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A multicriteria knapsack approach to economic optimization of industrial safety measures

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ABSTRACT

The selection of safety measures to be applied in an industrial plant to reduce risk to an acceptable level is a critical task for safety engineers. However, to select a portfolio of safety measures is quite hard as a number of different hazards have to be counteracted simultaneously and a wide range of preventive or protective measures can be chosen, including either technical, administrative and managerial actions, within the constraints of a given budget. In this paper a multi-criteria "knapsack" model is described to help safety analysts in selecting the most cost-effective safety measures to be adopted. The problem is formulated as that of maximizing the utility of the portfolio of safety measures subject to a number of constraints including a maximum allowable budget. In the paper at first the problem formulation is given as a knapsack model, then the approach to compute the utility level of a given portfolio of safety measure is described utilizing a multi-criteria method. Finally, an application example is presented and the advantages and disadvantages of the method are discussed.

1. Introduction

Multiple hazards occur simultaneously in industrial plants. In such cases the safety manager has the responsibility of identifying the most critical hazards and properly select safety measures (SMs) in order to obtain the highest risk reduction while complying with enforced regulations and the available safety budget. This may be quite a hard task as a wide range of preventive or protective SMs exist to counteract any given hazard including either technical, administrative and managerial actions. In this context the large number of competing alternatives requires a methodology for prioritizing the candidate SM, so that the benefit within a limited budget is maximized. The choice is made harder by the fact that when multiple SMs exist for a given hazard, a dominant SM may not be easily discernible. In fact, each SM might imply a different overall cost (including capital and operating expenses) but also a different risk reduction potential which even leads to a different expected monetary loss from an accident. This also asks for a multi-criteria analysis and a trade-off evaluation in order to define the most cost-effective portfolio of SMs to be adopted. However, the technical literature is lacking of formalized methods to assist in the selection of safety measures while from the mathematical standpoint this may be considered as a hard to solve combinatorial optimization problem. In practice, it is not possible a thorough enumeration and review of all possible combinations of SMs and usually only one SM at a time is evaluated resorting to a simple cost/benefit analysis. This merely allows to find an economic justification to the candidate SM (Antes et al., 2001). Nevertheless this subjective trial and error approach does not guarantee an optimal choice. Moreover, the safety engineer may not even be sure of having identified the proper set of candidate solutions before carrying out any comparative analysis of the available SMs. Therefore, the SM selection process can be quite inefficient and time consuming.

In the attempt of providing effective methods to assist in this decision making process, a research effort has been undertaken and several possible approaches have been already presented. In a previous paper of the same authors (Caputo et al., 2011) a somewhat advanced computer method for the minimization of total safety-related costs, i.e. the sum of adopted SMs cost and accident cost, was presented. The mix of SMs, able to attain the optimal risk level corresponding to the minimum overall cost, was found by solving the related combinatorial optimization problem resorting to a genetic algorithm. However, although that method proved to be quite powerful, it requires the development of proper stochastic optimization software, which might be unfeasible for the average safety analyst, and relies on fairly detailed knowledge about the characteristics of the hazards and the candidate SMs. Such quantitative information might not always be readily available and require considerable preparatory work to be gathered.

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To provide an easier to use method for selecting SMs, an alternative approach based on a set of rating indices was instead proposed in (Caputo, 2008) allowing a rapid screening of potential SMs. The methodology was based on the use of a novel set of easy-to-compute rating indices which allow the analyst to rank the competing safety measures on a cost-effectiveness basis while considering a number of relevant factors which are neglected by traditional cost/benefit analyses. In particular, efficiency, effectiveness, applicability range, the criticality of the affected hazards were also factored in. This allows the safety analyst to adopt a multiple-criteria approach in order to easily define a portfolio of preferred alternatives for direct application or any subsequent more detailed investigation. In fact, the method can assist plant safety practitioners in the practical identification of possible dominant SMs thus solving the implied trade-off conflicts when an adoption decision has to be made.

In this work, instead, the problem of choosing a set of safety measures is framed again in terms of combinatorial optimization, and a mathematical linear programming approach is adopted where the choice of SMs to be adopted is determined by solving a 0–1 linear programming model formulated as a knapsack problem.

In determining the "goodness" of each safety measure the concept of "utility" is adopted which lends itself to a multiple-criteria decision making (MCDM) also allowing the assessment of both qualitative and quantitative performances of the candidate SM.

With reference to the selection of a portfolio of interventions to optimize a performance measure subject to a set of constraint it should be noted that mathematical programming methods have been proposed in the field of civil engineering and buildings renovation, although this approach seems to be new in the field of industrial plant safety.

As an example Brown (1980) utilized a dynamic programming approach to select highway improvement projects, while Farid et al. (1994) utilized an incremental benefit-cost analysis in a similar context. Basing on the multiple choice knapsack problem (Sinha and Zoltners, 1979), Sinha et al. (1981) utilized binary variables to represent various highway improvement alternatives and solved an integer optimization model to select a portfolio of interventions, adopting the total crash rate as the objective function to be minimized. Pal and Sinha (1998) extended this model to consider the effectiveness of the various projects in future years by factoring in the expected growth in traffic. Melachronoudis and Kozanidis (2002) proposed a mixed integer knapsack model to allocate a given budget to highway safety improvements by including either discrete interventions at specific points and continuous improvements over variable lengths of a highway. Gustafsson (1998) utilized a mixed integer linear programming method to select actions in building retrofits. Alanne (2004), finally, adopted a knapsack model to select renovation actions for building retrofit and refurbishment also including multi-criteria rating of alternatives.

The paper is organized as follows. Firstly the methodology is described. Then an application example is presented and the advantages and disadvantages of this decision support method are discussed. Finally, some directions for future research are suggested.

It is believed that this approach can help safety engineers to select the most feasible and cost effective portfolio of safety measures for risk reduction in industrial plants and represents a further valuable tool for the safety analyst who is in charge of risk reduction in industrial plants.

2. The knapsack optimization model

In this work we assume an industrial plant where a set of hazards exist and consider a set of candidate safety measures (i.e. a set of single actions expected to reduce risk) to be possibly implemented. The problem is that of allocating an available budget among these safety measures in order to optimize a safety-related measure of effectiveness broadly defined in terms of utility, which results from a multi-criteria assessment of the safety measures effects. In this respect the problem at hand can be included in the broader area of portfolio optimization.

We adopt an additive knapsack formulation were the objective function to be maximized is expressed in the context of the utility theory as follows

$$\mathrm{Max}\sum_{i=1}^{n} x_i U_i \tag{1}$$

where x_i (x_1, x_2,...x_n) are the decision variables representing the candidate safety measures, with $x_i = 1$ if the i-th safety measure is selected, else $x_i = 0$, and U_i being the utility score achieved by selecting the safety measure x_i.

The problem is subject to the basic constraints

$$x_i \in \{0, 1\} \tag{2}$$

$$\sum_{i=1}^{n} x_i C_i \leqslant C_{\mathrm{MAX}} \tag{3}$$

where C_i is the cost of safety measure x_i and C_{MAX} is the maximum available budget.

Apart from these general constraints, some additional case-specific constraints can be added. In particular when facing safety-related problems the following constraints may be relevant.

- Compatibility constraints, i.e. avoid selecting incompatible safety measures (as an example a water sprinkler and a CO_2 fire fighting system owing to the solubility of carbon dioxide in water) or safety measures acting on the same hazards and having non-additive effects.
- Case-based constraints, i.e. necessary actions dictated by laws and regulations or by case-specific situations.
- User defined constraints, i.e. minimum required risk reduction.

However, no general expression can be given for such constraints as they have to be expressed depending on the specific case at hand. A discussion about the possible formulation of such constraints is given in a subsequent section.

By computing the utility U_i of a safety measure we provide a means to quantitatively express the value that can be expected by a decision maker when paying a certain amount of money to implement that safety measure (Alanne, 2004).

To compute the utility we at first define a set of *Evaluation Criteria* according to which the *Attributes* of a given safety measure will be ranked by assigning a score S_j. Then the overall utility score of a safety measure is computed by aggregating the distinct evaluation criteria scores through a simple additive weighted average.

$$U_i = \sum_{j=1}^{m} w_j S_j \tag{4}$$

being

$$\sum_{j=1}^{m} w_j = 1 \tag{5}$$

In (Eqs. (4) and (5)) m is the number of Evaluation Criteria adopted, w_j is the normalized weight associated to evaluation criterion j, and S_j is the score number corresponding to criterion j which describes the utility associated to the attributes of the considered safety measure respect the evaluation criterion j. To assign the single utility score values S_j in a homogenous manner respect the various evaluation criteria, the procedure suggested by Alanne (2004) is adopted here where