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Development of an Inherent Safety Index Using Fuzzy Logic

Michela Gentile,
W. Rogers, and M.S. Mannan
Mary Kay O'Connor Process Safety Center
Chemical Engineering Department Texas A&M University
College Station TX 778433122

Phone: 979/862-3985
Email: m0g1884@chennov2.tamu.edu

ABSTRACT

The Inherently Safer Design is a concept known since 1870. However, there is a general resistance to adopt and systematically apply its principles because they are subjective. For instance: "Reduce the inventory of a hazardous chemical substance." But, how much should the inventory be reduced? "Simplify your process." How to know if the process is simple enough?

Things cannot be classified strictly as "safe" or "unsafe". Something can be perceived as "not very safe" or "highly unsafe." One of the greatest challenges is to answer quantitatively the question "How safe is a chemical plant?" In order to quantify the safety level we need to capture all the possible options between the extremes of safe/unsafe. If we think in terms of traditional mathematics (Boolean logic), an element can only be inside or outside of a set. In other words, the element can only be safe or unsafe. What happens with the "not very safe" element?

The approach proposed here is based on fuzzy set theory. Here we will show how to use fuzzy logic to answer these questions. We will show how to develop the required membership functions and how to apply the methodology to calculate the index for a simple processing unit.

Development of an Inherent Safety Index Based on Fuzzy Logic

Michela Gentile, William J. Rogers, M. Sam Mannan
Mary Kay O'Connor Process Safety Center
Chemical Engineering Department,
Texas A&M University System
College Station, TX 77843-3122 USA

ABSTRACT

During the last few years researchers in the United States 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. The present paper presents preliminary results on the development of an inherent safety index based on fuzzy logic theory that is an extension of Boolean theory. The inherent safety index developed by Heikkila is taken as a base against which the results of the proposed index are compared. This new index is based on the evaluation of various safety aspects; each aspect requires the evaluation of specific parameters for which membership functions are developed as illustrated by the inherent safety evaluation of a storage tank. Strengths and limitations of the proposed methodology also are presented herein.

INTRODUCTION

Inherent safety principles are well known by most safety practitioners, but the application is problematic for design and process engineers because it is difficult to quantify the application of the principles. Many 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 and it is difficult to integrate all the results under one unique evaluation.

In the early '90s the European Union started the INSIDE Project (Inherent SHE In Design) with the objective of promoting inherent safety, health, and environmental protection within the European industry. Another main objective was the development of a toolkit 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].

The first overall inherent safety index 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. As a result, 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 twelve 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 analyzes heats of reaction for the main and side reactions, and chemical interaction between substances) and one for hazardous substances (that analyzes 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 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 (i.e., the higher the score the more hazardous the situation) [Heikkila *et all* 1996].

The Heikkila index is based on Boolean mathematics and each sub-range can be seen as a set with crisp or sharp boundaries and an element can belong only to one set at 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 sub-range to obtain a score that suggests a safer process. The second effect is more serious because the efforts to reduce the value of one parameter (i.e., temperature reduction from 290 to 160 °C), 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 resulting system is very complex. 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.

Not all human knowledge can be described by mathematical equations. When researchers tried to "teach" a computer to park a vehicle they discovered how complex and inefficient the mathematical model used to describe the position of the car and distance from the obstacle was. However, a new driver can learn to park a car in a short time following only a few spoken indications or heuristic rules.

Engineers work comfortably with crisp limits, but these values are used as fuzzy numbers and the flammability range of a substance demonstrates this. The range is limited by the upper and lower flammability limits (i.e. 5% to 20%) which are crisp numbers. The measurement of gas concentration is a punctual 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, as humans we know or can assume that the explosion is very possible. This linguistic knowledge (i.e., 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 (i.e., around 5%).

METHODOLOGY

The fuzzy logic system used to calculate the proposed inherent safety index is based on a Mamdami [Yen and Langari, 1999] model and IF-THEN rules that describe the knowledge related to inherent safety. The main concepts of this fuzzy system are explained and exemplified by the evaluation of the inherent safety level of a storage tank.

Many factors can contribute to the safety level of a tank; for example, 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
- Pressure and temperature
- Chemical hazard degree of the stored substance
- Location of the tank (inside/outside the battery limit or density of equipment in the area of the tank)

The volume and the hazard of the chemical substance are related to the inherent safety principles of intensification and substitution. Temperature and pressure are related to the principle of attenuation while the location is related to the avoidance of possible domino effects.

Each factor is described by a LINGUISTIC VARIABLE whose range of interest is divided into FUZZY SETS. The main characteristic of a fuzzy set is that the extremes overlap at least with the adjacent sets, and because of this overlap an element can belong at the same time to more than one fuzzy set. The degree of membership into each set indicates how much an element belongs to each fuzzy set, and it is described by the MEMBERSHIP FUNCTION (μ). This function is defined over a specific range of the fuzzy set and has a specific shape that describes the physical behavior of the set. When an element belongs completely to a particular fuzzy set, the value of the membership function is 1 ($\mu = 1$), and this value decreases proportionally according to the amount the element belongs to the set until the limiting case, when $\mu = 0$.

Definition of the fuzzy set for the volume of the tank

The volume of industrial tanks spans from a few gallons (i.e., 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 Lee [1986] for various types of storage tanks, and then the shapes of the membership functions are selected, as shown in Table 1.

Table 1: Types of membership functions for the parameters of "tank volume"

FUZZY SET for **"TANK VOLUME"**	Nominal Volume [gal]	Ln(Volum e)	Fuzzy set support [gal] $0 < \mu < 1$	TYPE of MEMBERSHIP FUNCTION
VERY SMALL	55	4	0 - 200	sigmf
SMALL	600	6.4	3 - 3000	psigmf
MEDIUM	20,000	10	250 – 60,000	psigmf
LARGE	500,000	13	5,000 – 3,000,000	psigmf
VERY LARGE	25,000,000	17	160,000 –	sigmf

The membership functions are shown in Figure 1. For a specific fuzzy set A the value of the linguistic variable where $0 < \mu_A$ is known as SUPPORT, and this concept is equivalent to the range of a mathematical function. A fuzzy set, with at a least one point where $\mu_A = 1$, is known as a normal set; otherwise the set is known as subnormal. In order to avoid normalization steps, all fuzzy sets used for this paper are normal sets.

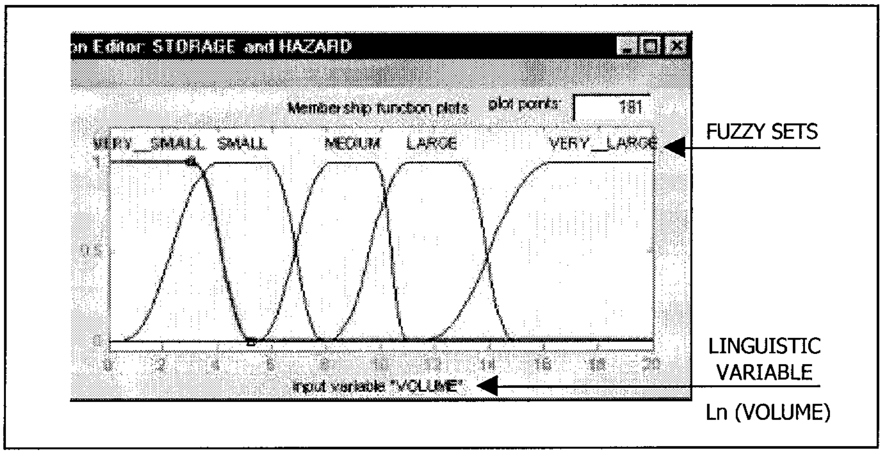

Figure 1: Fuzzy sets for the linguistic variable "tank volume" (VOLUME).

For the fuzzy sets "Very Small" and "Very Large" the shape selected for the membership function is an open sigmoidally-shaped function (sigmf), while the functions for the other sets are closed sigmoidally-shaped (psigmf) [MATLAB, Fuzzy Logic ToolBox, User manual]. The design of 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 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.

Definition of the fuzzy set for chemical substance evaluation

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 sane time penalize the higher ratings, the following calculation was performed:

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

where S : hazard ratings for each one of the three characteristics, $S \in N$ and S= 0, 1, 2, 3 or 4

i : properties (flammability, reactivity, and health hazard), $i \in N$ and 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 presented in Table 2.

Table 2: Type of membership functions for the parameters of "chemical hazard"

FUZZY SET for **"Chemical Hazard"**	Hazard =H where $\mu \cup 1$	Fuzzy set support $0 < \mu < 1$	TYPE of MEMBERSHIP FUNCTION
NOT HAZARDOUS	0 - 3	0 - 5	sigmf
SLIGHTLY HAZ.	4 - 8	1 - 9	psigmf
HAZARDOUS	9 - 15	7 - 20	psigmf
VERY HAZARDOUS	16 - 24	10 - 30	psigmf
EXTREMELY HAZ.	25 - 48	23 - 48	sigmf

The fuzzy sets are shown in Figure 2. 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 characteristics. Following the same reasoning, the substances that 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.

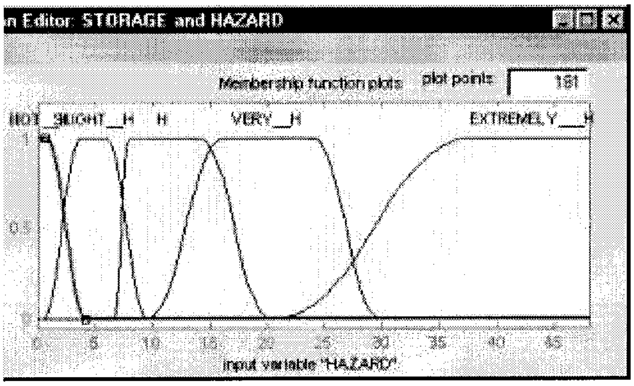

Figure 2: Fuzzy sets for the linguistic variable "chemical hazard" (HAZARD)

The selection of these sets allows modeling the hazard of a chemical in an easy and systematic way, however it is assumed that all the characteristics have the same importance to the total score. If one of the three NFPA ratings is assumed to be more important (i.e., reactivity or instability), weighting factors should be used. A better approach is to convert each characteristic into a linguistic variable and each score into a fuzzy number. This approach is equivalent to converting into a fuzzy relation the table proposed by the Dow F&EI for the material factor and expanding it to include the health hazard.

Strategies for the development of IF-THEN rules

The next step of the methodology requires the development of rules that describe the relation between the selected linguistic variables and their fuzzy sets. As discussed previously for the evaluation of a tank, at least four factors (linguistic variables) are required. Assuming that only one linguistic variable define 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 the four linguistic variables at the same time

B) Working with pairs of variables by dividing the procedure into three evaluation steps arranged in a cascade

The first option requires the development of 625 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 system could be simplified by selecting only the most important rules, but this would require deciding which rules to discard.

The second approach requires fewer and simpler rules (a total of 100 rules divided into four sets of 25) because only two variables are analyzed at the same time. The result from the first evaluation is used as input for the second evaluation, along with one additional factor, and so on until all four linguistic variables are evaluated. The system can be further simplified by working with fewer rules, and because these rules are simple it is easy to select only the most important ones. This is the simpler approach that is chosen for the present work, so it is used to develop fuzzy sets for the first evaluation.

Development of IF-THEN rules

The result from the evaluation of "tank volume" and "chemical hazard" is a new linguistic variable called "hazard" with a range of [0, 1]. Its fuzzy sets are described by a gaussian bell-shaped membership function and are presented in Table 3 and Figure 3.

Table 3: Type of membership functions for the parameters of "hazard"

FUZZY SET for **"Hazard"**	Hazard where $\mu \cup 1$	Fuzzy set support $0 < \mu < 1$	TYPE of MEMBERSHIP FUNCTION
VERY SAFE	0.00	0 – 0.25	gaussian
SAFE	0.25	0 – 0.50	gaussian
UNSAFE	0.50	0.25 – 0.75	gaussian
VERY UNSAFE	0.75	0.50 – 1.00	gaussian
EXTREMELY UNSAFE	1.00	0.75 – 1.00	gaussian

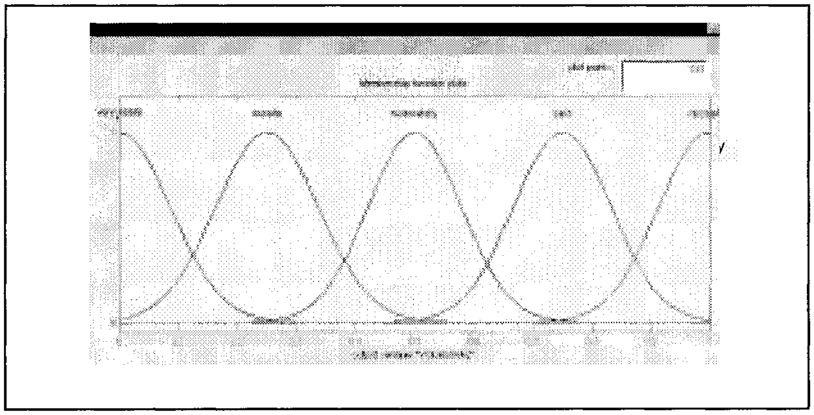

Figure 3: Fuzzy sets for the linguistic variable "hazard" (HAZARD).

The index for the evaluation of the first two factors for the tank is calculated from these fuzzy sets. When the defuzzified result (see below) approaches zero, the linguistic conclusion is that the tank is very safe and follows the inherent safety principles. When the value approaches 1, the conclusion is that the design of the tank does not follow the inherent safety principles.

The linguistic variables described above are related by IF-THEN rules that describe the heuristic knowledge about the relations among the fuzzy sets. The variable "tank volume" sets as well as the variable "chemical hazard," has five fuzzy sets, and a total of 25 (5x5) rules can be developed to describe the system. In this case 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 "hazard" = *very safe*

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

. . .

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

These rules can also be expressed in a matrix format as shown in Figure 4.

HAZARD		CHEMICAL HAZARD				
		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 4: Rule matrix for the linguistic variables "tank volume" and "chemical hazard"

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 5. 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 5, $\mu_{\text{very hazardous}} = 1$ indicates that the substance is very hazardous but it could also be (i.e., under specific circumstances) less hazardous ($\mu_{\text{hazardous}} = 0.75$).

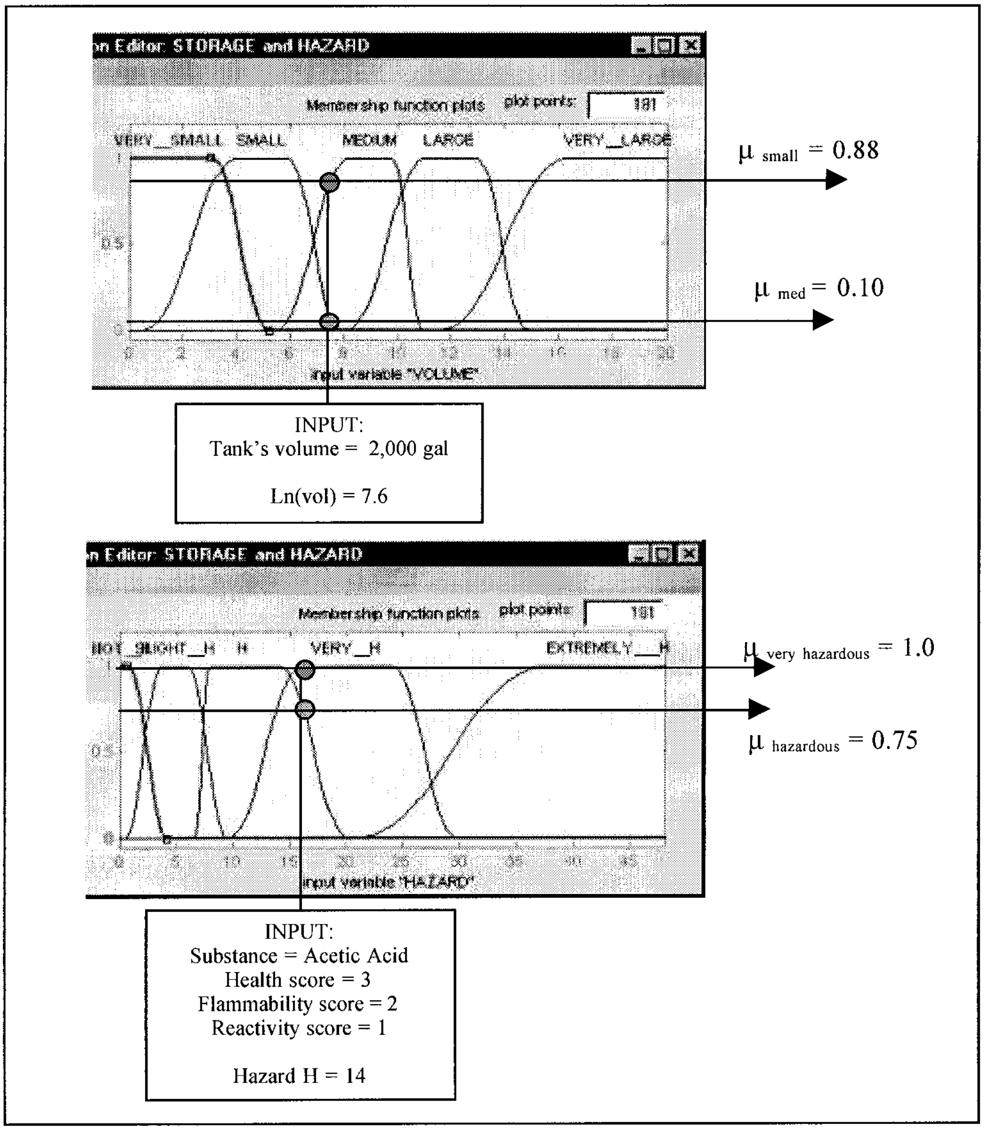

Figure 5: Evaluation of "tank volume" and "chemical hazard" for a tank of acetic acid

The four evaluated rules are indicated in Figure 4 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 6 for the rule

IF "tank volume" = _small_ AND "chemical hazard" = _hazardous_ THEN "hazard" = _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 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.

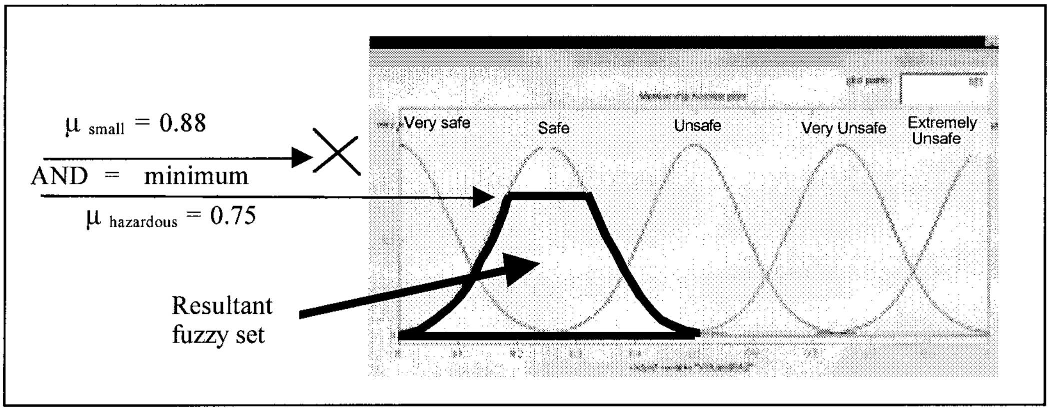

Figure 6: Output from the rule that relates SMALL and HAZARDOUS

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 7). This graphical result is an advantage of working with only two linguistic variables at time.

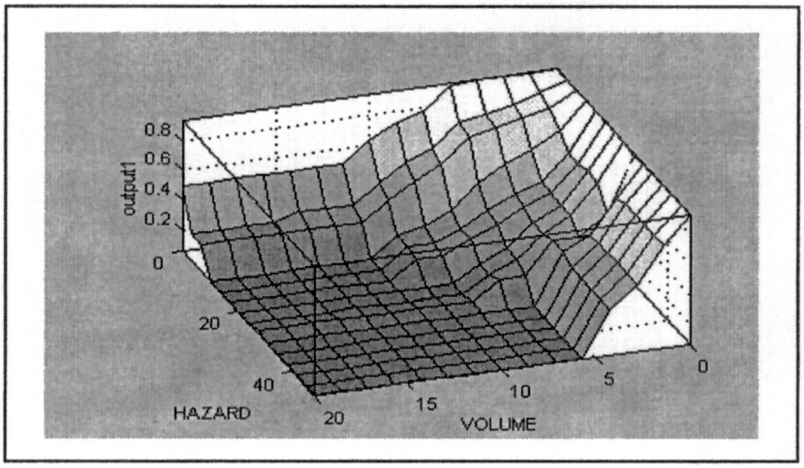

Figure 7: Output from the evaluation of "tank volume" and "chemical hazard"

FUZZY MODEL DESCRIPTION

The fuzzy system described above is based on a Mamdami model [Yen and Langari, 1999] with the characteristics reported in Table 4.

Table 4: 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	$\mu_c(x) = \min(\mu_A(x), \mu_B(x)) = \mu_A(x) \wedge \mu_B(x)$
Implication	MIN	T-norm	
Aggregation	MAX	T-conorm	
Defuzzification methodology	Center of mass (area) of the surface	N.A.	$COA = \frac{\int z\mu_C(z)dz}{\int \mu_C(z)dz}$

$\mu_c(x)$ = 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)

The safety level of a tank is just one aspect of the overall inherent safety index proposed here. The procedure described for the inherent safety evaluation of the tank is applied for the evaluation of other factors, which are reported in Table 5, analyzed in this work. As shown in Figure 8, the structure of the proposed index is divided into three major blocks; each block requires specific factors listed in Table 5. This list is based on the factors used by Heikkila [1999] with some additional factors, such as personal safety equipment.

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 general structure of the plant. The block for "Process Equipment and Tanks" evaluates the hazards related to type of equipment and location in the plant. The processing plant is divided into two areas OSBL (outside the battery limits) and ISBL (inside the battery limits). 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. Figure 8 shows the general structure of the system.

Table 5: 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 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

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

1) Divide the chemical plant into operating sub-processes 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, processing equipment.
3) Evaluate the inherent safety index for each unit by feeding the input information
4) Add the values of the indices for each area

The software used to develop the calculation is the Fuzzy Logic Toolbox and the Simulink package of the MATLAB software.

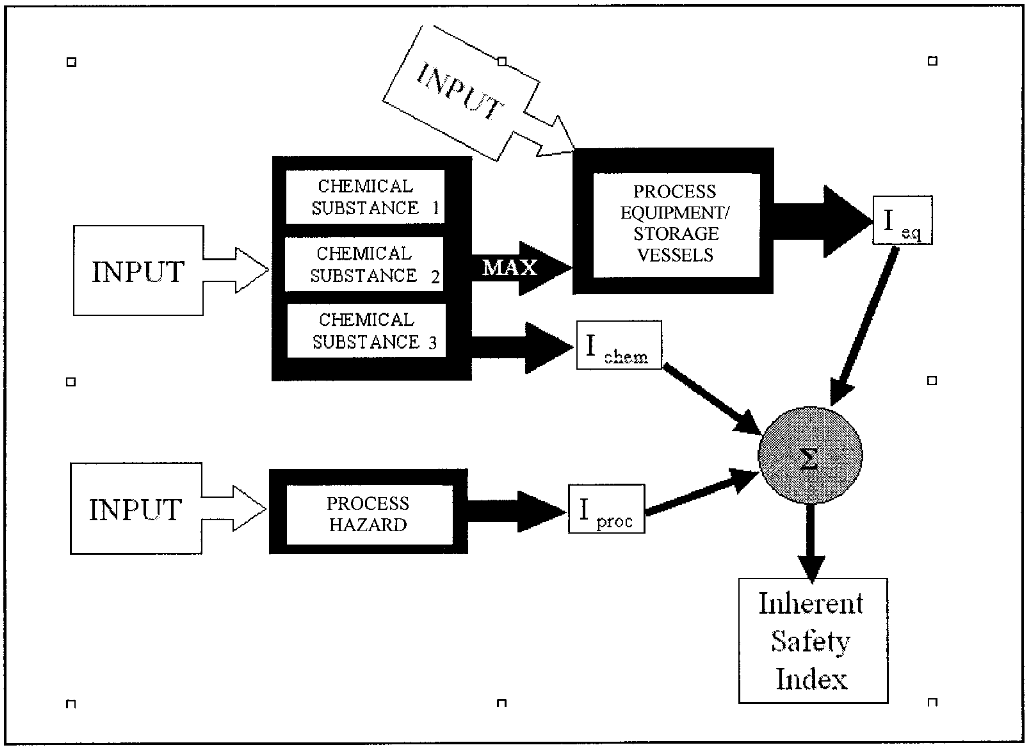

Figure 8: General structure of the proposed inherent safety index

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 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, 1999].

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 bars, respectively. The results of this test are reported in Table 6 for various values of temperature and pressure.

Table 6: Results for the test on the REACTION SECTION changing two inputs (pressure and temperature)

Temperature °C	Pressure bar	Heikkila INDEX	Fuzzy logic-based index
175	30	29	10.47
150 (lower limit)	25 (lower limit)	29	10.04
300 (upper limit)	50 (upper limit)	29	10.83
149	24	27	9.95

The first row of results indicates the value of the indices when the temperature and pressure are in the middle of the range. The next two rows indicate the results when the variables are at lower and upper limits of temperature and pressure. The last row indicates the values of the indices when both temperature and pressure are one unit below the lower limits of the ranges.

The most important observation from these results is that 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 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 over penalization.

The selection of the rules describing the knowledge and safety perception is one of the most important steps of this method. In some cases the linguistic variables have been evaluated two by two and the output from the first inference system has been used as input for the next one. In this way the number of rules required is fewer and the system is simpler. However, 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.

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.

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