

Economic optimization of industrial safety measures using genetic algorithms

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ABSTRACT

The paper presents a computer-aided methodology for economic optimization of industrial plants safety. The method is based on the minimization of total safety-related cost including investment, operating expenses of adopted safety measures, and expected monetary loss from accidents. The objective function minimization is pursued resorting to a genetic algorithm which selects the best mix of safety measures able to attain the optimal risk level at minimum cost by factoring in the cost and risk reduction potential of each candidate safety measure. After a detailed description of the optimization approach the paper discusses two numerical examples showing the method application to both easy and complex decision making scenarios.

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1. Introduction

In order to reduce risk in industrial plants, the safety engineer can usually choose among a vast array of different safety measures (SMs) according to the pursued degree of risk reduction. Given that risk is conventionally defined as $R = p \times M$, a generic SM can reduce risk by lowering the accident probability p (preventive SM), by mitigating the magnitude of the resulting loss M (protective SM), or both.

For instance, in an attempt to reduce fire risk one could improve the number of components or the training level of emergency fire fighting squads, or could install an improved set of fire sensors, or could change some structural materials in order to improve the fire response of the buildings, or could install a number of different fire extinguishing equipments (i.e. a sprinkler system, a foam system, deluge barriers, water mist systems etc.).

Different perspectives may be assumed when judging the risk level in any civil or industrial activity. For instance, one can refer to a personal acceptable risk level, or to a social acceptable risk level (Arends, Jonkman, Vrijling, & van Gelder, 2005). However, it is widely agreed that the economic factor is one of the main criteria utilized when taking decisions concerning industrial safety and risk reduction. In this respect each SM, when applied, not only implies a different overall cost (including capital and operating expenses), but also a different risk reduction potential which even leads to a different monetary value of the expected loss from an accident. A

cost-benefit trade-off then arises. In greater detail, according to the economic risk approach (Arends et al., 2005; Jongejan & Vrijling, 2009; Van Dantzig, 1956; Vrijling, van Hengel, & Houben, 1998) an increased cost (C_{SM}) of preventive or protective safety measures is incurred to increase the plant safety level S . However, a decrease of the expected cost of the accidents (C_D) is simultaneously obtained (Fig. 1). This happens thanks to the reduced accident probability and/or the lower loss resulting from the implemented measures, given that, in general, the expected economic loss is $C_D = p \times L$, where p is the accident probability and L is the loss monetization. It follows that the economic optimization of plant safety is a relevant problem and that, in theory, an economic optimal safety level may be found corresponding to the minimum total safety-related cost $C_{TOT} = C_{SM} + C_D$.

However, although this schematization is conceptually valid, it may not lend itself to a practical utilization. In fact, the optimal economic safety level may not be consistent with the notion of acceptable risk level or with existing regulations. In this case one should perform the search of the best SM only after an acceptable personal or societal risk level has been attained. Moreover, it could be extremely difficult to actually plot the C_{SM} and C_D functions, because the curves would be discontinuous and might present multiple cost values corresponding to a same safety level. This happens because different kinds of accidents could occur for the same risk level, having different probabilities and magnitude of consequences, or because the same risk level could be obtained adopting different SMs having different costs.

Nevertheless, if one accepts this schematization, then the problem arises of choosing the best mix of SMs able to “optimize”

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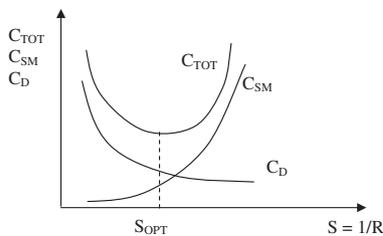


Fig. 1. Scheme of Safety Cost Optimization.

the risk level, i.e., to minimize the total safety-related cost. As an alternative, the best set of SMs may be searched in order to obtain the maximum risk reduction within the constraint of a given budget or a predefined risk level at minimum cost. In all cases the safety improvement of industrial installations relies on the optimal allocation of available resources. However, given that multiple choices of SMs are possible and that the economic consequences of each one may be very different, this search for the best mix of SMs actually involves the solution of a combinatorial optimization problem. The solution is made even harder considering that not only a very large number of different subsets of applicable SMs is theoretically possible, but also that for any given subset of SMs, a different weight can be given to any specific adopted measure in terms of a percentage budget so that an even greater number of possible solutions has to be examined. Nevertheless, in practice it is unfeasible to enumerate and review all possible combinations of SMs, and usually only one SM at a time is evaluated resorting to a simple cost/benefit analysis in order to merely find an economic justification to that candidate SM (Antes, Miri, & Flamberg, 2001). However, this prevents from optimally solving the risk optimization problem.

In order to provide a practical solution to the safety optimization problem, in this work a genetic algorithm (GA) approach which proves to be effective in the practical selection of the optimal mix of SMs is suggested. According to this approach the decision variables are the specific SMs to be chosen and the budget allowed for each of them, while the objective function to be minimized is the total safety-related cost (Caputo et al., 2006, 2008). Constraints may be a minimum safety level and/or the maximum allowed SMs budget.

In the paper at first a formulation of the optimization problem amenable to the solution through a GA is presented, where the relationships between SM investments, the achieved safety level, and the resulting economic loss are explicitly modelled in a generalized manner. Afterwards, the working logic and implementation of the GA are described. Finally, two numerical examples are given to compare the method application in both an easy scenario, where some dominant hazards and preferred safety measures are easily identified, and a difficult scenario, where no dominant hazard or SM exists so that multiple combinations of SMs could be pursued. Clearly the proposed optimization method is better suited to the latter kind of scenarios where traditional SM selection approaches, based on expert judgement, best practices, and cost-benefits analysis applied to one measure at a time, fail to be effective. It is believed that this new approach to SMs selection through economic optimisation of the safety level can represent a valuable tool for the safety analyst who is in charge of reducing risk in industrial plants.

2. Literature review

Cost-benefit analyses are widely adopted to justify specific SMs (Antes et al., 2001), even if companies often use only rude estimates of costs and benefits resulting from safety investments (Reniers & Audenaert, 2009). This means that, from a company-wide

perspective, only limited managerial insights are obtained with scarcely useful results. Therefore, most companies fail to optimize the benefits offered by investments in safety measures. Moreover, companies find difficult to quantify financial losses from prospective accidents and consider the balance of incurred costs and avoided losses to be only a theoretical exercise. Reniers and Soudan (2003) report, in fact, that out of 24 chemical companies questioned, not one had taken time to calculate in detail the hypothetical benefits resulting from implemented safety measures. Some structured quantitative approaches to compare alternative SMs have been thus proposed in order to assist in this evaluation process. Reniers and Audenaert (2009) further explore the cost-benefit approach by describing a model allowing to identify and justify safety-related investments within a chemical company from a managerial perspective by differentiating serious and less serious accidents. They include fixed and variable as well as direct and indirect costs of prevention measures, and compute benefits factoring in direct benefits from avoided accidents and, for instance, reduced insurance premiums, as well as indirect benefits such as non-absenteeism, non-turnover of staff and non-over investment in a restructured work environment. Avner (2004) proposed a fault tree based heuristic algorithm to identify the most cost-effective primary failures to be acted upon, to achieve maximum probability reduction of the top event given an available budget, or to minimize the required budget necessary to obtain a given probability reduction of the top event. Caputo, Palumbo, and Tartaglia (2004) presented a methodology utilizing fault tree analysis and cost-benefit evaluation to select the most cost-effective options for risk reductions in industrial plants including structural changes and preventive maintenance. Caputo (2008) also presented a index based approach to rank competing SMs as well as a mathematical programming approach, based on the solution of a knapsack problem, to assist in the selection of SMs (Caputo et al., 2009).

However, given the complexity and large scale of the problem it has not yet found a general solution. Recently, GA based methods have been proposed in the safety-related field of plant maintenance and have shown a potential in effectively dealing with large scale optimization problems (Liu & Frangopol, 2005; Kumral, 2005; Marseguerra & Zio, 2000; Lapa, Pereira, & Mol, 2000; Yang, Sung, & Jin, 2000). However, in such maintenance based applications, the focus was on optimizing maintenance planning parameters (i.e. frequency of inspection or preventive maintenance) and the safety issue was considered only as a side effect in terms of cost of accidents. Other authors, instead, explicitly included safety issues and costs in the problem formulation but still in the framework of maintenance optimization (Giuggioli Busacca, Marseguerra, & Zio, 2001; Martorell, Sánchez, Carlos, & Serradell, 2004; Martorell et al., 2005). At an increased level of detail, GAs have been also proposed to optimize the design and technical specifications of safety systems (Andrews & Bartlett, 2003; Marseguerra, Zio, & Podofilini, 2004; Pattison & Andrews, 1999), in civil engineering applications to optimize the life cycle management of infrastructures (Furuta, Kameda, Fukuda, & Frangopol, 2003) or in the optimization of construction site layout to find the right compromise between safety and material movements cost (El-Rayos & Khalafallah, 2005). Even the problem of safety-conscious process plant layout has been faced adopting GAs (Castell, Lakshmanan, Skilling, & Banares-Alcantara, 1998; Caputo et al., 2007). However, no approach is available to optimize the economic safety level of whole industrial plants through the systematic selection of SMs, as proposed in this paper.

3. A model for economic optimization of safety level

In an industrial plant a multiplicity of different hazards exist, which can be counteracted by applying safety measures. Let us

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