

The inputs to the fuzzy logic models are linguistic variables and its fuzzy sets. The outputs can be linguistic variables described by fuzzy sets (Mamdami model) or linear functions (Sugeno Model) (Yen and Langari, 1999). The fuzzy sets for the inputs are related to the output fuzzy sets through if-then rules, which describe the heuristic knowledge about the behavior of the system. The process of fuzzyfication of the inputs, evaluation of the rules, and aggregation of all the required rules is known as Fuzzy Inference. The mathematical foundations of fuzzy logic and the fuzzy inference are reported by several specialized references (Yen and Langari, 1999; Duboise and Prade, 1998; Riza and Sheldon, 1997; Bárdossy and Lucien, 1995; Schmucker, 1983; Zimmermann, 1996; MATLAB Fuzzy Logic Tool Box).

Which question do we want to answer?

Safety, as many other concepts used in chemical engineering, is a fuzzy idea that cannot be limited to only two possible states, safe/unsafe. In other words a piece of equipment, a processing unit, or a chemical plant cannot be classified as safe or unsafe because of the complex nature of these systems and the many factors (objective and subjective) that are to be taken into consideration. However, when safety is evaluated by using a Boolean approach, an element can only be classified into the two categories, and this establishes another problem related to how to set the limit between the two states. Fuzzy Logic allows a gradual transition between the two extremes (safe/unsafe), and the degree of safety can be related to the value of the membership function into the "inherently safer" fuzzy set.

In order to accomplish a goal it is fundamental to ask the right question. While the Boolean approach asks "Is the plant safe?", the Fuzzy Logic approach asks "How safe is the plant?". It is widely accepted that a plant can be only inherently safer (or unsafer) with respect to another; hence, it is required to measure safety rather than classify it. These ideas are explained by Figure 2, and constitute the fundamental idea of the present methodology.

Examples

How inherently safer is a storage tank?

The fuzzy logic methodology explained previously is applied here to evaluate a storage tank. Many factors can contribute to the safety level of a tank; for instance, a large tank of water can have a hazard level similar to that of a small tank of a strong acid. Because of this fact several factors must be considered to evaluate the inherent safety of a tank, and the most important are:

- Volume;
- Chemical hazard degree of the stored substance;
- Pressure;
- Difference between storage and ambient temperature and (T-Tt);

• Difference between ambient temperature and boiling temperature (T-Tb); and

• Location of the tank (inside/outside battery limit or density of equipment in the area of the tank)

Each one of these factors represents a linguistic variable described by a specific number of fuzzy sets and membership functions. In order to evaluate the hazard inherent to a tank, the variable "volume" is combined with the variable "chemical hazard" to give a first evaluation (H1) of the hazard caused by the quantity and type of substance. The hazards inherent to the physical state inside the storage tank, and the general behavior expected after the chemical is released into the atmosphere (H2), is given by the evaluation of three variables. The first one is the difference between the ambient temperature and the boiling point of the chemical; the second is the difference between the ambient temperature and the storage temperature; the third one is the storage pressure. The general heuristic knowledge modeled by these three variables is the following:

• As the boiling point of a substance increases, its volatility decreases reducing the hazards due to dispersion. The effect of heavy gases is not taken into account here.

• As the storage temperature increases, the hazards due to dispersion increase. The hazard reduction due to high temperature release is not taken into account by the rules.

• As the storage pressure increases, the mass flow from a leak increases and the possibility of aerosol formation is higher. Hazard reduction due to jet mixing is not taken into account here, however, by modifying the if-then rules, it is possible to model the effect.

• The atmospheric stability and wind velocity affects the shape of the cloud in a similar way, and, however, are not taken into account here because, under similar conditions, the size of the cloud depends mainly on the properties of the chemicals and the storage conditions.

The next step requires the combination of H1 and H2 to calculate H3, which represents the combination of the hazards due to the chemical and the storage conditions. The last step is the adjustment of H3 depending on the congestion of the site of the tank. The design of the membership functions for "volume" and "chemical hazard" are described.

Definition of the fuzzy set for the volume of the tank

The volume of industrial tanks spans from a few gallons (that is, a 55-gal drum) to several million gallons. Because the volume range is extremely broad, the natural logarithm of the nominal volume is required to preserve the smaller volume values. Then, the range is divided into sub-ranges according to the approximate values given by Lees (1986) for various types of storage tanks, and then the shapes of the membership functions are selected, as shown in Table 1. The membership functions are shown in Figure 3.

The design of the membership functions is one of the most important steps for the design of a fuzzy system. In this case, the nominal volumes presented in Table 1 are selected to be around the upper limit of the support for the associated fuzzy set. In this way, the volumes close to the lower limit of the set are more likely to be similar to the previous smaller set, while values closer to the upper part of the set have a certain degree of membership in the next larger set.

Table 1. Fuzzy Sets and Membership Functions for the Factor "Tank Volume"

Fuzzy Set for **"VOLUME"**	Nominal Vol. [gal]	*Ln* (Vol.)	Fuzzy Set Support [gal] ($0 < \mu < 1$)
Very small	55	4	0–200
Small	600	6.4	3–3000
Medium	20,000	10	250–60,000
Large	500,000	13	5,000–3,000,000
Very large	25,000,000	17	160,000–

Definition of the fuzzy set for chemical hazard

The hazard posed by the chemical substance in the tank is another important factor that must be evaluated to quantify the inherent safety of the tank. This aspect is described by the linguistic variable "chemical hazard," and its evaluation is based on the material factor used by the Dow Fire and Explosion Index (F&EI) and National Fire Protection Association (NFPA) ratings for the properties of flammability, reactivity, and health hazard. The scores for these three substance properties have a range between zero and four. In order to include all three aspects under the same linguistic variable "chemical hazard" and, at the same time to penalize the higher ratings, the following calculation was performed

$$\text{Hazard} = H = \sum_{i=1}^{3} S_i^2$$

where S is NFPA hazard ratings for each one of the three properties, $S = 0$, 1, 2, 3 or 4, and i are properties (flammability, reactivity, and health hazard), $i = 1$, 2, 3.

When a substance has a score of zero for all three ratings, its total score is zero (minimum); if a substance has four for each rating, its total score is 48 (maximum). When a substance has a combination of ratings, its total score will be between zero and 48, which represents the range of the linguistic variable "chemical hazard." The selected fuzzy set and their supports are shown in Table 2.

The fuzzy sets are shown in Figure 4. The supports of the fuzzy sets were selected to restrict the first two sets ("not hazardous" and "slightly hazardous") to substances that have only zero and one in their NFPA scores. The most hazardous substance in this set can have a score of only one for all three properties. Following the same reasoning, the substances that

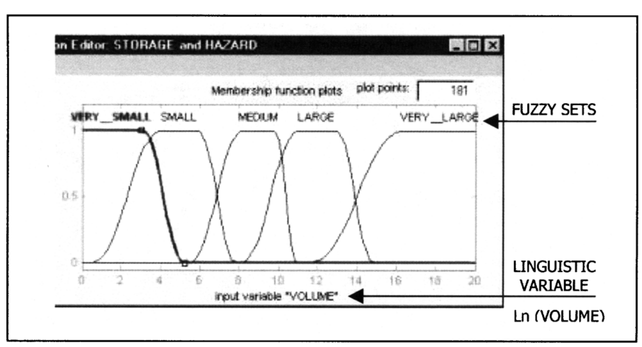

Figure 3. Fuzzy sets for the linguistic variable "tank volume" (VOLUME).

Table 2. Type of Membership Functions for Parameters of "Chemical Hazard"

Fuzzy Set for **"Chemical Hazard"**	Hazard = H $\mu \approx 1$	Fuzzy Set Support $(0 < \mu < 1)$
Not hazardous	0–3	0–5
Slightly haz.	4–8	1–9
Hazardous	9–15	7–20
Very hazardous	16–24	10–30
Extremely haz.	25–48	23–48

Table 3. Type of Membership Functions for Parameters of "Hazard"

Fuzzy Set for **"Hazard"**	Hazard = H $\mu \approx 1$	Fuzzy Set Support $(0 < \mu < 1)$
Very safe	0.00	0–0.25
Safe	0.25	0–0.50
Unsafe	0.50	0.25–0.75
Very unsafe	0.75	0.50–1.00
Extremely unsafe	1.00	0.75–1.00

fall into the "slightly hazardous" set can have at most two scores of two with one zero. When a substance has at least one score of three, it will be in the "hazardous" set even if the other two scores are zero. When a substance has at least one score of four, it will be in the "very hazardous" set; a substance with at least one score of four and one score of three will be in the "extremely hazardous" set.

It is assumed that all the characteristics have the same importance for the total score. If one of the three NFPA ratings is assumed to be more important (that is, reactivity or instability), weighting factors should be used.

Definition of the fuzzy set for H1, H2, H3 and H4 (outputs)

Each one of the four fuzzy systems evaluated requires defining the fuzzy sets for the output variables (H1, H2, H3 and H4). As an example, the result from the evaluation of "tank volume" and "chemical hazard" is a new linguistic variable called "hazard" (or H1) with a range of [0, 1]. Its fuzzy sets are presented in Table 3 and Figure 5.

The index H1 for the evaluation of the first two factors for the tank is calculated from these fuzzy sets. When the defuzzified result approaches zero, the linguistic conclusion is "the tank is very safe and follows the inherent safety principles." When the value approaches one, the conclusion is "the design of the tank implies a high inherent hazard."

Strategies for the development of IF-THEN rules

The development of the if-then rules that define the relation between the selected linguistic variables and their fuzzy sets is a critical step, because they describe the heuristic knowledge about the behavior of the physical system. For the evaluation of the storage tank, a total of 225 rules are used (25 for each system to calculate H1, H3 and H4 and 150 for H2). The calculation of H2 requires three inputs at the same time and the rules are

$$\text{IF } (T\text{-}Tt) = X_i \text{ AND } (T\text{-}Tb) = Y_j \text{ AND } P = Z_l = K_g \quad \text{THEN } H2 = K_g$$

where X, Y, Z and K are the linguistic variables with respectively i, j, g = 1 to 5 and l = 1 to 6 fuzzy sets. The calculation of H1, H3 and H4 require only two inputs each, with 5 fuzzy sets.

Assuming that only one linguistic variable defines each factor, the IF-THEN rules must describe the relation among four variables with its number of fuzzy sets. Two different approaches are possible:

(a) Working with all the linguistic variables at the same time

(b) Working with pairs of variables by dividing the procedure into four evaluation steps arranged in a cascade

The first option would require the development of an extremely large number of rules, which poses problems not only because of the complexity of the system, but also because the rules itself would be difficult to understand. The second approach requires fewer and simpler rules, because only two variables (three at most) are analyzed at the same time. The system can be further simplified by discarding the least significant rules. Rules can be built from expert knowledge or from data. When enough data is available, the design of the rule can be developed by using the Adaptive Network Fuzzy Inference System (ANFIS) (The Mathworks, 2000).

As an example, the variables "tank volume" and "chemical hazard," have five fuzzy sets each and a total of 25 (5×5) rules can be developed to describe the system. In this case

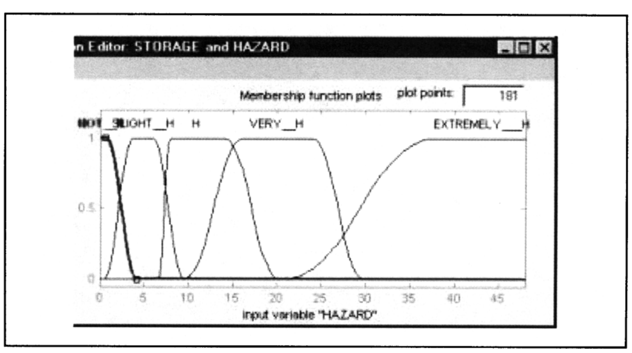

Figure 4. Fuzzy sets for the linguistic variable "chemical hazard" (HAZARD)

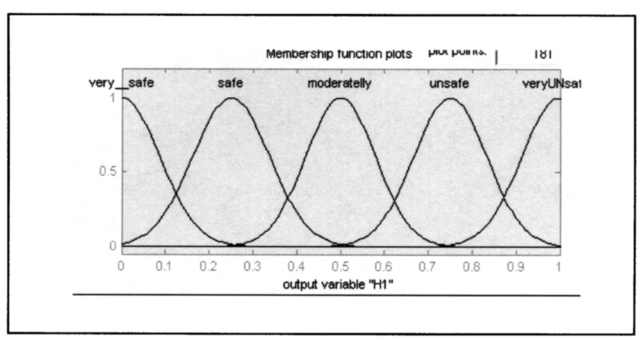

Figure 5. Fuzzy sets for the linguistic variable "hazard" (H1).

HAZARD		CHEMICAL HAZARD (H1)				
		NOT HAZARDOUS	SLIGHTLY HAZARDOUS	HAZARDOUS	VERY HAZARDOUS	EXTREMELY HAZARDOUS
TANK VOLUME	VERY SMALL	VERY SAFE	VERY SAFE	SAFE	SAFE	SAFE
	SMALL	VERY SAFE	VERY SAFE	SAFE	UNSAFE	UNSAFE
	MEDIUM	VERY SAFE	SAFE	UNSAFE	UNSAFE	VERY UNSAFE
	LARGE	SAFE	UNSAFE	VERY UNSAFE	VERY UNSAFE	EXTREM. UNS.
	VERY LARGE	UNSAFE	UNSAFE	VERY UNSAFE	EXTREM. UNS.	EXTREM. UNS.

Figure 6. Rule matrix for the linguistic variables "tank volume" and "chemical hazard."

the system was not simplified by taking into consideration only a few important rules. An example of rules is presented below:

Rule 1: IF "tank volume" = *small* AND
"chemical hazard" = *not hazardous*
THEN "H1" = very safe

Rule 2: IF "tank volume" = *medium* AND
"chemical hazard" = *very hazardous*
THEN "H1" = unsafe

. . .

Rule 25: IF "tank volume" = *very large* AND
"chemical hazard" = *extremely hazardous*
THEN "H1" = extremely unsafe

These rules can also be expressed in a matrix format, as shown in Figure 6.

Rules evaluation

Each rule relates one fuzzy set from each linguistic variable, but the fuzzy sets overlap, so more than one rule is evaluated for each single input. In this case, four rules are evaluated for each pair of inputs, as shown in Figure 7. It is important to note that ($\mu_{\text{very hazardous}} + \mu_{\text{hazardous}}$) can be greater than 1, since the membership function μ represents the possibility (not the probability) that an element belongs to a fuzzy set. In Figure 7, $\mu_{\text{very hazardous}} = 1$ indicates that the substance is very hazardous, but it could also be (that is, under specific circumstances) less hazardous ($\mu_{\text{hazardous}} = 0.75$).

The four evaluated rules are indicated in Figure 5 by shading of the relative cells. Each rule combines the two membership values of two inputs into one fuzzy set. Because the rules are combined by AND, only the smaller of the two values is used in the inference step to evaluate the output of the rule. This step is shown in Figure 8 for the rule:

IF "tank volume" = *small* AND
"chemical hazard" = *hazardous*
THEN "H1" = safe

When all four rules are evaluated, the results (four fuzzy sets represented by areas) must be aggregated by using an OR operation, which selects the maximum output value for each fuzzy set indicated by the consequent part of each rule

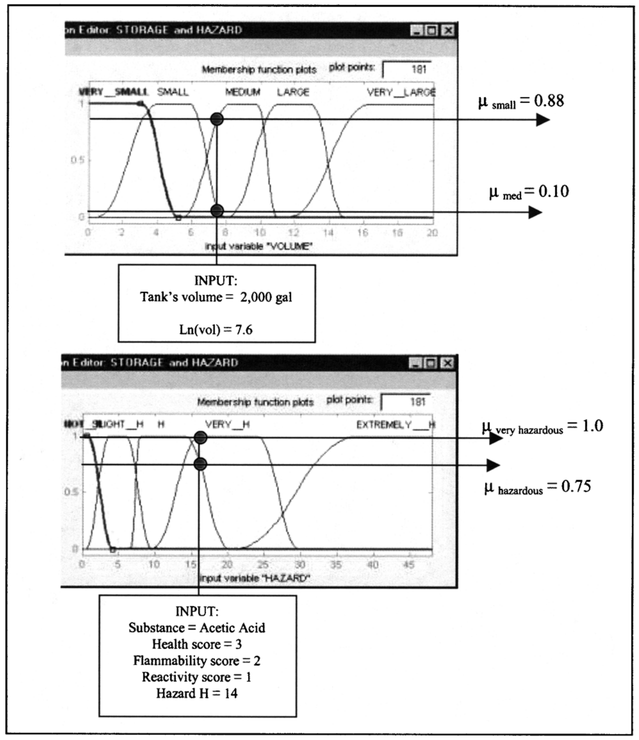

Figure 7. Evaluation of "tank volume" and "chemical hazard" for a tank of acetic acid

being evaluated. The resultant total area represents the fuzzy outcome from the evaluation of the pair of values for volume and chemical substance for a specific tank. In order to obtain a numerical value (which will be used as input for the next evaluation together with the tank operating conditions) the fuzzy output must be defuzzified. The technique used here is the center of mass of the fuzzy surface.

When this inference procedure is repeated along the complete range of both linguistic variables ("tank volume" and "chemical hazard"), we obtain a surface that describes the behavior of the variables for any volume of substance hazard (see Figure 9). This graphical result is an advantage of working with only two linguistic variables at a time.

Example 1. In some cases toxic solvents can be substituted by other less toxic as, for example, cyclohexane (C_6H_{12}) could be used instead of benzene (C_6H_6). Assuming that the same volume is required and they are stored under the same conditions, the results are reported in the Table 4.

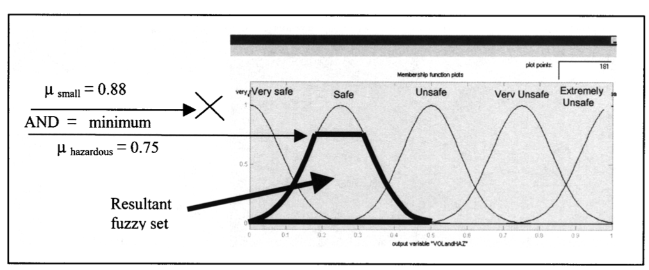

Figure 8. Output from the rule that relates SMALL and HAZARDOUS

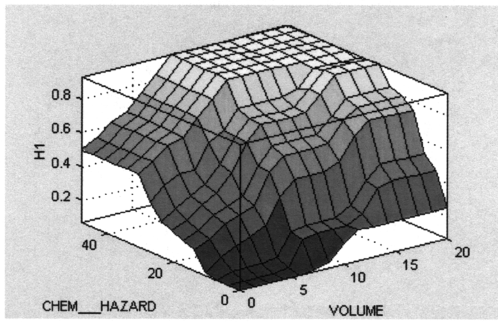

Figure 9. Output from the evaluation of "tank volume" and "chemical hazard."

Table 5. Comparison of Anhydrous and Diluted HCl

INPUT	HCl 30% w/w	HCl Anhydrous
NFPA health	3	3
NFPA reactivity	0	2
NFPA fire	0	0
Boiling point (°C)	109	−84.9
Storage temp. (°C)	25	25
Storage press. (atm)	1	1
Storage vol. (gal)	0.7	215
OUTPUT	**HCl 30% w/w**	**HCl anhydrous**
Hazard $= H = \sum_{i=1}^{3} S_i^{2}$*	9	13
H1†	65.9	34.94
H2†	43.99	91.68
H3†	12.55	45.52

*On a scale 0–48.
†Normalized on a scale 0–100.

The reduction of H1 for cyclohexane is caused by its lower NFPA score for health hazard and this causes H3 to be lower. H3 can be interpreted as the Inherent Safety Index.

Example 2. As suggested by the inherent safety principle "moderation," the inherent hazard level of a chemical substance can be reduced by dilution. In this example a small volume of muriatic acid (30% w/w) is compared against the correspondent volume of hydrogen chloride at ambient conditions (Table 5): The strong reduction of H3 is produced by the reduction in reactivity and by the increased boiling temperature of the diluted acid mixture.

Example 3. The procedure can also be used to analyze the inherent hazard posed by pipelines assuming a fixed length and calculating the volume depending on the diameter.

Fuzzy Model Description and Application to a Chemical Plant

The fuzzy system described above is based on a Mamdami model (Yen and Langari, 1999) with the characteristics reported in Table 6.

The safety level of a tank is just one aspect of the overall inherent safety index proposed here. The approach described for the inherent safety evaluation of the tank is applied for the evaluation of other factors, which are reported in Table 7. As shown in Figure 10, the structure of the proposed index is divided into three major blocks; each block requires specific factors listed in Table 7. This list is based on the factors used by Heikkila (1996) with some additional factors, such as personal safety equipment.

Table 4. Comparison of the Solvents Benzene and Cyclohexane

INPUT	(C_6H_{12})	(C_6H_6)
NFPA health	1	2
NFPA reactivity	0	0
NFPA fire	3	3
Boiling point (°C)	80.7	80
Storage temp. (°C)	25	25
Storage press. (atm)	1	1
Storage vol. (gal)	40	40
OUTPUT	(C_6H_{12})	(C_6H_6)
Hazard $= H = \sum_{i=1}^{3} S_i^{2}$*	10	13
H1†	20.25	29.50
H2†	54.5	54.92
H3†	26.58	30.40

*On a scale 0-48.
†Normalized on a scale 0–100.

The block for "chemical substances" must be evaluated for each chemical involved in the process. For the evaluation of the index, the sum of the output for each chemical is taken into account. For the evaluation of storage vessel hazard, only the output for the most hazardous chemical is used, following normalization to a range [0 1]. The block for "Process Hazard" evaluates safety factors related to general aspects of the plant such as maximum pressure and temperature, heats of reaction that occur in the process being evaluated, required personal safety equipment, and a general structure of the plant. The block for "Process Equipment and Tanks" evaluates the hazards related to type of equipment and a location in the plant. The processing plant is divided into two areas outside the battery limits (OSBL) and inside the battery limits (ISBL). Equipment or storage tanks located in OSBL areas are considered safer, because the plant is not so congested with pipelines, instrumentation and processing equipment. For the evaluation of the final index, the output from each block is added in a weighted sum. Here the four sub-indices receive the same importance; hence, the weighting factors are one.

To complete the inherent safety evaluation, it is necessary to perform the following four steps:

(1) Divide the chemical plant into operating subprocesses according to the unit operations of each area. For instance: reaction unit, purification train, reactants preparation, and storage area.

(2) For each unit identify chemical substances, operating conditions, and processing equipment.

(3) Evaluate the inherent safety index for each unit.

(4) Add the values of the indices for each area.

Results and Analysis

The fuzzy logic-based index was tested with the results from the Heikkila index. Both indices were used to evaluate the same process with the same input conditions. This test was

Table 6. Characteristics of the Mamdami Model

Operation	Operator	Norm	Formula
Intersection (OR)	MAX	T-conorm	$\mu_c(x) = \max(\mu_A(x), \mu_B(x)) = \mu_A(x) \vee \mu_B(x)$
Union (AND)	MIN	T-norm	$\mu_c(x) = \min(\mu_A(x), \mu_B(x)) = \mu_A(x) \Lambda \mu_B(x)$
Implication	MIN	T-norm	$\max(\min(\mu_A(x), \mu_B(x)))$
Aggregation	MAX	T-conorm	
Defuzzification Methodology	Center of Mass (Area) of the Surface	N.A.	$\mathrm{COA} = \dfrac{\int z \mu_C(z) dz}{\int \mu_C(z) dz}$

$\mu_c(x)$ = value of the resultant membership function.
$\mu_A(x)$ = value of the membership function when the input belongs to the fuzzy set A.
z = abscissa value, ($\mu_c(z)$ is the ordinate).

performed on a simplified processing plant for the production of acetic acid from methanol and CO. The plant is divided into two sections. The reaction section requires analyzing two substances (methanol and CO), and has one chemical reaction that can have a side reaction. The distillation section requires only the evaluation of acetic acid as a chemical substance and does not include any main or possible side reactions (Heikkila et al., 1996).

Only the temperature and pressure are changed to show the behavior of the fuzzy logic-based index and the Heikkila index based on intervals. The temperature and pressure are selected within and close to the limits of the ranges of 150−300°C and 25−50 bar, respectively. The results of this test are reported in Table 8 for various values of temperature and pressure.

The first row indicates the values of the indices when both temperature and pressure are one unit below the lower limits of the ranges. The third row of results indicates the value of the indices when the temperature and pressure are in the middle of the range. The second and fourth rows indicate the results when the variables are at lower and upper limits of temperature and pressure. As shown in Table 8, the results for the Heikkila index is constant throughout all the intervals of pressure and temperature, but the fuzzy logic-based index exhibits changes. When the Heikkila index is reduced due to small changes in the temperature and pressure (that fall in the next lower range), the fuzzy logic index yields a reduction in proportion to the reduction of the input values. This behavior of the proposed fuzzy logic-based index is practical for smooth and continuous evaluations of inherent safety quantification for complex chemical plants.

Because of smooth transitions between fuzzy sets, this new index does not present problems associated with crisp ranges. However, there are aspects of the proposed methodology that require more research to assure that the index is reliable, efficient, and practical. Some problems have been detected

Table 7. Factors Analyzed by the Proposed Inherent Safety Index

Parameters	Required Information
	Chemical Substances
Flammability	Flash temperature
Toxicity	TLV
Explosivity	Explosive range = UEL−LEL
Chemical interaction	Possibility of FIRE and EXPLOSION Production of TOXIC and NON-TOXIC GASES, FLAMMABLE GASES, HEAT, TOXIC HYDRO-SOLUBLE COMPOUNDS, POLYMERIZATION.
Reactivity	Runaway temperature (if any)
Water	Reactivity with water
	Process Hazard
Higher temperature	Higher temperature in the unit or process being analyzed
Higher pressure	Higher pressure in the unit or process being analyzed
Material	Metal/plastic/special materials
Personal Protection Equipment	Safety equipment required for personal protection
Process safety	Evaluation based on safety and performance information available for similar processes
Packing degree of the area	Evaluation of the density of process equipment present in the unit that is being analyzed.
Heat of the main reaction	Heat that must be supplied/removed
Heat of the side reactions	Heat that must be supplied/removed
	Process Equipment and Tanks
Type of process equipment	Safety degree of equipment inside the battery limit
Type of other equipment	Safety degree of equipment outside the battery limit
Tank volume	Volume of the tank
Tank's pressure	Pressure of the tank

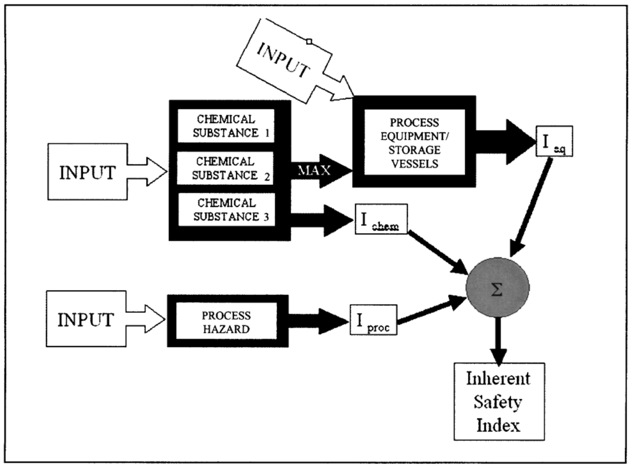

Figure 10. General structure of the proposed inherent safety index

with the defuzzification method when more than one linguistic variable is evaluated at the same time. Another problem is related to the aggregation by weighted sums, which is efficient when no redundant evaluations are used. However, in this case, there are elements that are evaluated more than one time in implicit forms. An example of this is high pressure associated with high temperature; when these two parameters are evaluated at the same time for the same element, the system receives a double penalty even when one variable is implicit in the other one (high temperature is a synonym of high pressure) such as the evaluation of highly endothermic reactions. Since this type of reaction requires heat produced by furnaces, they are doubly penalized. First, the reaction is penalized because it is highly endothermic, and, second, the unit is penalized because of the higher temperature in the furnace. One possible solution to this problem is the substitution of the aggregation method by fuzzy measures to avoid the overpenalization.

The selection of the rules describing the knowledge and safety perception is one of the most important steps of this method. To optimize the system, it is necessary to identify the smallest and most effective set of rules that describe the system. This selection requires additional testing and analysis of each linguistic variable and requires also the collaboration of experts who can judge the output of the system.

An interesting application of this methodology concerns the interaction of changes with interconnected processing units. When this tool is linked to a process simulator, the processing options and safety evaluations can be accomplished at the same time to detect unsafe conditions derived from changes in another unit.

Table 8. Test Results on the Reaction Section Changing Two Inputs

Temperature °C	Pressure bar	Heikkila Index	Fuzzy Logic-Based Index
149	24	27	9.95
150 (lower limit)	25 (lower limit)	29	10.04
175	30	29	10.47
300 (upper limit)	50 (upper limit)	29	10.83

Conclusions

The application of fuzzy logic to the analysis and quantification of inherent safety yields continuous results and eliminates the problems presented by the traditional interval approach. This index represents the first step toward the development of a methodology useful for evaluating in a simple and systematic form the inherent safety aspects that otherwise would be impossible to analyze under a unified index. More research is required to assure that the selected parameters, the design of membership functions, and the development of the IF-THEN rules describe an efficient and reliable method to analyze the safety properties and behavior of chemical plants and processing units.

The fuzzy logic methodology here has been applied to a safety problem, however, it can be applied to a large number of problems characterized by uncertainty caused by fuzziness rather than randomness. It must be recognized that fuzzy logic is a powerful tool, however, it should not be applied to problems easily solvable by other traditional approaches. In the case of inherent safety, fuzzy logic provides a tool to model heuristic knowledge that cannot be described by traditional mathematical equations.

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