Automatic Accident Scenario Generation and Multiobjective Optimization for Safety-Related Decision Making in Chemical Processes

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Abstract
Safety investment in Chemical Process Industries (CPI) has been required regarding process safety together with economic aspects. This paper concerns an automatic accident scenario generation and multiobjective optimization method for finding the most effective investment scenario set in CPI. Accident scenarios make up a decision pool for safety investment, and the multiobjective optimization method determines the efficient investment scenario set under the given constraints, such as a limited budget, environmental requirements and social demands.

Keywords: accident scenario, multiobjective optimization, decision making, safety

1. Introduction
Safety-related activities are important to save life and property, and this notion is the most important in running a plant. However, considering only safety without economic, environmental, and social objectives has no meaning. So considering many aspects simultaneously is important in safety activities. After the 9/11 terrorism in the USA, we are becoming more aware of the catastrophic threats posed by large quantities of chemicals in our communities. To prevent a disastrous accident in advance, we need to consider (1) credible accident scenarios and (2) a systematic strategy of adopting the scenarios for safety activities.

The risks associated with chemical plants have attracted considerable public attention, especially in plants where toxic or flammable substances are handled. In order to reduce a risk or to mitigate accident consequences, many safety activities have been conducted. Safety analysis is a basic task applied to chemical industries to ensure the safety of chemical plants. Despite the efforts of safety activities to prevent accidents, similar incidents have been occurred again and again (Kletz, 1985). The reason is that it is impractical to analyze all chemicals and all process areas because of time and budget limits. To improve the efficiency of safety activities, credible accident scenarios and profitable scenario sets needed for safety investments are required. This paper describes a new methodology for automatic generation of accident scenarios and safety-related decision making based on selection of accident scenarios in chemical processes. The

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technique proposed results in safety investments that maximize the cost to benefit ratio, as well as ensuring process safety.

2. Accident Scenario Approach for Safety Analysis

The accident scenario approach is widely used in safety analysis and emergency planning as a top event (Cadwallader et al., 1990). Methods used to identify credible accident scenarios vary from informal techniques to formal process safety analyses. In these techniques, accident scenarios are classified into two types, as follows: 1) worst possible accident; the highest consequence accident identified that is physically possible regardless of likelihood, 2) worst credible accident; the highest consequence accident identified that is considered plausible or reasonably believable (Kim et al., 2003).

2.1 Automatic approach

The accident scenario approach results in reducing the duration of the implementation of various steps, bringing down cost of study and improving the reliability of results. Some approaches deal with automation of some areas, but they do not contain a scenario generation module. In contrast to previous studies, our methodology focuses on generating accident scenarios automatically. The application of the method results in information on hazardous locations, accident sequences at selected locations and their priority. The automatic generated accident scenarios have an important role in supporting decision making on safety investment.

2.2 Conventional Decision Making for Safety Analysis

The selection of top events is the most important step in the safety analysis, in that they define the extent of a given hazard analysis. And the required time for conducting a hazard analysis increases rapidly as the number of study nodes increases.

To select an accident scenario for use in quantitative analysis, conventional hazard analyses take the following three steps: 1) Identifying potential accident scenarios, 2) Screening accident scenarios, and 3) Prioritizing accident scenarios.

After identifying process hazards using the qualitative hazard analysis, a limited number of accident scenarios will be selected for more detailed consequence analysis and impact analysis. The level of potential risk is the most common criteria for ranking the accident scenarios. In all safety analysis procedures, the potential risk ranks the identified accident scenarios for further quantitative analysis. For an accident scenario, it is necessary to estimate the approximate likelihood and severity by using the empirical semi-quantitative risk analysis method. After hazard analysts have assigned every accident scenario to likelihood and severity categories, a risk matrix is used to prioritize the accident scenarios associated with each potential accident. The sizes of the matrix and category definitions are defined to meet the needs of the organization.

2.3 Goal programming model for multiobjective optimization

Goal Programming (GP) is a well known multi-objective programming technique. The overall purpose of GP is to minimize the deviations between the achievement of goals and their aspiration levels. This is based upon the idea that we minimize one objective while constraining the remaining objectives to be less than the given target values ( \( g_i \)).
GP is a powerful technique that has found a wide range of applications in many chemical processes. On the other hand, Badri et al. (1998) have discussed models for locating fire stations. They considered cost related objectives. A mathematical description of GP (Foued and Sameh, 2001) is expressed as follows:

\[
\min \sum_{i=1}^{n} |f_i(X) - g_i|, \quad s.t. \quad X \in F
\]

where, \( g_i \) denotes the target or goal set by a decision maker for the \( i \)th objective function \( f_i(X) \), and \( F \) represents the feasible region from which the choices of vector \( X \) must be effected.

### 2.4 Summation of Weighted Objective Function (SWOF)

Ciric and Huchette (1993) presented a multiobjective approach based on the SWOF method for process synthesis and optimization problems where profitability conflicts with waste reduction. The SWOF method minimizes a convex combination of objectives:

\[
\min_{\alpha \in \Omega} \left[ u_i(f_i, \alpha_i) = \sum_{i=1}^{n} \alpha_i f_i(x) \right], \quad s.t. \quad \sum_{i=1}^{n} \alpha_i = 1, \quad 0 \leq \alpha_i \leq 1
\]

where, \( u_i(f_i, \alpha_i) \) is called the utility function, and the parametric weighting factors \( (\alpha_i) \) is under the constraint set \( (\Omega) \). Ko et al. (2002) proposed mSWOF (modified from conventional SWOF) to find the Pareto points efficiently. The method overcomes the demerit that nonconvex parts of the Pareto set cannot be obtained from minimizing convex combinations of the objectives, and the mapping between the parameters, \( \alpha \) and the Pareto points is not one to one even if the Pareto point is convex.

### 3. Multiobjective Optimization Procedure for Safety Investment

This approach is achieved by substituting the GP method for the RRI matrix at the scenario selection step in hazard analysis. The risk of the hazard identified is first estimated by semi-quantitative risk analysis or expert heuristics similar to conventional hazard analysis methods. Then the goals of this analysis should be determined to consider multiple aspects for further quantitative risk analysis. The objective functions are normalized by using a normalized technique when deviational variables are identified in different units. Depending on the target value of the GP method, further Pareto points are found within the interesting zone of the objective function. The mSWOF is used to determine efficiently a Pareto curve. Pareto points contain all information on objective variables and decision variables, and the accident scenario choice. Finally, one can make trade-offs between the conflicting objectives and through Pareto curve analysis to determine an ideal set of accident scenarios as well as decision making guidelines for safety activity.
4. Multiobjective Optimization Model

4.1 Preparing accident scenarios
Accident scenarios produced by using the automatic generator described in the above section are utilized to construct a multiobjective model. GP and mSWOF are then employed to process the constructed model. Thirty accident scenarios of the styrene process within the generated scenarios are considered in this model.

4.2 Model Formulation
We consider four goals in this model: (1) minimization of total safety activity cost; (2) minimization of total accident severity; (3) minimum number of accident scenarios with unreasonable frequency; and (4) minimization of non-operating time and indicated Goal 1...Goal 4, where \( pd_i \) is the positive deviation from target of goal \( i \) \( (i=1,2,...,N) \) and \( nd_i \) is the negative deviation from target of goal \( i \) \( (i=1,2,...,N) \).

Goal 1 **Total Safety Activities Cost Goal** (minimize overachievement \( pd_1 \))

\[
\sum_{i=1}^{N} y_i c_i + nd_1 - pd_1 = ta_1
\]

where, \( c_i \) is the safety activity cost for preventing the \( i \)th accident scenario, which involves equipment repairing cost and safety analysis cost, and \( ta_1 \) is the target for the first goal.

Goal 2 **Total Accident Consequence Goal** (minimize overachievement \( pd_2 \))

\[
\sum_{i=1}^{N} S_i - \sum_{i=1}^{N} y_i S_i + nd_2 - pd_2 = ta_2
\]

where, \( S_i \) is the accident consequence of the \( i \)th accident scenario. The first term in the above expression is the total consequence exposed in a given process, and \( ta_2 \) is the target for the second goal.

Goal 3 **Minimum number of accident scenarios for unreasonable frequency** (minimize overachievement \( pd_3 \))

\[
\sum_{i=1}^{N} y_i E_i + nd_3 - pd_3 = ta_3
\]

where, \( E_i \) depends on accident frequency. If the frequency of the selected scenario has less than a reasonable frequency, \( E_i \) takes one. Otherwise, \( E_i \) takes zero. The first term in the above expression is the sum of selected accident scenarios, which have the unreasonable frequency, for top-event in safety analysis, and \( ta_3 \) is the target for the third goal.

Goal 4 **Non-operating Time Goal** (minimize overachievement \( pd_4 \))

\[
\sum_{i=1}^{N} y_i N_i + nd_4 - pd_4 = ta_4
\]
where, $N_i$ is the non-operating time, and $ta_i$ is the target for the fourth goal.

The variables under control in this model are associated with the selection or non-selection of the given accident events. It implies that our decision variables may just be taken on the values of zero or one. The variable determines the accident scenarios which are used as the top event in hazard analysis.

$$y_i = \begin{cases} 1: & \text{if $i$th accident scenario is selected} \\ 0: & \text{otherwise} \quad (i = 1, 2, \ldots, N) \end{cases}$$

(7)

where, $N$ is the number of accident scenarios, $\alpha$ reflects the importance of goal $t$.

5. Results of Multiobjective Optimization

In the criteria of reasonable frequency, the consequence of the scenario represents the risk. The optimization results for a top-event selection problem are summarized in Table 1. The multiobjective optimization results for this example, the Pareto curve from mSWOF, are shown in Figure 1.

Judging from the optimization result, if only the cost objective is considered, as in Pareto point $D$, the minimum Cost is equal to 11,200. In this case, the Risk objective is equal to 16,124, and the selected scenarios which are to be analyzed are scenario 1, 4 and 21 which are to be analyzed, and the non-operating time is 154. If only the risk objective is minimized, as in Pareto point $C$, the minimum Risk is equal to 6,762. In this case, the Cost objective is equal to 68,200, and the selected scenarios are scenario 1, 2, 3, 4, 5, 6, 8, 12, 13, 15, 16, 18, 22 and 23, and the non-operating time is 531. If the risk and cost objectives are of equal importance, such as Pareto point $E$, Cost and Risk are 27,700 and 11,232 respectively, and the selected scenarios are scenario 1, 2, 3, 4 and 5.

Figure 1. Pareto curve of top-event selection example.
The non-operating time is 254. It can be noted that Cost significantly increases with a slight reduction of Risk from Pareto point $G$ to $A$ in the efficient frontier, and that Risk is significantly reduced with a slight increase of Cost from Pareto point $D$ to $B$. The next section will explain it more systematically by sensitivity analysis.

6. Conclusion

This research suggests a safety-related decision making method based on an automatic accident scenario generation methodology and multiobjective optimization approaches. In comparison with the conventional techniques, the method generates accident scenarios automatically and systematically decides the investment target considering multiobjective, safety and economic aspects. This system has been applied to a typical chemical process, a SM plant, and generated more than three thousand accident scenarios. To systematically select safety investment scenarios considering process safety and economic aspects, a multiobjective optimization model is proposed. The noninferior solution curve (Pareto curve) resulting from the GP model and mSWOF are presented. Based on the Pareto curve the ideal compromise solution set (best investment scenario set) is determined. It allows a decision maker to select the best compromise in safety analysis between improving process safety and considering economic aspects. Automatic generation of accident scenarios is valuable in the identification of dangerous states in complex chemical plants, as well as giving important input data for safety analysis. The multiobjective approach presents a guideline that decision makers can efficiently determine the safety investment scenarios for safety activity in view of safety and economic aspects.

References


Table 1. Pareto point and the determined scenarios

<table>
<thead>
<tr>
<th>Pareto point</th>
<th>( $\hat{f}<em>{\text{COST}}$, $\hat{f}</em>{\text{RISK}}$ )</th>
<th>Cost</th>
<th>Consequence</th>
<th>Non-OP. Time</th>
<th>Selected Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D$</td>
<td>(0.1076, 0.7580)</td>
<td>11,200</td>
<td>16,124.20</td>
<td>154</td>
<td>1, 4, 21</td>
</tr>
<tr>
<td>$E$</td>
<td>(0.1816, 0.5988)</td>
<td>18,900</td>
<td>13,362.23</td>
<td>192</td>
<td>1, 3, 4, 5</td>
</tr>
<tr>
<td>$F$</td>
<td>(0.2248, 0.5369)</td>
<td>23,400</td>
<td>12,287.92</td>
<td>220</td>
<td>1, 3, 4, 5, 6</td>
</tr>
<tr>
<td>$G$</td>
<td>(0.2661, 0.4760)</td>
<td>27,700</td>
<td>11,232.11</td>
<td>254</td>
<td>1, 2, 3, 4, 5</td>
</tr>
<tr>
<td>$H$</td>
<td>(0.3402, 0.4315)</td>
<td>32,200</td>
<td>10,557.80</td>
<td>282</td>
<td>1, 2, 3, 4, 5, 6</td>
</tr>
<tr>
<td>$A$</td>
<td>(0.4102, 0.4102)</td>
<td>42,699</td>
<td>10,090.23</td>
<td>412</td>
<td>1, 3, 4, 5, 6, 10, 13, 14, 16</td>
</tr>
<tr>
<td>$C$</td>
<td>(0.6551, 0.2184)</td>
<td>68,200</td>
<td>6,762.61</td>
<td>531</td>
<td>1, 2, 3, 4, 5, 6, 8, 12, 13, 16, 18, 22, 23</td>
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