

Inherent safety evaluation in process plants – a comparison of methodologies

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Abstract: A global population increase and an improved standard of living are generally expected. To meet these demands, an increased production of chemicals will be necessary while protecting human health and the environment. However, most current methods of chemical production are unsustainable. New designs must result in plants that assure process and operator safety, the sustained health of workers and the community, and the protection of the environment. Traditional safety precautions and process controls minimize risk but cannot guarantee the prevention of accidents followed by serious consequences. Therefore, the general approach to environmental and safety problems must be changed from reactive to proactive. One way is to further develop the concept of inherent safety.

In this paper some methods for inherent safety evaluations are reviewed. The aim of the study is to analyze the different tools available for inherent safety evaluation and identify the most important criteria in determining the inherent safety of a process plant. A model is proposed to show the interactions of different factors on the inherent safety level of a process and the model is illustrated by a case study.

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1 Introduction

The traditional approach to minimizing process risks is to provide layers of protection between the hazard and the people, property or environment. In this way the likelihood of an accident or its impact can be reduced. This can have some disadvantages including:

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costly construction and maintenance of layers, unanticipated accidents, and the continued existence of the hazards which may lead to an accident in case of failure of protection [1].

In 1977 Trevor Kletz introduced the inherent safety concept for the first time in his lecture “What you don’t have, can’t leak”. “Inherent” is defined by the Cambridge International Dictionary of English as: “existing as a natural or basic part of something; not able to be removed or changed”. An inherently safer chemical process is safer because of the basic characteristics of the process. Inherent safety is an approach to chemical accident prevention that differs fundamentally from secondary accident prevention and accident mitigation. Inherent safety (primary prevention) develops technologies which prevent the possibility of a chemical accident. Layers of protection (secondary prevention) reduce the probability of a chemical accident, and mitigation and emergency responses reduce the seriousness of injuries, property and environmental damage.

Inherent safety, which is a proactive approach to risk management, can be cost optimal (considering operating and maintenance costs) because eliminating the hazard eliminates the need for expensive layers of protection. Although the ultimate goal of inherent safety is elimination of all hazards, some control systems are always required. Basic Process Control Systems (BPCS) and Safety Interlock Systems (SIS) play an important role in improving the safety and reducing the risk [1].

Despite the benefits of inherent safety, there are still some problems including: difficulty in changing existing plants; introduction of possible new risks; and difficulties in changing ways of thinking (conventional safety features) [2]. There are also other problems which limit the application of the inherent safety concept. First, the effect of changes due to the inherent safety approach is difficult to measure; second, how can whether a plant is following inherent safety principles be evaluated? [3].

In comparison to alternative processes, inherently safer processes reduce or eliminate hazards associated with the materials and process operations. This is accomplished by characteristics which are permanent and inseparable parts of the process [4]. According to Bollinger *et al.* [1] the principles of inherent safety are:

- *Minimize* – Use smaller quantities of hazardous substances (also called Intensification).
- *Substitute* – Replace a material with a less hazardous substance.
- *Moderate* – Use less hazardous conditions, a less hazardous form of a material, or facilities that minimize the impact of a hazardous material or energy.
- *Simplify* – Design facilities that eliminate unnecessary complexity and make operating errors less likely.

Most process options can be inherently safer with respect to one hazard while less safe from another viewpoint [5]. Unfortunately, many times it is not clear which of several process alternatives is inherently safer. According to Hendershot [6] “nearly all chemical processes have a number of hazards associated with them. An alternative, which reduces one hazard, may increase a different hazard.” To implement inherent safety in practice, a method to compare the inherent safety of different design alternatives is needed. Knowledge of the specific details of each process option and identification of all

hazards will allow ranking of the process options in terms of inherent safety.

The aim of this study is to review and compare the existing tools for inherent safety evaluation and find criteria for their improvement. These criteria will be used to develop the index method presented by Heikkilä [7]. To determine this index the most important factors affecting inherent safety and their interactions are considered.

2 Inherent safety evaluation methods

Processes can be evaluated in two ways: qualitative or quantitative. In qualitative ranking, consequence and likelihood analysis are carried out based on experience and engineering judgments. The American Petroleum Institute (API) has developed such a method which aims at risk-based inspection [8].

In addition to the qualitative risk ranking method, index methods have been developed as quantitative/semi-quantitative risk ranking methods. Indices such as the Dow Fire and Explosion Hazard Index (F&EI) [9], Dow Chemical Exposure Index (CEI) [10,11] and the Mond Index [12] have been suggested to assess the degree of inherent safety of a process for existing plants or at detailed design stages [13].

F&EI is a hazard index [12] widely used to quantify fire and explosion damage and identify equipment contributing to an accident. It is primarily designed for operations in which a flammable, combustible, or reactive material is stored, handled or processed. F&EI is calculated as the product of a Material Factor (MF) and Unit Hazard Factor (F3). MF is a value based on flammability and reactivity of the most hazardous substance in the process unit. F3 is the product of the general and special process hazards. General process hazards include exothermic chemical reactions, endothermic processes, material handling and spill control. Special process hazards contain the factors for toxic materials, sub atmospheric pressure, operation in or near flammable range, dust explosion, elevated pressure, low temperature, quantity of flammable and unstable materials, corrosion and erosion, leakage of joints and packings, use of flame heaters, hot oil systems and rotating equipment.

CEI rates the relative acute health hazard by determination of Airborne Quantity (AQ) and Emergency Response Planning Guidelines (ERPG) values. AQ is the rate at which the material can become airborne under process conditions. ERPG represent toxicity limits in mg/m³ or ppm. The computation of the CEI is based on ERPG level 2 values, considering serious or irreversible health effects.

The Mond index is a modified version of F&EI which, for example, includes toxicity in the assessment and can be used for a wider range of processes. The elements (hazard factors) of the Mond method are: Material factor, special material hazards, general process hazards, special process hazards, quantity factor, layout hazards, and toxicity hazards.

Edwards *et al.* [14,15] have developed a prototype index of inherent safety (PIIS) to analyze the selection of a process route. PIIS is the sum of a chemical score and a process score. The chemical score consists of inventory, flammability, explosiveness and toxicity. The process score includes temperature, pressure and yield. The scoring system is partly

based on the Dow and Mond indices. The other scores have been constructed by dividing the domain of values of a parameter into ranges and assigning a score to each range.

On the basis of Edwards' study, Heikkilä [7] has developed an Inherent Safety Index (ISI) based on inherent safety principles to classify process alternatives during preliminary process design. It consists of chemical and process inherent safety indices. The chemical inherent safety index contains sub indices of chemical interaction, flammability, explosiveness, and corrosiveness. The process inherent safety index contains sub indices of inventory, process temperature and pressure, equipment safety and process structure safety.

In another work Gentile *et al.* [16] have improved Heikkilä's work by using fuzzy logic in their assessment instead of Boolean algebra. The purpose was to help model the uncertainty and subjectivity implicit in evaluating certain variables. According to fuzzy set theory the transition from one interval to the next is smooth. In a Boolean set, an element can only be inside or outside the set, but in a fuzzy set the element can be partially or totally inside or outside depending on the shape of the membership function. In this method each factor is presented by a Linguistic Variable. This variable is divided into sub-ranges, or fuzzy sets. The fuzzy sets for inputs are related to the output fuzzy sets through if-then rules, which describe the heuristic knowledge about the behaviour of the system.

The INSET toolkit developed by the INSIDE project (INherent She In DEsign) [17] represents the consensus and combined expertise of a number of companies and organisations. It is intended to consider safety, health and environmental factors in one set of tools. The tools can be used separately as required depending on the actual stage of the plant under study. The indices must be interpreted individually since no attempt is made to aggregate the indices into an overall index.

In another attempt Koller *et al.* [18] have developed a method to estimate the magnitude of the SHE problems. The structure of the method is flexible combining the best available practices from risk analysis and environmental assessment. The categories used to assess safety problems are mobility, fire/explosion, reaction/decomposition and acute toxicity. The index values for each dangerous property are modified with a relevant fate index to obtain the effective dangerous property. The values of the fate indices represent the relevance of the corresponding fate factors on the SHE effects. The effective dangerous property is then transferred to a physical value (using a defined equation) considering the relevant mass of the substance. The resulting potential danger represents the magnitude of SHE aspect in some kind of physical unit such as releasable energy content of a system. These physical values can be summed for all substances resulting in a total potential danger of the process for each of the SHE effects. In the last step of the assessment technologies provided to reduce SHE problems are considered. Each technology factor reduces the potential danger depending on the effectiveness of the technology. Although the tool is highly automated and processes can be assessed easily, combining different SHE effects or even safety effects to obtain a single index is not attempted.

Khan and Amyotte [19] have presented a conceptual framework for an integrated in-

herent safety index (I2SI). This tool has the potential for economic evaluation as well as hazard identification. I2SI is comprised of sub-indices which account for hazard potential, inherent safety potential and add-on control requirements. Hazard potential index calculation is based on a damage index and a process and hazard control index. The damage index is calculated considering fire and explosion, acute toxicity, chronic toxicity and environmental damage [20,21]. The process and hazard control index is determined after applying the guidelines giving the control arrangements required. The inherent safety potential index is determined after applying inherent safety principles and any requirement to install add-on process and hazard control measures after the implementation of the inherent safety measures.

3 Comparison of the methods

The methods for assessing inherent safety of chemical processes vary in goal, scope, structure and the way the safety aspects are considered. Their advantages and disadvantages are compared in Table 1.

4 Inherent safety criteria factors

This paper is focused on a literature search for the most effective criteria to evaluate inherent safety. The study compares available methods to select those criteria. Several methods have been reviewed and compared.

The selection of criteria to evaluate the inherent safety of a process must be based on inherent safety principles. The first principle is minimization, and the relevant parameter is the quantity of the material present in the process. This parameter is evaluated in all of the methods reviewed. Large inventories are undesirable when there could be a fire, explosion, or tank rupture. Therefore the amount of materials in a plant has a direct effect on the degree of hazard.

The second principle is the substitution of hazardous materials with non hazardous ones. The properties considered are those that measure a material's hazards; these include flammability, explosiveness, toxicity, corrosiveness and reactivity. Here, physical characteristics of a material such as viscosity, boiling point, solubility in water, evaporation rate, and environmental toxicity are not taken into account. Flammability, the ease of burning of a material in air [22], is a very important factor in cases of leak. It can be measured by the flash point. Explosiveness is the tendency of chemicals to form an explosive mixture with air [7] and is described by upper and lower explosion limits (UEL and LEL). LEL is the concentration of the vapour at which the vapour cloud can ignite. Therefore a wider range between LEL and UEL means a higher possibility of explosion. This factor is considered in all reviewed methods; the difference is in their scoring systems. Toxicity destroys life or injures health when introduced into or absorbed by living creatures [22,23]. Toxicity is measured by animal experiments; it depends on duration of exposure, path of entry and dose. The Threshold Limit Value (TLV), the most common

used toxicity term [23], considers long term exposures. TLV is the concentration in air which can be breathed without harmful effect for 5 working days (8 hour day). Edwards and Heikkilä have considered this factor in their indices, but it is not considered in the Dow F&EI. Corrosiveness decreases the reliability of a plant, reduces the strength of materials, and causes leaks [7]. Heikkilä has included this factor in her approach, while Edwards has not. The Dow F&EI also considers corrosion risks, but the penalties are given through unacceptable corrosion rates [9]. The reactivity of substances can cause safety problems. This parameter evaluates potential unwanted reactions like the reaction of a substance with other compounds in the process, with oxygen, with water, or with itself [7]. This factor has been considered in some extent in Dow F&EI. Heikkilä has also included this into the ISI while Edwards has not.

The third principle of inherent safety considers moderation. This means carrying out a reaction under less hazardous conditions, or storing or transporting a hazardous material in a less hazardous form. The obvious factors to evaluate this component of inherent safety are temperature and pressure (reaction or storage conditions), which are included in all evaluation approaches. Another aspect of moderation concerns the reaction itself. The reaction is considered less hazardous when it releases less heat. Therefore evaluation of the heat of reaction (both main reaction and side reactions) is needed. The Dow F&EI gives a penalty for this factor when an exothermic reaction exists. Heikkilä specified two sub indices for the heats of main and side reactions. Edwards doesn't consider this parameter at all. The term reactivity discussed above can also be placed in this category, since it considers some unwanted reactions that can lead to release of energy in the form of heat or overpressure (fire or explosion).

The last principle, simplification, is difficult to evaluate. The basis is that simpler plants provide fewer opportunities for error, but how to judge the complexity of a process in a plant is not yet completely understood. According to Koolen [24] the level of complexity of a unit in a chemical process plant is a function of: amount of equipment accessible by the operator (M), number of degrees of freedom (DOFs) including manual/actuated valves/switches and set points of control loops (N), number of measurement readings (O), number of input and output streams including energy streams (P), interactions in the unit requiring operator intervention (Q), and number of external disturbances (for the unit) requiring action from an operator (R). Scuricini [25] has defined a system as complex when it is built up of a plurality of interacting elements of a variety of kinds, in such a way that no evidence can be found of the characteristics of single elements in the overall result. Therefore, the amount of equipment is an important factor indicating the level of complexity in a system. The number of input and output streams becomes important when the interaction of different equipment is assessed. Fewer degrees of freedom (DOFs) result in more simplified operation, which in practice is realized by the introduction of automation (less opportunity for human error). Equation (1) introduced by Koolen [24] is a summation of complexity factors, adding a weighting factor for each term:

$$\text{Complexity} = mM + nN + oO + pP + qQ + rR \quad (1)$$

where m , n , o , p , q , r are the weighting factors per item. These are in our opinion very important to the inherent safety of a process plant. None has been considered in the inherent safety evaluation methods discussed above.

In addition to these four main principles of inherent safety, Kletz [26,27] has introduced some secondary principles under the limitation of effects. This is considered when it is not possible to make plants safer by intensification, substitution, moderation, or simplification. In this case the effects of a failure should be limited. One of the important concepts is layout and configuration. In order to evaluate this, some factors include: accessibility of equipment (both for maintenance and emergencies); spacing of processes and unit operations within a process; shape factor (how well different items are arranged); and connection factor (how well different items of a process are connected).

The selection of safer technical alternatives must also be considered. The type of equipment used in a process has an important role. Heikkilä [7] has pointed out that the inherent safety is affected by process equipment; therefore the index of inherent safety should reflect this fact. There is always a possibility that equipment is unsafe. Heikkilä has introduced an index for the evaluation of process equipment safety.

On the basis of the above discussion those criteria needed for evaluation of inherent safety have been identified. These criteria are presented and summarized in the Table 2. Their interaction should be considered in an index calculation.

5 Modelling

The model introduced by Heikkilä [7], simply adds all the sub indices of inherent safety. This is a drawback since it does not consider the interactions between different factors. There are also some other factors which have not been considered by Heikkilä. Therefore a model has been developed to include the missing factors and also to consider the interaction between different factors more explicitly. It is based on the studies by Dow and Heikkilä [7,9] and is constructed on inherent safety principles.

The important factors influencing the inherent safety discussed in the last section are: inventory, flammability, toxicity, explosiveness, temperature, pressure, heat of main and side reactions, chemical interactions, complexity (including: amount of equipment, number of DOFs, number of measurement readings, number of input and output streams, interactions requiring operator invention and number of external disturbances), lay out (including accessibility, shape and connection factors) and finally, type of process equipment. It should be noted that this model is useful only for comparison of two or several alternative processes and can not predict the level of inherent safety for a single process. In our model, as in earlier indices, we still split the inherent safety index into two sub indices related to material and process (Figure 1). The material index (MI), equation 2, depends on both the material hazard index (I_{Mat}) and the inventory hazard index (I_{Inv}). Thus, these two factors (I_{Mat} and I_{Inv}) affect each other. The index for material hazard is compounded by the magnitude of the inventory. Therefore, MI is calculated as the product of material hazard index and inventory hazard index

$$MI = I_{Inv} \times I_{Mat} \quad (2)$$

I_{Inv} is the inventory hazard index

I_{Mat} is the material hazard index

The material hazard index (equation 3) includes flammability, explosiveness, toxicity and corrosiveness sub indices:

$$I_{Mat} = I_{Fla} + I_{Exp} + I_{Tox} + I_{Cor} \quad (3)$$

I_{Fla} is the sub index of flammability

I_{Exp} is the sub index of explosiveness

I_{Tox} is the sub index of toxicity

I_{Cor} is the sub index of corrosiveness

The process index (PI) is calculated (equation 4) as the sum of all contributed sub indices:

$$PI = I_{Con} + I_{Rea} + I_{Lay} + I_{Equ} + I_{Com} \quad (4)$$

I_{Con} is the sub index of process condition

I_{Rea} is the sub index of process reaction

I_{Lay} is the sub index of process layout

I_{Equ} is the sub index of process equipment

I_{Com} is the sub index of process complexity.

Sub indices of process condition and process reaction are determined by their contributing factors according to equations 5 and 6:

$$I_{Con} = I_{Tem} + I_{pre} \quad (5)$$

$$I_{Rea} = I_{Hmr} + I_{Hsr} + I_{Cin} \quad (6)$$

I_{Tem} is the sub index of temperature

I_{Pres} is the sub index of pressure

I_{Hmr} is the sub index of heat of main reaction

I_{Hsr} is the sub index of heat of side reaction

I_{Cin} is the sub index of chemical interactions

Reasoning identically, the Inherent Safety Index itself can be calculated from its two factors, Material Index (MI) and Process Index (PI). Thus, considering the compounding effect of these two factors, the product of MI and PI (equation 7) is the value for Inherent Safety Index (I_{IS}).

$$I_{IS} = MI \times PI \quad (7)$$

6 Case study

The application of I_{IS} is illustrated through the comparison of two different technologies for production of acetic acid. The results of this application are then compared to the inherent safety calculated by Heikkilä's method. Below is a description of the two acetic acid processes: the ethane direct oxidation process and methanol carbonylation process. Scores for calculating all sub indices involved in calculation of I_{IS} are taken from Heikkilä [7] except for the process layout and process complexity.

6.1 Process description

6.1.1 Methanol carbonylation

The liquid methanol and homogeneous catalyst (methyl iodide complex) are mixed with a gaseous feed (compressed CO) and preheated to the reaction conditions (462 K, 30 bar, two phase system) (Figure 2). The carbonylation in the stirred tank reactor is followed by flash separation of gas and liquid phases. The catalyst is recycled back to the feed. In a small column residual CO is separated and subsequently the water and acetic acid mixture is distilled in the distillation column. The gas phase from the flash consists of CO and CO₂; after purification CO is recycled back to the feed gas.

6.1.2 Ethane oxidation

The process is illustrated in Figure 3. The ethane and oxygen stream is mixed with steam and compressed and preheated to the reaction conditions (515 K, 16 bar). The chemical reaction occurs in a multi-tube reactor. The reaction temperature in the reactor is maintained by an additional heat-exchanger to cool the molten salt. The product from the reactor is cooled to 303 K in two steps; high pressure steam is produced in the first step. The gas - liquid mixture formed is flash separated. The acetic acid - water mixture is subsequently separated in a distillation column. Pure acetic acid is withdrawn as a bottom product. The gaseous stream consists of unreacted ethane, ethylene and CO₂. A portion of the CO₂ produced is separated in an absorber; ethane and ethylene are recycled to the feed gas.

6.2 Index Calculation for Acetic Acid process

The reactions involved in these two processes are as follow:

- (1) *Methanol carbonylation* - Methanol + carbon monoxide acetic acid ($\Delta H = -1532$ j/g)
- (2) *Ethane oxidation* - Ethane + oxygen acetic acid + water ($\Delta H = -9809$ j/g)

The analysis of the data and results are presented in Table 3. The scoring system used in this analysis is shown in Table 4. The assumed capacities of both processes are 50 kt/year. The inventory in the processes was roughly estimated knowing the yield of the process together with a one hour residence time. The yield of process 1 is 99 percent while the yield of process 2 is 25 percent. Thus the inventories for these processes are

calculated to be about 100 (score 3) and 400 (score 4) tonnes. For process 1, the material that gives the maximum value for the sum of scores for flammability, explosiveness and toxicity is carbon monoxide, which is 10. For process 2 this score is 7, which belongs to ethane. As construction materials stainless steel and hastalloy are needed for process 1 (score value of 2) while for process 2 stainless steel is required giving a score of 1. The process temperatures of 462 K and 515 K each give the score of 2. The pressure of 30 bars for process 1 will receive the score of 2 while a score of 1 goes for the 16 bar pressure of process 2. Three sub indices are evaluated for the process reaction index. In process 1, the heat of the main reaction is 1532 j/g (score 3), and the heat of the side reaction, which is the formation of propionic acid, is about 1000 j/g (score 2). The worst chemical interaction may occur between methanol and hydriodic acid resulting in heat evolution and even fire, which gives the score 4. In process 2, the heat of the main reaction is 9809 j/g giving a score of 4, while the side reaction, complete combustion of ethane, produces 46 kj/g, resulting in a score of 4. No chemical interaction was found for this case (score 0). The scoring of process layout is based on a 0 to 4 scoring system (recommended, sound engineering practice, neutral, probably unsafe, unsafe) based on expert judgment. A score of 2 is assumed for both processes. The process equipment index is determined for both processes by a gas compressor, resulting in a score of 3. For the process complexity index, not all the assessed parameters are available, so a qualitative evaluation was done. Since the amount of equipment in process 1 is greater, the number of measurement readings and number of input and output streams are expected to be larger as well. In this case the process complexity indices were assumed to be 2 and 1 respectively for processes 1 and 2. These scores are given based on a scale ranging from 0 as simple to 3 as very complex.

The results show that the inherent safety level in the ethane oxidation process is higher than methanol carbonylation (a lower index corresponds to higher inherent safety level), since in this process the material in use is less hazardous and the process is simpler and requires more moderate conditions.

7 Results and discussion

In Table 5 the results of the evaluation of acetic acid technologies are given and compared with the results obtained from Heikkilä's index. All the results are normalized, since each index has a scale of 0-100. According to both methods process 2 is inherently safer than process 1. The inherent safety index reduction is 15 % when Heikkilä's method is applied, while application of our proposed method shows a reduction of 25 %. The greater index reduction in our method may be explained by two factors:

- Our method considers complexity - Complexity can be important in inherent safety evaluation. The effect of the complexity factor on the inherent safety index is to give a greater index reduction, since process 2 is simpler than process 1.
- The index is calculated differently - Heikkilä adds all sub indices of inherent safety. However, in our proposed method the compounding effect of different factors on each

other are considered. Therefore in some cases, e.g. inventory and material hazard index, multiplication is used instead of addition. As a result, in process 2 the material index is reduced more significantly as the material hazard index is decreased.

8 Conclusion

Inherent safety evaluation methods were reviewed and compared. The criteria most significant for inherent safety were identified and discussed. The index calculation method proposed by Heikkilä [7] has been improved by adding some important criteria such as complexity, and changing the calculation method by considering interactions of some factors of inherent safety. Interaction of these factors is presented in a model. Finally, in a case study the application of the proposed Inherent Safety Index Calculation (ISIC) was illustrated. Two types of acetic acid production processes are compared. The results show that the ethane oxidation process is inherently safer than methanol carbonylation, since this process follows the inherent safety principles by using less hazardous materials, more moderate process conditions and a simpler process. Comparing the results of the proposed method with Heikkilä's shows that the compounding effect of material factors can lead to a further reduction of the inherent safety index. In addition, the effect of the complexity factor is recognized by our proposed method. It should be noted that further research work is needed to develop the scoring system, especially for the complexity factors. Another important issue is the validation of the new index method. This can be accomplished by applying the method to some real cases which have been previously judged by experts.

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Method	Designed for	Advantages	Disadvantages
Dow F&EI	Damage quantification of fire and explosion, Identification of contributed equipments in an accident for operation involved in storing, handling and processing flammable or combustible material	Covers well the risks and hazards existing on a chemical plant	A lot of detailed information is needed - can not be used in the early stage of process design – all aspects relevant to inherent safety are not evaluated (e.g. toxic exposure and complexity factors)
Mond F&EI	Modification of the Dow method	Covers well the risks and hazards existing on a chemical plant	A lot of detailed information is needed, can not be used in the early stage of process design
PIIS	Selection of process route	Low information requirement - Suitable in the pre design stage – suitable for selection of the chemical route (raw material)	All aspects relevant to inherent safety are not evaluated (other parts of the process e.g. equipments, piping and the lay out) – incorporate some kind of build-in judgment of the relative importance of the various type of hazards- Not flexible enough to incorporate additional available data- Employs a step function within the mathematical framework

Table 1 Advantages and disadvantages of inherent safety evaluation methods.

Method	Designed for	Advantages	Disadvantages
ISI	Classification of process alternatives during the preliminary process design	Low information requirement, Suitable in the pre design stage	Selection of the scores and weighting factors is a subjective and knowledge based process – the results will not be reproducible when other people use the tool – still some aspects of inherent safety have not been evaluated (e.g. complexity)- Not flexible enough to incorporate additional available data- Employs a step function within the mathematical framework
Fuzzy logic based index	Improve some of the subjective factors concerning with inherent safety index developed by Heikkilä	Eliminates the problems presented by the traditional interval approach- Simple and systematic form	Problems when more than one linguistic variable is evaluated at the same time
I2SI	Inherent safety evaluation by hazard potential identification as well as economic evaluation	Good applicability in the initial phase of process design (process selection and design decision making)- Systematic frame work for calculating the index	Necessitate subjective judgment to estimate the sub-indices

Table 1 (continued): Advantages and disadvantages of inherent safety evaluation methods.

Method	Designed for	Advantages	Disadvantages
INSET toolkit	Identification, evaluation, optimization and selection inherent SHE processes and designs	Applicable to new process or plans, or modifications to an existing plant and process- Inherent safety performance indices involve simple computations result in rapid evaluation	No attempt is made to combine different indices of inherent safety
Koller method	Identification of SHE problems of a chemical process, estimation of magnitude of the SHE problems and analysis those problems to find the source and possible solutions.	Can be applied from the first stages of the process development on- The structure of method is flexible combining best available practices for risk and environmental assessment- Assessment can be done on the basis of a variety of information from different sources- The tool is highly automated result in easy and rapid assessment	Combining different SHE effects to a single index is not attempted- Does not consider hazards related to equipments and their configuration- Does not consider complexity of the process

Table 1 (continued): Advantages and disadvantages of inherent safety evaluation methods.

Principles of Inherent Safety	Criteria
Minimization	Inventory
Substitution	Flammability Explosiveness Toxicity Corrosiveness
Moderation	Temperature Pressure Heat of Main Reaction Heat of Side Reaction Reactivity (Chemical interaction)
Simplification	Number of equipments Number of DOFs (Degree of Freedom) Number of measurement readings Number of input and output streams Interactions requiring operator intervention Number of external disturbances
Limitation of effects	Lay out: Accessibility, shape and connection factors Equipment used in process

Table 2 Criteria factors for evaluation of inherent safety.

	Process 1: Methanol carbonylation	Process 2: Ethane oxidation
I_{Inv}	3	4
$I_{Mat} = \text{Max}(I_{Fla} + I_{Exp} + I_{Tox}) + I_{Cor}$	$(4+3+3)+2=12$	$(4+2+1)+1=8$
$I_{Con} = I_{Tem} + I_{Pre}$	$2+2=4$	$2+1=3$
$I_{Rea} = I_{Hmr} + I_{Hsr} + I_{Cin}$	$3+2+4=9$	$4+4+0=8$
I_{Lay}	2	2
I_{Equ}	3	3
I_{Com}	2	1
$MI = I_{Inv} * I_{Mat}$	36	32
$PI = I_{Con} + I_{Rea} + I_{Lay} + I_{Equ} + I_{Com}$	20	17
$I_{IS} = MI * PI$	720	544

Table 3 Inherent Safety Index Calculation (ISIC) for acetic acid processes.

Heat of reaction	Score	Toxic limit (ppm)	Score	Process pressure(bar)	Score
Thermally neutral $\leq 200\text{J/g}$	0	TLV >10000	0	0.5-5	0
Mildly exothermic $<600\text{J/g}$	1	TLV ≤ 10000	1	0-0.5 or 5-25	1
Moderately exothermic $<1200\text{J/g}$	2	TLV ≤ 1000	2	25-50	2
Strongly exothermic $<3000\text{J/g}$	3	TLV ≤ 100	3	50-200	3
Extremely exothermic $\geq 3000\text{J/g}$	4	TLV ≤ 10	4	200-1000	4
		TLV ≤ 1	5		
		TLV ≤ 0.1	6		
Chemical interaction	Score	Construction material re-	Score	Type of equipment	Score
Heat formation	1-3	quired		Equipment handling non-	0
Fire	4	Carbon steel	0	flammable, non-toxic materials	
Formation of harmless gas	1	Stainless steel	1	Heat exchangers, pumps, towers,	1
Formation of toxic gas	2-3	Better material needed	2	drums	
Formation of flammable gas	2-3			Air coolers, reactors, high hazard	2
Explosion	4			pumps	
Rapid polymerization	2-3			Compressors, high hazard reactors	3
Soluble toxic chemicals	1			Furnaces, fired heaters	4
Flammability	Score	Inventory(tons)	Score	Safety level of process struc-	Score
Non-flammable	0	0-1	0	ture	
Combustible(flashpoint $>55^{\circ}\text{C}$)	1	1-10	1	Recommended	0
Flammable(flash point $\leq 55^{\circ}\text{C}$)	2	10-50	2	Sound engineering practice	1
Easily flammable(flash point $<21^{\circ}\text{C}$)	3	50-200	3	No data	2
Very flammable(flash point $<0^{\circ}\text{C}$	4	200-500	4	Probably unsafe	3
&boiling point $\leq 35^{\circ}\text{C}$)		500-1000	5	Minor accidents	4
				Major accidents	5

Table 4 Scoring system given by Heikkilä.

Explosiveness(UEL-LEL) vol%	Score	Process temperature(C)	Score
Non explosive	0	<0	1
0-20	1	0-70	0
20-45	2	70-150	1
45-70	3	150-300	2
70-100	4	300-600	3
		>600	4

Table 4 (continued): Scoring system given by Heikkilä.

	Heikkilä index		Our index	
	Process 1	Process 2	Process 1	Process 2
Inherent safety index	33	28	720	544
Max. value for inherent safety index	50	50	2560	2560
Normalized index	66	56	28	21
Index reduction	15% $\longrightarrow$		25% $\longrightarrow$	

Table 5 Comparison of results.

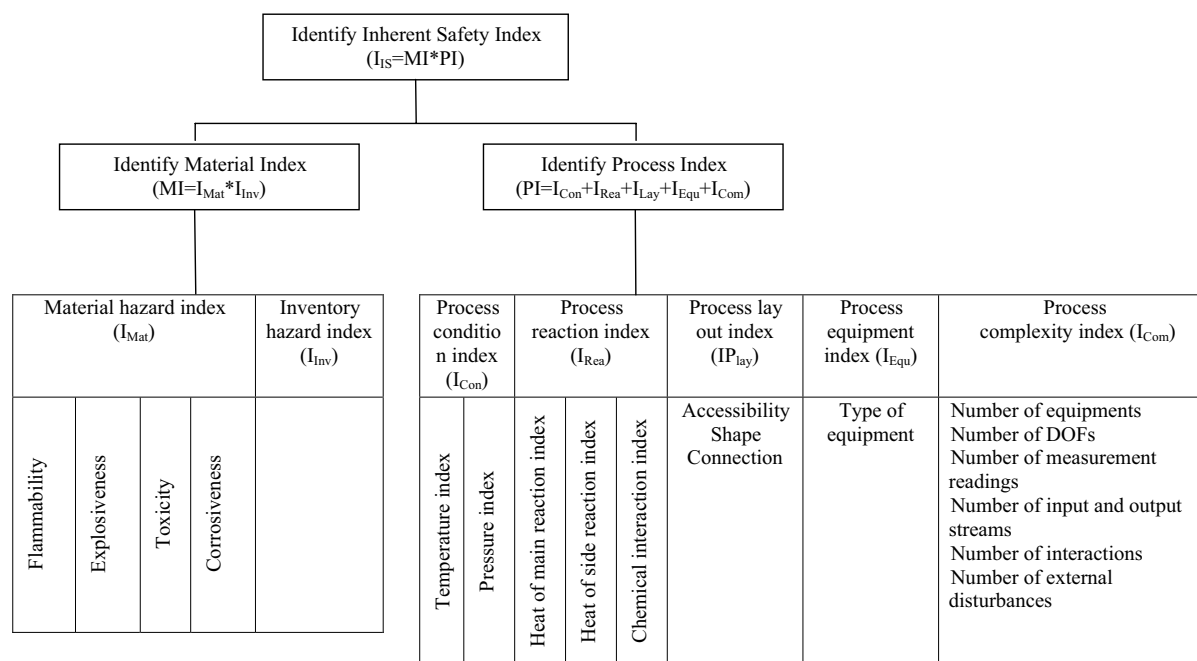


Fig. 1 Inherent Safety Index Calculating (ISIC) procedure.

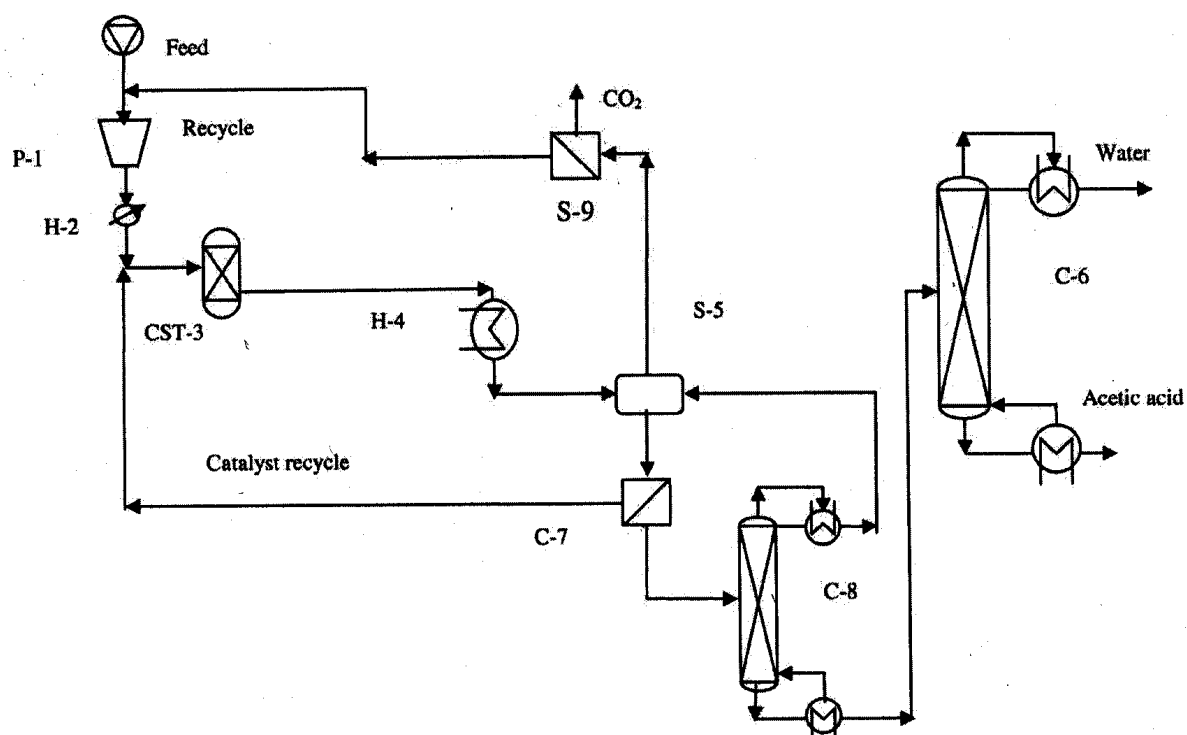


Fig. 2 Methanol carbonylation process:

P- 1: compressor, H-2: heating, CST-3: CST reactor, H-4: cooler, S-5: flash, C-6: rectification of water-acetic acid, C-7: separation of homogeneous catalyst, C- 8: pre-separation of reaction mixture, S-9: CO_2 separation.

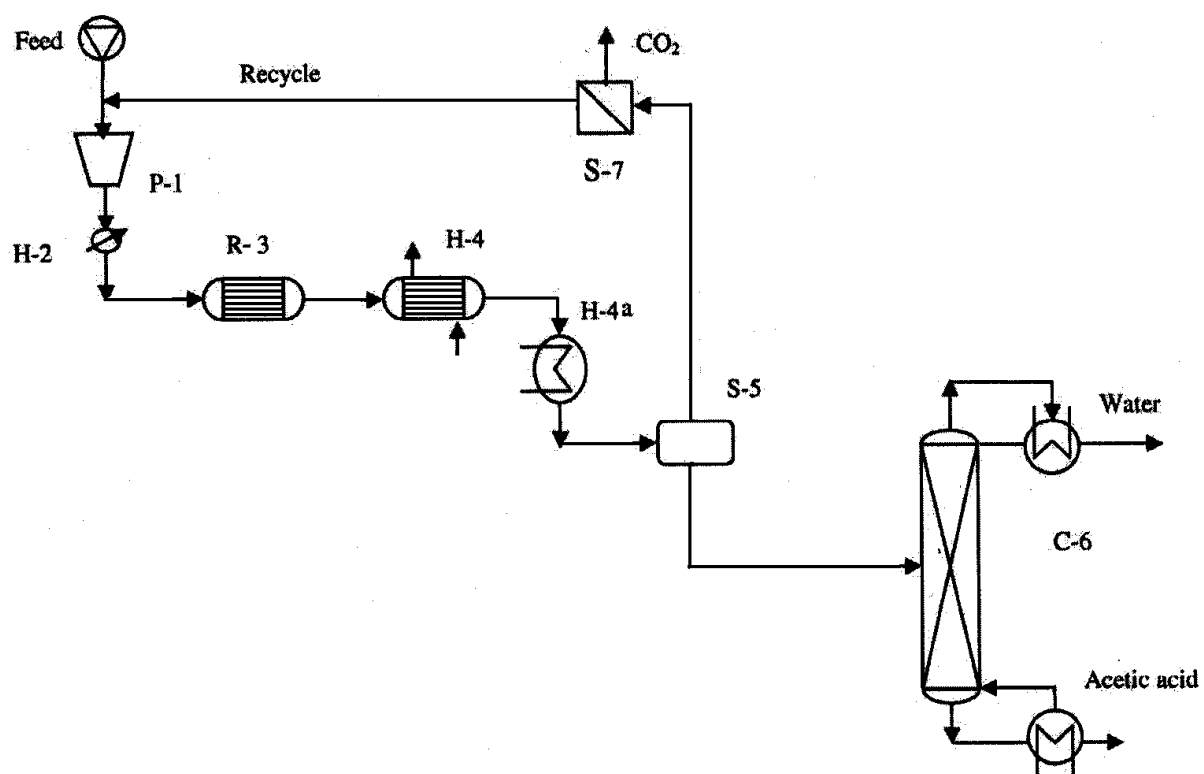


Fig. 3 Ethane oxidation process:

P-1: compressor, H-2: pre-heater, R-3: multi-tubular fixed-bed reactor, H-4,4a: cooler, S-5: flash, C-6: rectification of water-acetic acid, S-7: CO_2 separation.