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Quantitative Inherent Safety Assessment by Key Performance Indicators (KPIs)

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The effective design of process systems based on the strategies of inherent safety asks for practical, reliable and systematic assessment tools. Despite the valuable procedures proposed in the literature, relevant biases in the outcomes may be introduced in the analysis when general scoring techniques or subjective judgment are adopted to a large extent. The present study introduces a consequence-based method for the inherent safety assessment of process systems. The output of the analysis is a metric (a set of Key Performance Indicators, KPIs) which provides a sound and reproducible quantification of the inherent safety fingerprint of the system considered. The analysis is particularly suitable for application in the preliminary project development stages, and may be applied to large industrial applications as well as to small and medium scale facilities.

1. Introduction

The final goal of inherent safety (IS) is “avoiding hazards rather than keeping them under control” (Kletz 1998). For process plant the major hazards can be effectively eliminated or reduced by proper choices in the design activities. For practical design choices IS guidelines are not sufficient, and quantitative/semi-quantitative tools are required to test and validate the safety improvements achieved. The engineering literature proposes a few tools, generally based on indexing/scoring of relevant hazardous proprieties. A good review of the topic is provided by Khan and Amyotte (2003). Despite the valuable research effort that resulted in development of the current tools, they are heavily based on simplifications and built-in assumptions. Embedded experience of the developers may hardly retain its value when further information on the process become available. On the other side, some subjective elements are introduced in the comparison when expert judgment is required (Tugnoli et al. 2007).
In the present paper, an alternative method for IS assessment in early process design is presented. Key performance indicators (KPIs) for IS, strongly based on consequence assessment of potential accidents, are defined and a procedure for their quantitative assessment is developed. Pre-set scores and expert judgment are replaced by application of conventional consequence models. An example of application is provided.

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2. The KPI Assessment Methodology

The aim of the method is to compare the inherent safety of alternative process schemes by the calculation of quantitative hazard and risk indexes for single units and for the overall process. The conceptual flow diagram of the method is reported in Figure 1.

2.1 Identification of Process Units (PU)

The process units (PU) are the basic elements of the process (e.g. reactor unit, compression unit, etc.). Equipment units are sorted by a specifically defined classification, based on the geometrical similarity (e.g. shell&tube equipment). Sub-categories feature specific characteristics of the units related to their function/operative condition. The input data required on the units are typically available in definition of simplified process flow diagram (PFD) and preliminary equipment design: (i) substances and operating conditions (pressure, temperature, phase); (ii) input/output material flows; (iii) general technical specifications of units; and (iv) a preliminary estimation of inventories.

2.2 Identification of Failure Modes and Credit Factors

Failure of a unit leads to a loss of containment (LOC). Reference LOCs were associated to the more common classes of pieces of equipment on the basis of approaches suggested in the technical literature (Uijt de Haag and Ale, 1999). Table 1 reports some examples. When non-standard equipment needs to be considered in the analysis, Failure Mode and Effect Analysis (FMEA) may be applied to identify the credible events leading to LOC. Several LOC events are possible for each piece of equipment. "Credit Factors" (*cf*) may be determined in order to assess the credibility of the LOCs identified. In the present approach, the likelihood of the reference LOCs was used to quantify credibility. Reference failure frequency data may be easily used to evaluate the hazard linked to each class of equipment (Uijt de Haag and Ale, 1999), and to represent the susceptibility to particular failure modes of the equipment class. Specific failure frequency data, e.g. derived from available statistical data or from conventional fault-tree analysis, can be introduced for the adoption of technologies with higher safety standards. Credit vectors are arrays containing the credit factors for each LOC considered for a PU. Table 1 provides an example of credit vector from standard literature data.

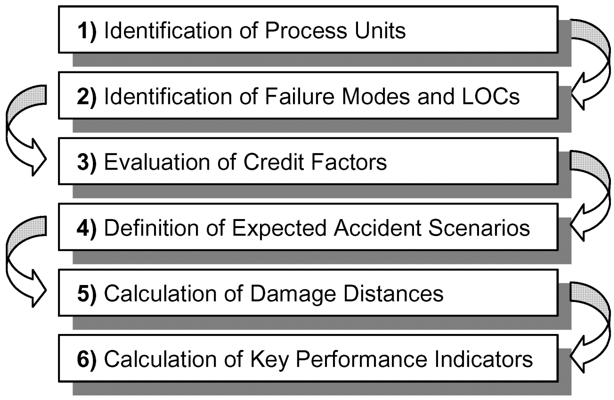

Figure 1. Conceptual block diagram of the proposed method.

2.3 Evaluation of Scenarios and Damage Distances

The identification of the accidental scenarios that may be associated with each PU is obtained by the consequence event trees for each LOC. A set of reference event trees, derived from conventional approaches proposed in the technical literature (Delvosalle et al. 2006) were defined for shortcut application in conventional cases. The selection of the proper event tree follows the criteria used in conventional risk analysis, that are based on the characteristics of the LOC event and of the stream released (hazard, physical state, properties, temperature, etc.). The identification of scenarios allows the calculation of areas interested by expected accidents. The characteristic dimension of this area (e.g. maximum distance) is assumed as severity parameter for each scenario that may be triggered by the identified LOC events. Since different types of physical effects (thermal radiation, overpressure or toxic concentration) must be taken into account and compared in the analysis, damage distances were calculated for a given physical effect (i.e. 1% fatality) on human targets. Reference threshold values were derived from conventional land use planning studies (Christou et al. 1999). Damage distances are calculated for each scenario using consequence analysis models. Several widely accepted models and commercial software tools are available for consequence analysis, and may be used for current purpose. However the same model should be used in the assessment of similar scenarios in order to obtain the more coherent results. Modelling the scenarios for each LOC yields an array of damage distances ($m_{i,j,k}$) named impact matrix. The hazard vector ($h_{i,k}$) of a PU contains the maximum damage distances calculated for each LOC event:

2.4 Calculation of Hazard Indices

Two Key Performance Indicators (KPIs) are introduced in the following, both for single PU and systems of units: the potential hazard index (PI) represents effects which may derive from the worst case accidents; unit inherent hazard index (HI) represents the effects which may derive from the worst credible accidents, accounting the safety performance (robustness to LOCs) of the PUs. The Key Performance Indicators (KPIs) are calculated from the hazard and credit vectors as follows:

$$UPI_k = \max_i (h_{i,k})^2 \tag{1}$$

$$UHI_k = \sum_i cf_{i,k} \cdot h_{i,k}{}^2 \tag{2}$$

where the subscripts i and k refer to LOC mode and to PU respectively. Credit factors (*cf*) are introduced in UHI in order to take into account the safety scores of the equipment, and to consider differences in inherent safety performance deriving from equipment technology. The overall indexes of a system with *N* units (e.g. the entire plant) are calculated as follows starting from the unit indexes:

$$PI = \sum_{k=1}^{N} UPI_k \tag{3}$$

$$HI = \sum_{k=1}^{N} UHI_k \tag{4}$$

3. Case Study

The present methodology was applied to several case studies, in order to test its suitability for the assessment of the inherent safety of alternative process schemes. Some results of a case study about hydrogenation of phenol are discussed in the following. The process options taken into account represent three alternative industrial production processes used in the last 50 years for the production of cyclohexanol. Figure 2 reports the simplified block diagram of the three process alternatives considered. The main difference among the alternatives concerns the operation of the reactor. In alternative A, the reaction takes places in a slurry pressurized reactor (1 MPa and 408 K). In alternative B the slurry (418 K) is not pressurized and products are continuously stripped by a gas flow. The condensable fraction of this stream is recovered by quenching. In alternative C a gas-phase reaction occurs in a fixed bed reactor. Phenol feed is vaporized and mixed with hydrogen. Reaction products are condensed and distilled. A common production potential (98Gg/year) was assumed to define a simplified PFD for each process. The heat and mass balances were carried out. A preliminary estimation of the inventories was also carried out for each PU.
Table 1 reports, for some units the damage distances and credit factors resulting from the application of the method described above. The table shows that important differences (up to some orders of magnitude) may be present both in the damage distances and in the credit factors for different LOCs concerning the same piece of equipment. As expected, scenarios involving toxic dispersions are those resulting in higher damage distances. On the other hand, higher credit factors are obtained for units that are more likely to cause loss of containment (e.g. heat exchangers, compressors and pumps etc.).

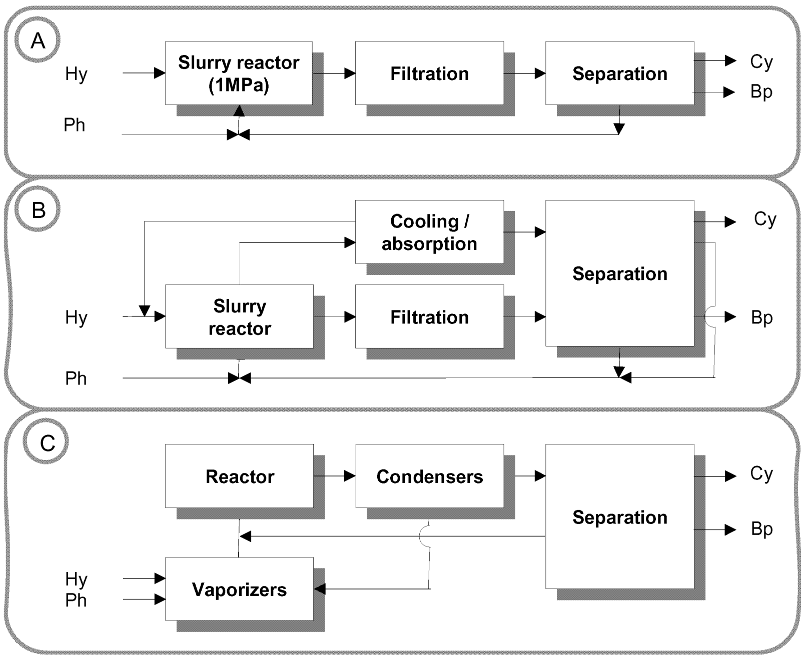

Figure 2. Simplified block diagram of the alternative processes considered in the case-study. Hy: hydrogen, Ph: phenol, Cy: cyclohexanone, Bp: by-products.

Table 1. Example of intermediate results in the study. VCE: vapor cloud explosion, TD: toxic dispersion.

Unit	Class	LOC	Scenario	$cf_{i,k}$ (1/y)	$h_{i,j,k}$ (m)	*Threshold Value*
Slurry reactor (A)	Pressure vessel	Small leak (10mm hole)	Jet Fire	$1x10^{-4}$	7.6	7 kW/m^2
			VCE	$1x10^{-4}$	12	14 kPa
			Flash Fire	$1x10^{-4}$	7.4	7 kW/m^2
			TD	$1x10^{-4}$	58	IDLH
			Pool Fire	$1x10^{-4}$	14	7 kW/m^2
		Release of inventory in 600s	TD	$5x10^{-6}$	66	IDLH
			Pool Fire	$5x10^{-6}$	14	7 kW/m^2
		Instantaneous release	JF	$5x10^{-6}$	23	7 kW/m^2
			VCE	$5x10^{-6}$	19	14 kPa
			Pool Fire	$5x10^{-6}$	13	7 kW/m^2
Hydrogen cooler (A)	S&T heat exchanger	Small leak (10mm hole)	Jet Fire	$1x10^{-3}$	8.2	7 kW/m^2
			VCE	$1x10^{-3}$	13	14 kPa
			Flash Fire	$1x10^{-3}$	7.5	7 kW/m^2
		Instantaneous release	Jet Fire	$1x10^{-5}$	22	7 kW/m^2
			VCE	$1x10^{-5}$	14	14 kPa
Phenol pump (A)	Pump	Leak, (hole 10%)	Pool Fire	$5x10^{-4}$	8.1	7 kW/m^2
		Rupture, full-bore	Pool Fire	$1x10^{-4}$	13	7 kW/m^2

Table 2 shows the results obtained in the calculation of the equipment potential and of the inherent hazard indexes. The potential hazard index only gives information on the equipment that may potentially trigger the most severe scenario, while the inherent hazard index also includes information concerning the credibility of the possible scenarios. Thus, the inherent hazard index yields a more realistic description of the credible accidental events that may be associated to plant operation. In particular, this index points out the importance of the safety performance of small pieces of equipment, as compressors and heat exchangers, on the inherent safety of the plant, since these components may have per se relatively small damage distances but are more vulnerable to undergo loss of containment events. As shown in the table, these units have inherent hazard indexes that are often comparable to those of major process units (e.g. columns or reactors), that have potentially more severe scenarios but higher safety scores and thus lower credit factors.

If the overall indexes are considered, the ranking among alternatives given by potential indexes becomes straightforward due to the presence of different numbers of units that may trigger long distance scenarios in the alternative processes, process A being the more penalized. However, the potential hazard gap between options A and B is decreased if credit factors are considered, since the three reactors of option A results more hazardous due to the higher operating pressure, and the effect of the UPI index of the quenching columns in option B is limited by the low credit factor of catastrophic failure scenarios.

Alternative C is identified as the preferable option by both inherent safety performance indicators, PI and HI. In particular, the choice of a non pressurized gas phase reaction minimizes both hazard distances and the hazard related to small, but highly credible, leaks, that played a major role in the reactor hazard of former options.

Table 2. Values of KPIs as obtained for the reaction section of the discussed case study.

Option A	**UHI_k**	**UPI_k**		
Slurry reactor (1 of 3)	$3.7x10^{-1}$	$4.3x10^{3}$		
Hydrogen cooler	$1.7x10^{-1}$	$4.8x10^{2}$		
Phenol feed pump	$4.9x10^{-2}$	$1.6x10^{2}$	**HI**	**PI**
Hy. compressor	$3.9x10^{-1}$	$4.8x10^{2}$	$1.9x10^{0}$	$1.8x10^{4}$
Option B	**UHI_k**	**UPI_k**		
Slurry reactor (1 of 3)	$2.2x10^{-1}$	$7.9x10^{3}$		
Quencher #1	$3.0x10^{-1}$	$5.2x10^{4}$		
Quencher #2	$7.2x10^{-2}$	$8.6 x10^{3}$		
Quencher #1 cooler	$2.5x10^{-1}$	$4.2x10^{3}$		
Quencher #2 cooler	$2.3x10^{-1}$	$2.4x10^{3}$	**HI**	**PI**
Condensate cooler	$1.6x10^{-1}$	$2.7x10^{3}$	$1.7x10^{0}$	$9.4x10^{4}$
Option C	**UHI_k**	**UPI_k**		
Fixed bed reactor (1 of 2)	$2.6x10^{-2}$	$2.5x10^{3}$		
Feed evaporator	$9.2x10^{-2}$	$1.8x10^{3}$	**HI**	**PI**
Product condenser	$1.2x10^{-1}$	$4.6x10^{3}$	$2.6x10^{-1}$	$1.1x10^{4}$

4. CONCLUSIONS

A consequence-based method for the quantitative assessment of the inherent safety during early process design was developed. The methodology yields KPIs representing the inherent safety performance of the process, based either on a direct assessment of potential worst-case scenarios (PI) or of likely safety performance and release scenarios of process units (HI). The methodology developed introduce a direct relation among hazard factors and consequence analysis of potential scenarios, overriding several problems evidenced in the application of previous methods. Moreover, the proposed KPIs take into account the hazards coming from auxiliary equipment, that are often as relevant for safety as those expected by major process units.

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