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Optimization procedure to select an inherently safer design scheme

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ABSTRACT

There are different well-established strategies for making a process plant inherently safer. The benefits of applying these strategies on reducing the overall risk inside a plant are obvious. However, some of these changes are rejected many times because they appear to be too costly. But if the effects of applying inherently safer design strategies are investigated not only on the processing costs of a plant but also on the potential accident costs, the decision would in fact be different. In this paper an optimization procedure is proposed which integrates both processing and accident costs for different design schemes. In this procedure, some of the design variables are chosen with regard to inherently safer design strategies. The objective function is the sum of accident costs and plant lifecycle processing costs. For assessing accident costs, consequence modeling techniques and probit functions are applied. Consequence modeling formulas and an objective function are codified in an optimizer package (MATLAB) and to accomplish the optimization process a process simulator (called HYSYS) is coupled with this package. The application of the proposed procedure is demonstrated by selecting an optimum process scheme for a Refrigeration plant as a case study.

Keywords: Process safety; Optimization; Inherently safer optimum design; Consequence modeling; Safety economics; Inherent safety

1. Introduction

A chemical manufacturing process is inherently safer if hazards associated with materials and operations have been reduced or eliminated. This reduction or elimination should be permanent and inseparable. This strategic approach is best implemented at an early stage in the process or plant design (Bollinger et al., 1996). Khan and Amyotte (2002, 2003) indicate that inherent safety can be incorporated at any stage of design and operation, and that its application at the earliest possible stages of any process yields the best results.

There are four basic principles of inherently safer design (Kletz, 1991):

- 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 release of hazardous material or energy (also called attenuation and limitation).
- Simplify: design facilities which eliminate unnecessary complexity and make operating errors less likely.

Application of inherent safety strategies can lead to improving safety in a plant and also lowering capital and

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operating costs (CCPS, 2000; Edwards and Lawrence, 1993; Hendershot, 2000). Khan and Amyotte (2002) replicated similar findings in their studies, which stated that considering the lifetime costs of a process and its operation, an inherently safer approach is a cost-optimal design option. However, implementation of inherent safety strategies requires a comprehensive economic analysis and risk assessment of all parts of a process since applying inherent safety to reduce a particular hazard may result in the increase of other hazards or may lead to unacceptably higher processing costs.

Generally, the evaluation and comparison of the inherent safety level with respect to different design options can be categorized in two groups:

- Evaluation by scoring the process features and the development of indices.
- Quantitative assessment using consequence modeling and the calculation of accidents' consequences.

The majority of the attempts have been made in order to obtain indices to evaluate the inherent safety level. One the earliest indices was proposed by Edwards and Lawrence (1993) (Lawrence, 1996). An overall inherent safety index prototype was developed to illustrate the inherent safety potential of different process routes for manufacturing the same end products (Edwards et al., 1996). Another inherent safety index was developed using fuzzy logic by Gentile et al. (2003), using if-then rules to calculate the index. Palaniappan et al. (2002) developed a systematic methodology and an automated tool (known as i-Safe) to compare process routes for their inherent safety level and select the inherently safer ones developing flowsheets among different design options. A detailed review of available tools and techniques for evaluating inherent safety using indices is given by Khan and Amyotte (2003, 2005). Also, a conceptual framework was proposed by Khan and Amyotte (2005) to integrate an inherent safety index throughout the life cycle of process design.

The application of indices is a simple approach to evaluate inherent safety levels and to compare risk levels of different design schemes. However, it only provides a relative evaluation of the level of risk between different design options and does not consider vulnerable elements in the surrounding environment as possible hazard receptors. More important however, these indices do not demonstrate the possible, and often important, economic benefits of implementing inherent safety.

In the second approach of evaluating inherent safety, it is possible to consider hazard receptors and to have a more clear understanding of the risk, using consequence modeling. Mohd Shariff et al. (2006) have developed a demonstrative tool called "integrated Risk Estimation Tool" (iRET) that uses process simulation software (HYSYS) and spreadsheets (MS Excel) as platforms. iRET was developed for estimating risk levels and consequence analysis from vapor cloud explosions by using the TNT equivalence method and the TNO correlation method. Leong and Shariff (2008) reviewed available techniques for quantification of inherent safety levels and addressed the shortcomings of current techniques by proposing the direct integration of a process design simulator with an integrated inherent safety index called "inherent safety index module" (ISIM). An optimization methodology was proposed by Medina et al. (2009), in which both cost and risk were taken into account to obtain an optimum solution with respect to both economic aspects and safety features. The objective function defined by Medina et al. (2009) includes both investment costs and the cost of potential accidents. They applied the proposed procedure for two case studies, a toxic release and a BLEVE/fireball, to determine the optimum number of storage tanks in a chemical plant. Another tool called "Toxic release consequence analysis tool" (TORCAT) was developed by Shariff and Zaini (2010) to analyze the consequence of a toxic release in order to evaluate the inherent safety level of different process options by determining the concentration of the released gas at a specific distance. Patel et al. (2010) applied a "Computer Aided Molecular Design" (CAMD) technique to select inherently safer solvents for a solvent operation. In their work, consequence modeling and regulatory guidance from EPA RMP had been integrated into the process simulation to incorporate principles of inherently safer design into the early stages of conceptual process design. Recently, Bernechea and Arnaldos Viger (2013) presented a method for optimizing the design of storage plants and for minimizing the risk by calculating the ideal number of tanks. Unlike Medina et al. (2009), they used a probabilistic approach to assess risk.

To the best of the authors' knowledge, there is no comprehensive study that provides an optimization procedure to obtain the optimal inherently safer design schemes by considering the evaluation of economic benefits of implementing inherent safety strategies. Although Medina et al. (2009) and Bernechea and Arnaldos Viger (2013) used both financial and accident costs to obtain an optimum design scheme, they did not provide any conceptual procedure to consider inherent safety strategies in their optimization procedure.

In this paper, a procedure is developed to integrate inherent safety assessments in the synthesis of flowsheets and for the optimization of processes. In this procedure, the inherent safety strategies are considered in the synthesis and optimization procedure by considering decision parameters associated with each strategy. To study the effects of implementing inherent safety concepts the costs of accidents are considered besides other processing costs.

2. Methodology

In addition to the difference in processing costs (summation of fixed and operating costs), different designs and options have a different potential of accident occurrence and severity. It is possible that a design, which has lower processing costs, has more associated hazards and consequently more accident costs. An accident is linked to all kinds of direct and indirect costs (Reniers and Audenaert, 2009). To perform a realistic optimization, all costs associated with a process, including accident costs, which are influenced by decision parameters of a design procedure, should be taken into account, since in considering inherently safer design alternatives there are often conflicting benefits and deficiencies associated with each different option (Bollinger et al., 1996). It is thus essential to evaluate the effects of inherent safety implementation on all potential hazards and all economic aspects of the plant.

The developed procedure to incorporate accident costs into the optimization procedure is shown in Fig. 1 and will be explained further.