A Probabilistic Constraint Programming Model to Reduce Risk in Layouts with Toxic Release Scenarios

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A probabilistic approach is used in this work to provide additional information on risk in optimal facility layouts. The probability distribution for risk is produced via Monte Carlo simulations where stochastic variables are varied according to their own distributions. LOPA procedure is applied to reduce risk to acceptable levels. Thus risk is adopted as a stochastic variable where extra information can be extracted to help decision makers in defining the final optimal layout. A case study reported in the literature is used here to demonstrate the advantages of applying the proposed approach when risk is analyzed using the LOPA procedure.

1. Introduction

The plant layout problem can be defined as allocating a given number of facilities in a given land to optimize an objective function, which depends on the separation distance among facilities. It is believed here that optimal layouts can reduce the damage produced in typical industrial accidents. This hypothesis has been used in a previous work (Diaz-Ovalle et al., 2010; Jung et al., 2010; Vázquez-Román et al., 2010). In particular, chemical releases from any process or storage units can lead to the formation of flammable or toxic clouds. The results of these releases can produce deaths, injuries, asset damages, environmental effects and monetary losses, extending their effect beyond the boundary of the plant. The occurrence of these incidents emphasizes the relevance of planning and designing safer plants to minimize the consequence and frequency of chemical releases. Historical accidents such as Bhopal (1984) and BP Texas City (2005) involved gas dispersion in an unsuitable layout (Mannan, 2005). The plant layout has been commonly solved through heuristic rules. However, heuristic approaches do not necessarily produce optimal distributions (CCPS, 2003). An appropriate layout must balance several factors such as sustainability by keeping space for future expansions, environmental issues, reliability and safety in plant operations, construction and operating costs.

The paper by Penteado and Ciric (1996) is the earliest work reported in the literature where safety issues have been included in the layout optimization. However, a detailed analysis of the risk reduction based in layers of protection has not been included in layout optimization. In order to evaluate risk where layers of protection are implemented, it is necessary to take into account the probability and the consequences of a hazardous scenario. Commonly, probabilities and expected values are typically used to evaluate risk. Nevertheless, a risk description based on just these values does not provide a sufficiently informative picture of the risk. This work presents a methodology to assist the plant layout problem. The proposed methodology performs a detailed risk analysis by taking into account the effect of layers of protection and including the uncertainty effect into the analysis. The main purpose is to include the whole information of the stochastic behaviour. As a case study, the proposed methodology is applied to the facility layout under toxic release scenarios. The methodology and the case study are described in the following sections.

2. Methodology

The proposed methodology is based on applying the Layer of Protection Analysis (LOPA). LOPA is a tool for analysing risk, which incorporates simplified methods to characterize consequences and estimate frequencies (CCPS, 2001). The frequencies, probabilities of failure on demand, and consequences of hazardous scenarios are estimated so that several layers of protection are added to the process under analysis to decrease risk to an acceptable level. The adequacy of layers of protection is evaluated with this analysis and the number of layers of protection needed to reduce risk to a tolerable level is determined. Unlike the classic LOPA methodology, this work aims to present more information for the risk evaluation; therefore, continuous probability distributions are used to represent the uncertain parameters instead of using expected values. By modelling the uncertain parameters with continuous probability distributions, the standard deviation of the risk is provided. The proposed methodology applied to the facility layout problem with toxic release scenarios is described in the following steps:

a) Identify the release scenario.

b) Develop a source model to describe how materials are released and the release rate.

c) Estimate the downwind concentration using a dispersion model. The Pasquill-Guifford model and the Germeles' model, as indicated in Diaz-Ovalle et al. (2010), are used for modelling passive dispersion and dense gas dispersion, respectively. Parameters affecting the dispersion such as the wind speed are represented by continuous probability distributions.

d) Evaluate the consequence. The consequences are expressed as deaths in the case study. The probability of death is estimated with (Crowl and Louvar, 2011):

$$P = 50\left[1 + \frac{Y-5}{|Y-5|} erf\left(\frac{|Y-5|}{\sqrt{2}}\right)\right]$$

(1)

where Y is the probit variable, and erf is the error function.

$$Y = k_1 + k_2 In\left(C^n t\right)$$

(2)

where k_1, k_2 and n are probit parameters, C is the concentration in ppm, and t is the release time in minutes.

e) Estimate the frequency of the consequence. Monte Carlo simulation is used to obtain the form of the distribution of the frequency of the consequence. The frequency of the consequence for a specific scenario endpoint is estimated using the following equation:

$$f_i^C = f_i^I \times \prod_{j=1}^{i} PFD_{ij} \times p^{death}$$

(3)

where f_i^C is the mitigated consequence frequency for a specific consequence C for an initiating event i, f_i^I is the initiating event frequency for the initiating event i, and PFD_{ij} is the probability of failure of the j th IPL that protects the system against the specific consequence and the specific initial event i and p^{death} is the probability of death.

f) Determine the layers of protection that are necessary to reduce risk in the layout to an acceptable level.

3. Case Study

The case study used in this work has been described in Diaz-Ovalle et al. (2010). The optimal layout was obtained based on suggested minimum separation distances between facilities and it is shown in Figure 1. Four toxic industrial chemical gases: carbon monoxide, ammonia, phosgene and chlorine are used. Chlorine and phosgene behave as a dense gas whereas carbon monoxide and ammonia remain all time lighter than the air. Since the potential harm of toxic releases is considered important, the worst case scenario for the releases must be determined. In the case study, the following release scenarios are considered:
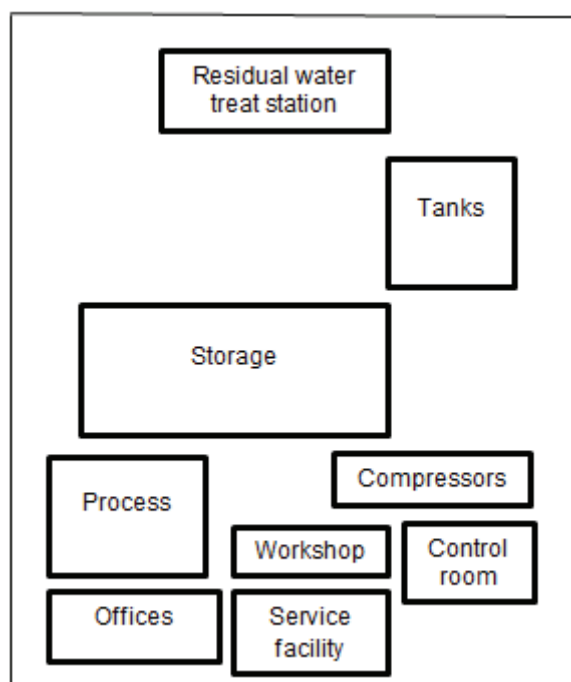
Figure 1: Optimal Layout

Table 1: PFD of protective layers

Protective layer	Parameter a	Parameter b
1	0.05	0.15
2	0.005	0.015
3	0.005	0.015
4	0.05	0.15
5	0.005	0.015

1) Ammonia (NH_3) is feed to compressors from a tank where conditions are 1 atm and -41.6 °C. A spill is expected to occur on a 50 mm inner diameter pipe. The rupture area is taken as equivalent to 50% of the transversal area in the pipe. The calculated mass rate is 0.2798 kilogram per second.

2) Phosgene (Cl_2CO) comes in a pipe, 0.014 m inner diameter, from a catalytic reactor operating at 150 °C and 1 atm. The rupture area, based on the worst-case scenario, occurs in a rupture area of 50% of the transversal pipe area. The calculated mass rate of the released phosgene in the process area is 0.01 Kilogram per second. In addition, phosgene can be released from a storage tank. The calculated mass rate is 0.005 Kilogram per second.

3) Chlorine (Cl_2) is also stored in a pressure tank. A rupture is considered to occur in 1.4 cm inner diameter pipe, 33 m far from the tank. Thus, the credible worst case scenario also indicates 50% of the transversal area in the pipe. The calculated mass rate of the release is 0.020 Kilogram per second. In addition, chlorine can be released from the residual water station. The estimated mass rate of the release is 0.01 Kilogram per second.

4) Finally, carbon monoxide (CO) is stored in a tank. A drain pipe having 19 mm of inner diameter is totally broken as a worst case scenario. The calculated mass rate of the release is 0.125 Kilogram per second.

The uncertain parameters are represented by continuous probability distributions. The wind speed in this problem is represented by the Weibull distribution with shape parameter equals to 3.198 and scale parameter 3.2090. In addition, the release time is also considered stochastic with a maximum value of 60 minutes. The release time is represented by a uniform distribution. The probability of death and probit function are calculated with Equations 1 and 2. The value obtained for the probability is used to estimate the frequency of the consequence by using Equation 3. The frequency of the initial event is assumed to follow a uniform distribution between (0.0001 and 0.001) for each scenario. The probability of failure on demand of the protective layers is assumed to follow a uniform distribution. The probability of failure on demand for each protective layer is shown in Table 1. The risk tolerance criteria for each release scenario are expressed as risk of fatality (per year) and the value is 10^{-7}.

4. Results

The optimal facility layout has been already reported in a previous work as above indicated, Figure 1. However, a risk analysis based on LOPA has not been performed to the obtained layout distribution. This work aims to assist the facility layout by applying the LOPA methodology to evaluate risk. The

methodology evaluates the risk and adds layers of protection to reduce the risk to a tolerable level. The main contribution of this work is that it incorporates the full picture of the uncertainty associated with the risk analysis. It is believed here that, in order to perform a more realistic analysis, it is necessary to include the whole continuous probability distribution instead of just using expected values. Uncertain variables included in this analysis are wind speed, release time, initial event frequency and probability of failure on demand of protective layers. The focus point of this work is to represent the uncertainty by using continuous probability distributions to obtain the risk distribution function. The frequency of the consequence is a function of uncertain parameters represented with continuous probability distributions. Then, the distribution or the frequency of the consequence in each release scenario was obtained by using Monte Carlo simulation. The frequency of the consequence for each toxic species depends on the layers added to the system. Figure 2 shows the result of adding layers of protection for each released gas on the expected frequency of the consequence.
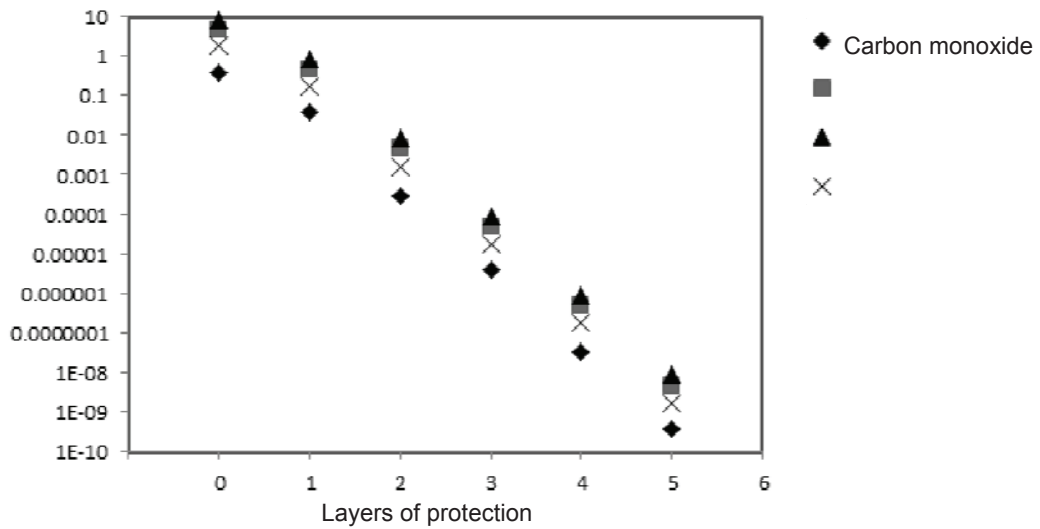

Figure 2: Frequency of the consequence of the toxic chemical gases

Monte Carlo simulations were carried out to obtain the whole distribution for the frequency of the consequence. The simulation allows analysing the frequency of the consequence when 0, 1, 2. 3, 4 and 5 layers of protection are added to reduce the risk in each release scenario. The results indicate that risk tolerance criteria are satisfied by adding 5 layers of protection for each release scenario. The distribution functions obtained for the frequency of the consequence, by Monte Carlo simulation, when 5 layers of protection are added are shown in Figures 3, 4, 5, 6, 7 and 8 for each toxic species.
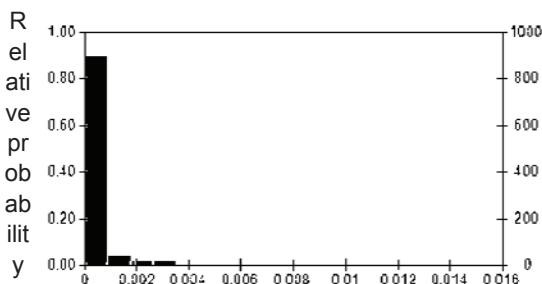

Figure 3: Frequency of consequence distribution for carbon monoxide release in process facility
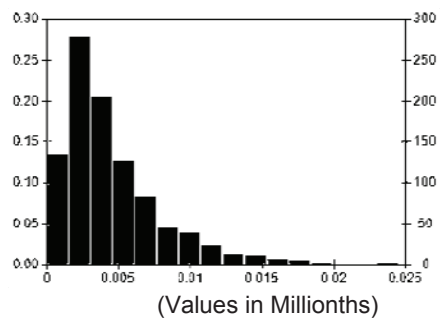
Figure 4: Frequency of consequence distribution for Ammonia release in compressors room
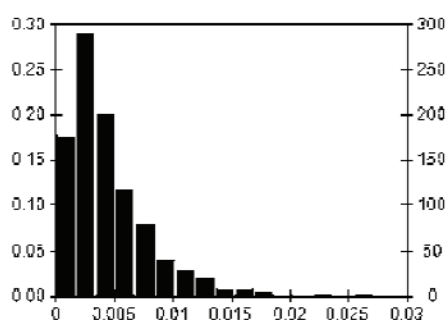
Figure 5: Frequency of consequence distribution for phosgene release in process facility
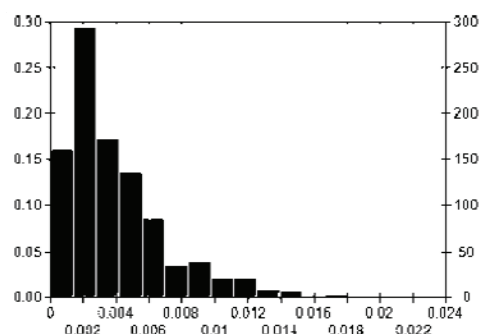

Figure 6: Frequency of consequence distribution for phosgene release in storage facility
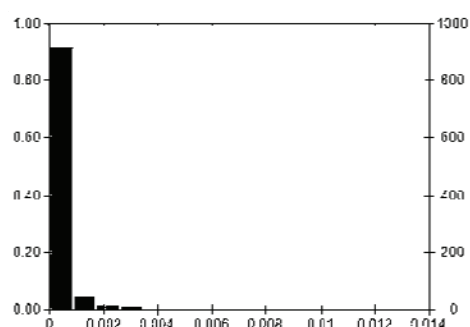

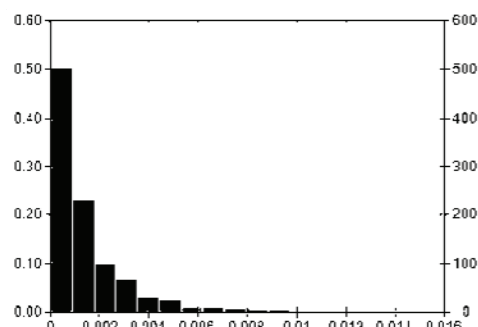*Figure 7: Frequency of consequence distribution for chlorine relesase in storage facility*

Figure 8: Frequency of consequence distribution for chlorine release in residual water treat station

The statistical information for the distribution of the frequency of the consequence includes mean, standard deviation and cumulative frequency of the target (risk tolerance criteria 10^{-7}). The estimated values are shown in Tables 2-4. Table 2 indicates that 4 protective layers would be sufficient to achieve the tolerance criteria in some cases. Table 3 shows standard deviations produced during the Monte Carlo simulation.

Table 2: Mean value of the frequency of the consequence of each release scenario

Protective layer	Carbon monoxide Process	Ammonia Control room	Phosgene Process	Phosgene Storage	Chlorine Storage	Chlorine Residual water treat
0	0.366	4.676	4.619	4.021	0.272	1.493
1	0.036	0.467	0.465	0.402	0.028	0.148
2	3.000E-4	0.004	0.004	0.003	2.000E-4	0.001
3	3.834E-06	4.646E-05	4.608E-5	3.994E-5	2.732E-6	1.494E-5
4	3.376E-08	4.745E-07	4.633E-7	4.063E-7	2.742E-8	1.459E-7
5	3.803E-10	4.695E-09	4.625E-9	4.046E-9	3.009E-10	1.451E-9

Table 3: Standard deviation of the frequency of the consequence of each release scenario

Protective layer	Carbon monoxide Process	Ammonia Control room	Phosgene Process	Phosgene Storage	Chlorine Storage	Chlorine Residual water treat
0	0.967	1.391	1.464	1.284	0.547	1.241
1	0.102	0.199	0.206	0.178	0.059	0.137
2	9.000E-4	0.002	0.002	0.002	5.000E-4	0.001
3	1.207E-5	2.763E-5	2.841E-5	2.525E-5	7.177E-6	1.595E-5
4	1.009E-7	3.474E-7	3.412E-7	2.971E-7	6.704E-8	1.574E-7
5	1.277E-9	3.715E-9	3.766E-9	3.283E-9	9.116E-10	1.690E-9

Table 4: Cumulative frequency of the frequency of the consequence of each release scenario

Protective layer	Carbon monoxide Process	Ammonia Control room	Phosgene Process	Phosgene Storage	Chlorine Storage	Chlorine Residual water treat
0	0.000	0.000	0.000	0.000	0.000	0.000
1	0.131	0.000	0.003	0.005	0.003	0.000
2	0.424	0.001	0.010	0.012	0.051	0.000
3	0.618	0.003	0.012	0.013	0.265	0.025
4	0.897	0.049	0.036	0.080	0.933	0.524
5	0.999	0.999	0.999	0.999	0.999	0.999

Using these standard deviations, Table 4 indicates the probability of satisfying the risk tolerance criteria. Thus using four layers in the case of ammonia release, only 4.9% of the events would be protected. Table 4 also shows that risk tolerance criteria are satisfied with a probability of 0.999 for all the release scenarios when 5 layers of protection are added. This information supports the results shown in Figure 2.

5. Conclusions

A probabilistic approach has been used in this work to provide more realistic information for the facility layouts. The information provided considers the analysis of the risk reduction due to the installation of layers of protection and the addition of the uncertainty effect in the risk analysis. The proposed methodology takes into account the uncertainty effect in the risk because, in reality, the risk may not take the form of expected values but may instead conform to probability distribution functions. In a future work, this work will consider including the LOPA analysis in the suggested form into the layout optimization procedure. It will also include the analysis for toxic exposures inside buildings as suggested by Sarrack (2012).

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