Multi-Objective Optimization of Hazardous Substance Storage Facilities. The Decision Between Risks and Costs Associated to the Project

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Abstract

The design storage installations for dangerous substances can be optimized from a safety and risk point of view by combining quantitative risk analysis and mathematical optimization techniques; the consequences of accidents are directly proportional to the mass involved in them, which means that in a storage installation, if the totality of the stored substance is divided into more tanks, the consequences when an accident occurs in any of the units will be less significant than if all the mass was stored in one tank (in installations where there is low possibility of domino effect occurrence). However, as more tanks are used to store the mass, the economical investment will also increase; then, a situation arises between two conflicting objectives, that can be solved through the use of multi objective optimization.

In this paper, a method to solve the multi objective optimization problem between risk and investment for storage facilities that have low domino effect probability of occurrence is proposed and applied to a case study involving a facility that stores chlorine. The final result is the design that represents the best compromise solution between risk and investment for the installation.

1. Introduction

Different types of risk analyses are generally performed on the chemical industry in order to determine if a plant or installation complies with the safety standards set by the regulatory organisms, these techniques are commonly applied to finished designs, and are rarely used to apply a modification on the layout or structure of the plant or process. It is a well known fact that safety can be incorporated at any stage of the design, but better results are obtained if it is applied at its earliest stages, however, when designing a hazardous substance storage facility, a lot of effort is put into planning the safety measures that it will require, like fire protection systems, insulation, or pressure relief valves, when the possibility exists to include safety at an earlier stage, by using quantitative risk analysis and optimization techniques.

The consequences of accidents like fires, explosions and toxic releases are directly proportional to the mass of substance involved in them, therefore, if all the mass is stored in one unit at the time of an accident, the consequences will be the worst possible; however, if the substance is stored in more units, and only one of them fails, the consequences will be reduced significantly; then, it is possible to think that at the earliest stage of the design of the installation, an optimal number of units to store the mass could be chosen.

Medina et al. [1] have demonstrated that it is possible to find an optimum number of tanks to store a certain quantity of a dangerous substance, using the cost of the consequences of possible accidents as an objective function that depends on the number of units used for storage and that can be minimized; this work was later expanded by Bernechea et al. [2], who included frequency of accident into the model, to combine it with the cost of consequences and produce an objective function that evaluates the risk associated to the installation. Both works managed to demonstrate that for installations with low probability of domino effect occurrence, risk decreases as more units are used to store the mass.

However, as more tanks are used, the cost associated to the construction of the installation increases, which leads us to the question of how many units should be used: more, in order to minimize risk (only to the point where it is possible to use more units), or less, in order to minimize costs, which is a classical multi-objective optimization problem. Multi-objective optimization is ideal to solve problems where a trade-off exists between different objectives. In this work, the risk minimization method for storage facilities will be briefly explained, then, a multi-objective optimization method to find a compromise solution will be described, and both techniques will be applied to a case study, which will allow optimizing the installations design, taking into account both risk and investment goals.

2. Methodology

In this section the design optimization to achieve risk minimization on hazardous substance storage facilities, and the method to find an optimal solution through the use of multi-objective optimization are explained next.

2.1 Design optimization of hazardous substance storage facilities to minimize risk

Design optimization for risk minimization in storage facilities is based on the idea that the design of the installation can be optimized to achieve risk minimization by dividing the stored mass in more tanks, which will make the consequences of the accidents that can occur in each unit less significant; this is a perfect concept for installations in which no flammable or explosive substances are stored, as accidents that occur in a unit will not likely affect other equipment, the probability of domino effect occurrence is virtually nonexistent. In this communication, the optimization methodology will be explained in a reduced form that can be used for installations where no danger of domino effect exists.

Obviously, the decision variable in this optimization problem is the number of tanks, and the objective function will be the risk associated to the installation, that varies depending on the decision variable. The risk associated to a possible design is calculated as the sum of all the products of cost of consequences and frequencies of occurrence of different accidents that are related to the possible LOCs presented in CPR 18E [3]: the instantaneous loss of all product (G.1), the loss of all the content in a 10 minute release (G.2), or the release through a 10 mm hole during a maximum time of 30 minutes (G.3). The risk is calculated for all the tanks used to store the mass, and the maximum one is used as the final risk. This risk calculation can be expressed as:

$$r = \sum_{G=1}^{3} \max(f \cdot C : n = 1 \dots n_{max}) \quad \text{Eq. [1]}$$

The calculation of the cost and frequencies of the accidents will be discussed in the case study section, where a certain type of installation and substance will be defined.

2.1 Finding a compromise solution using multi objective optimization

The general multi-objective optimization problem is:

$$\begin{aligned} &\min_{x}[F_1(x), F_2(x), \dots, F_k(x)]^T \\ subject\ to\!: \ &g_j(x) \leq 0, \qquad j = 1,2,\dots,m \quad \text{Eq. [2]} \\ &h_l(x) = 0, \qquad l = 1,2,\dots,e \end{aligned}$$

Where ***k*** is the number of objective functions, ***m*** is the number of inequality constraints, and ***e*** is the number of equality constraints, ***x*** is the vector of decision variables. ***F(x)*** is a vector of objective functions. ***F_i(x)*** are also called objectives, criteria, payoff functions, cost functions, or value functions.

The solution to a multi-objective optimization is a set of points that satisfy Pareto optimality; however, there exists the idea of the compromise solution, which can be applied to find a single solution point. By minimizing the difference between the potential optimal and a utopia point, that is the point where all the objectives reach their minimum, the best compromise solution for all the objectives is found.

For the design optimization of storage facilities, that is a problem with few decision variables, and only two objectives, all the possible solutions can be plotted for both goals, and the one closest to the utopia point will be the optimal compromise solution. However, as both objectives are measured in different units, they will have to be normalized to correctly calculate the distance between the points. This can be done using the following equation:

$$F_i^{Trans} = \frac{F_i(x) - F_i^o}{F_i^{max} - F_i^o} \quad \text{Eq. [3]}$$

Where:

$F_i(x)$: the value of the objective function.

F_i^o: the value of the objective function in the utopia point.

F_i^{max}: the maximum value of the objective function.

3. Case Study

The case study analyzes the optimization of a facility where 19,000 kg of chlorine have to be stored; there are houses inhabited by 18 people at 300 m of distance that can be affected if an accidental release occurs. The storage and atmospheric conditions are presented in Table 1.

Table 1. Storage and Atmospheric Conditions for the Case Study

Wind velocity	5 m s^{-1}
Temperature	12 ºC
Atmospheric Stability	Type D
Humidity	70 %
Ground Roughness	10 cm
Pressure Vessel	9.5 bar

To estimate the risk associated to an installation, the costs of different possible accidents has to be evaluated, and their frequencies of occurrence known. To calculate the costs, it is necessary to know how the accidents will affect the people or property surrounding the installation, this is, the effects of the accident. To estimate the effects of a chlorine release, the ALOHA code was used, with the atmospheric and pressure conditions as input data. As the resolution of the problem has been programmed in MATLAB, an equation obtained to calculate the concentration of the gas depending on the mass released at the distance specified in the example had to be developed. In Figure 1 the dependency between concentration and mass released is shown.

From Figure 1, the following equation can be obtained:

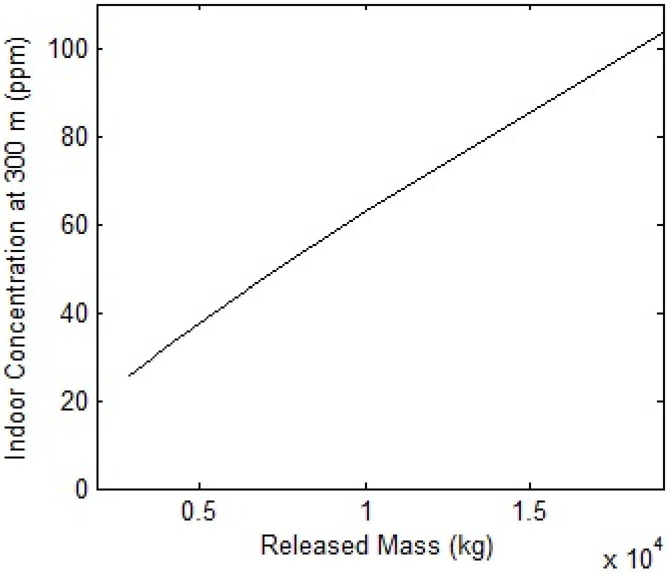
$$C = 0.076m^{0,74} \quad \text{[Eq. 4]}$$

Once the concentration is obtained, the number of affected people can be calculated using probit analysis. The probit variable **Y** associated to the fatal effects suffered by exposure to chlorine can be calculated as:

$$Y = -8.92 + 0.92 \cdot \ln \sum_i (c_i^2 \cdot \Delta t_i) \quad \text{[Eq. 5]}$$

Where:
$\boldsymbol{C_i}$ (ppm): chlorine concentration.
$\boldsymbol{\Delta t_i}$ (s): exposure time.

Figure 1: Indoor Concentration at 300 m (ppm) vs. Released Mass (kg)



Once **Y** is known, the percentage of affected people is calculated as:

$$P = 50 \cdot \left[1 + \frac{Y-5}{|Y-5|} \cdot erf\left(\frac{|Y-5|}{\sqrt{2}}\right)\right] \quad \text{[Eq. 6]}$$

Ronza et al. [4] have developed equations to calculate the number of injured people once the number of fatalities is known. For a toxic release:

$$N_i = 34 N_k^{0{,}54} \quad \text{for} \quad 1 < N_k < 30 \quad \text{[Eq. 7]}$$

Where:
$\boldsymbol{N_i}$: number of injured people.
$\boldsymbol{N_k}$: number of people that die due to the accident.

To finalize the calculation of the cost of accident, a value has to be assigned to the injury or death of a human being. This is a polemical issue, however, values that can be used for Spain, taking into account the numbers suggested by the Spanish legislation for traffic accidents have been suggested by Ronza [5]. These values have been updated taking a fixed interest rate of 4%. The average value for a fatal victim is of € 219,000 and for an injured victim € 103,000. The cost of accident consequences on human beings will be calculated as:

$$C = 219{,}000\, N_k + 103{,}000\, N_{ik} \quad \text{[Eq. 8]}$$

A chlorine release has no effect on the equipment of the plant or other material values; therefore, the cost of consequences on humans represents the total cost.

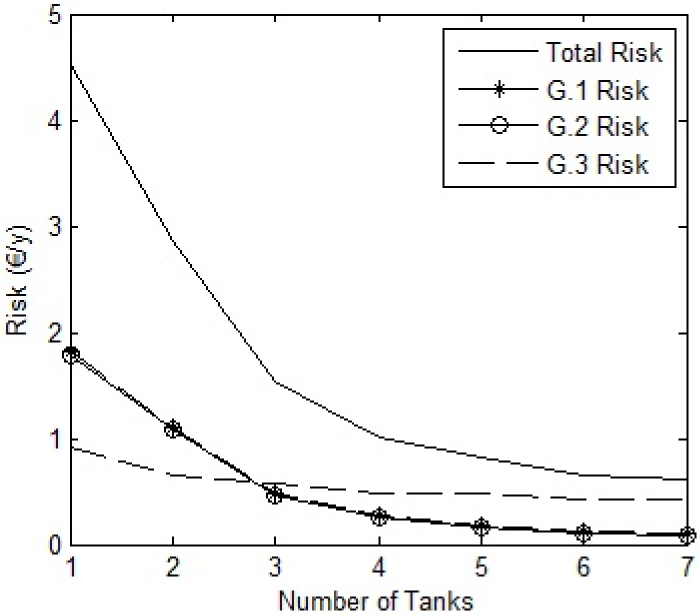
The frequencies used in this case study are those presented in CPR 18E [3] for the different types of LOCs.

Table 2. Frequencies of Different LOCs

Type of Unit	G.1	G.2	G.3
Frequency	$5 \cdot 10^{-7}$ y^{-1}	$5 \cdot 10^{-7}$ y^{-1}	$1 \cdot 10^{-5}$ y^{-1}

Once the cost of accidents are estimated, and the frequencies known, the risk associated to the facility can be calculated for different numbers of tanks using equation [1]. The results are shown in Figure 2.

Figure 2: Number of Tanks vs. Risk



The risk associated to the facility decreases as more units are built, as it is expected; this is because the mass released in possible accidents will decrease, as will the consequences of the accidents. The risk in the G.1 and G.2 scenarios are very similar, because the quantity of mass released in both cases, and the frequencies are the same; the difference between the cases is that the form in which the cloud forms and moves in both scenarios is different, as one release is instantaneous, and the other continuous. The analysis of the G.3 scenario presents an interesting opportunity from the frequency-consequences interaction point of view; when the consequences of G.1 and G.2 are severe, G.3 presents a lower value, however, as the consequences decrease for the other types of release, G.3 becomes the scenario that entrails the highest risk, and this is because of its high frequency of occurrence, that is two orders of magnitude above the G.1 and G.2 frequencies; even though the G.3 consequences will not be very severe, it occurs more often than the other scenarios, which will eventually make it the most hazardous release.

The other objective, the cost of the pressurized stainless steel tanks used to store the chlorine can be estimated using the following expression:

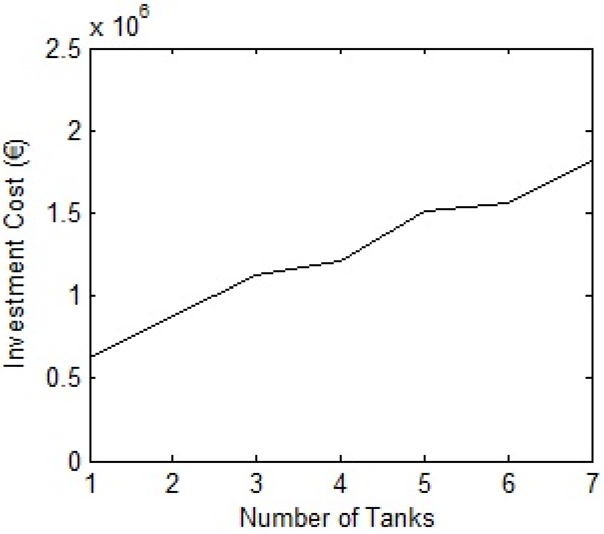
$$C_E = 85.165\left(\frac{V}{5}\right)^{0.53} \quad \text{[Eq. 9]}$$

Where:

V (m^3): volume of the tanks.

The investment cost will be estimated as the double of the cost of the tanks, accounting for instrumentation, installation, etc. Figure 3 shows how the investment cost increases as more tanks are built.

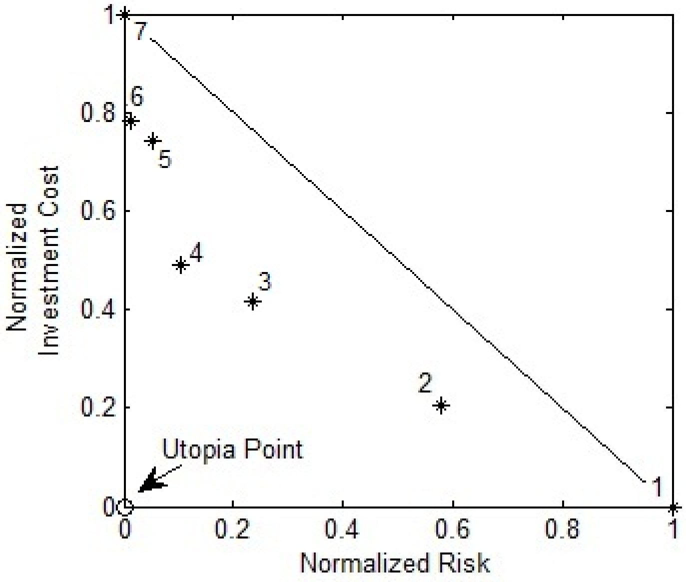
Figure 3: Number of Tanks vs. Investment Cost



The irregularities in the investment cost obey to the fact that in some cases, the volume of the tanks is the same, although more units have to be used. Also, if the volume decreases, it may be cheaper to build more tanks that are smaller.

To find the optimal solution, the normalization of both objectives for every possible decision is plotted, along with the utopia point; the result is shown in Figure 4, where each of the points that are accompanied by a number represents the decision to use that number of tanks to store the chlorine. The points located at the extremes of both axes represent the decisions that minimize one of the objectives, that is, to use only one tank, which minimizes the cost, or use seven, which minimizes the risk. The optimal solution for the case is to build 3 tanks, which is the solution closer to the utopia point, and the one that represents the best compromise between both goals.

Figure 4: Normalized Risk vs. Investment Cost



4. Conclusions

The methodology proposed allows optimizing the design of a storage installation taking into account the risk it poses to nearby populations, while also paying attention to the economic variable that exists in any project. It also demonstrates that various risk analysis and mathematical optimization techniques can be combined to introduce safety into the earliest stages of the design of storage facilities, understanding risk as the combination of consequences and frequencies of accidents.

5. References

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