Design Optimization of Storage Facilities Taking Into Account the Domino Effect

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Abstract

Storing hazardous substances is a process that entrails high risk, and in which many resources are spent in the planning of safety measures; however, safety could be included at the initial stages of the design of this type of installations, by optimizing the number of tanks that are used to store the substance. The effects and consequences of major accidents are directly proportional to the mass of materials involved in them; therefore, if the mass was divided in more containing units, the consequences at the moment of an accident occurrence would be lesser. However, as more units are used to store a dangerous substance in an installation, the risk of domino effect occurrence at the moment of an accident also increases. The objective of this paper is to develop a methodology that allows finding the optimum number of units that have to be used to store dangerous materials, taking the possibility of domino effect occurrence into account. The proposed methodology is described and applied to a case study as a decision making tool, obtaining results that demonstrate that the design of storage installations can be improved from a risk point of view, by combining quantitative risk analysis and optimization techniques.

1. Introduction

Storing hazardous materials is a necessary but risky process. Historical analysis [1] reveals that 17% of the major accidents in the chemical industry happen during the storage process, and the National Fire Protection Association (NFPA) reported [2] that in 2009, 13% of the major fire accidents that occurred in the USA happened in storage facilities, causing losses of $69,980,000. These numbers demonstrate that it is necessary to continue working on the improvement of safety in dangerous substance storage facilities.

When a process unit suffers an accident, the effects (mechanical or thermal) this event can have on the surrounding equipment can trigger subsequent waves of accidents, which can increase the consequences of the initial event significantly; this phenomenon is referred to as the domino effect, and it has been formally defined as a cascade of events in which the consequences of previous accidents are increased both spatially and temporally by following ones, thus leading to a major accident [3]. A historical analysis [4] of 225 accidents that have involved domino effect, and that occurred after 1961, analyzing origin, causes, materials involved, effects, consequences and most frequent sequences of accident as the main factors in the study revealed that thirty five percent of the accidents studied occurred in storage areas, which makes these types of installations the most prone to suffering cascading accidents, and that eighty nine percent of the accidents involved flammable materials; LPG was found to be the substance involved in more events.

The objective of this work is to propose a methodology that allows obtaining the optimum number of tanks to be used in the design of a facility where explosive or flammable materials are stored, where domino effect can take place, in order to minimize the risk associated to the facility; this is achieved by combining quantitative risk analysis and optimization techniques to calculate the risk associated to the facility, depending on the number of tanks used in the design, the mass and type of substance involved, the frequencies and possible consequences of the accidents that can occur. The methodology is based on the fact that the consequences of an accident are directly proportional to the mass of hazardous substance involved, which means that dividing the quantity of substance in more tanks will make the risk associated to the facility decrease; however, as more units are built the risk of domino effect occurring will increase. Then, an optimum number of units to use in the design can be found, for which the risk is minimized, taking into account the amount of mass involved in the accident and its consequences on vulnerable elements, and also the possibility that domino effect can occur, and will become a greater hazard as more tanks are used.

2. Methodology

To find the optimum design, a model that calculates risk based on the LOCs (and accidents that derive from them) described in the CPR 18E (Purple Book) [5] was designed, monetizing the consequences of the possible accidents and multiplying these costs by their frequencies of occurrence, to later choose the maximum risk derived from all the studied accidents, which will be the risk associated to the facility. Domino effect is studied and included in the methodology using a threshold approach: if the effects of a previous accident on another tank are higher than, or equal to a certain value, then this second unit will suffer another loss of containment event, that will lead (with a certain probability) to another set of accidents, and an increase in risk.

2.1 Modeling the domino effect

Various works have been published on the subject of effectively modeling domino effect by different researchers, like Khan, Abassi, Antonioni or Cozanni; samples of their work can be found in [6], [7], and [8]. These works have served as guidelines for the domino effect risk calculation model developed in this work; however, none of them could actually be used, as a new tool had to be developed that could be used within the framework of the design optimization methodology.

Modeling the domino effect is very difficult because it is a phenomenon that does not follow a determined pattern, and that depends on many variables, several of which have not been studied. To accurately describe this phenomenon all the possible accidents that could occur (taking into account that several events could occur at the same time) have to be defined, as must also be their effects and consequences over the vulnerable elements inside and outside of the installation.

Developing a methodology that follows the evolution of an accident from its start to its final consequences, estimating the probabilities, effects and consequences of all the possible occurrences in space and time would be highly taxing, this is why some simplifications have to be made to make possible the modeling of the domino effect in a quick but effective way. In this work, the domino effect is used as a way to describe how risk can increase or decrease for an installation when more or less equipment are used in the design, theorizing that an optimal number of units, for which the risk is minimum, must exist; to achieve this description in a satisfactory degree, the knowledge of the way in which the phenomenon changes in time was not totally necessary, and added a different level of complexity to the modeling, as the time evolution of an accident might depend on human response, location of the plant and the human emergency response teams, or the security measures of the installation, factors that would have to be studied and modeled; this led to the time aspect of the phenomenon being mostly omitted in the methodology proposed.

Domino effect can be caused by the thermal and mechanical effects of an initial accident; the thermal effect can come as the result of a jet fire, a fireball, a flash fire or a pool fire; the mechanical effects can be the overpressure wave of any explosion or the projectiles that result from an equipment's explosion. There are cases in which both thermal and mechanical effects can be present. For this work, modeling the domino effect will consist on defining various possible accident sequences that can occur. The first step to achieve modeling the phenomenon studied is to define the initial accident, which was done by using the LOCs presented in the CPR 18E; these were used to define which would be the initial types of releases that could occur, and what their frequencies would be.

Table 1. LOCs used to define initial accidents

Code	Definition
G.1	Instantaneous release of the complete inventory.
G.2	Continuous release of the complete inventory in 10 min at a constant rate of release.
G.3	Continuous release from a hole with an effective diameter of 10 mm.

Table 2. Frequencies for initial LOCs

Type of Unit	G.1	G.2	G.3
Pressure Vessel	$5 \cdot 10^{-7}\ y^{-1}$	$5 \cdot 10^{-7}\ y^{-1}$	$1 \cdot 10^{-5}\ y^{-1}$
Process Vessel	$5 \cdot 10^{-6}\ y^{-1}$	$5 \cdot 10^{-6}\ y^{-1}$	$1 \cdot 10^{-4}\ y^{-1}$
Reactor Vessel	$5 \cdot 10^{-6}\ y^{-1}$	$5 \cdot 10^{-6}\ y^{-1}$	$1 \cdot 10^{-4}\ y^{-1}$

Two different types of release can occur in the LOCs: instantaneous and continuous. Each of them has an associated event tree, which specifies the probability of different possible accidents; these trees can also be found in the CPR 18E or in the reference manual Bevi Risk Assessments [9]. This communication relates to storage facilities of pressurized flammable gases, and therefore, the event trees shown are the ones that relate to this type of substance.

Figure 1: Event Tree for the Instantaneous Release of a Pressurized Flammable Gas

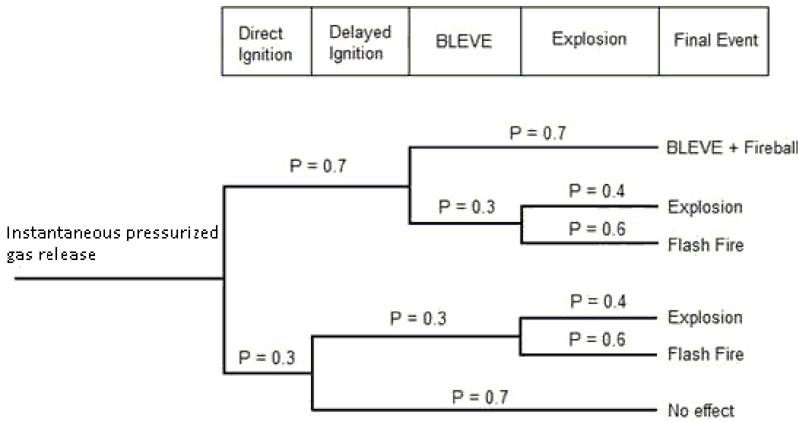
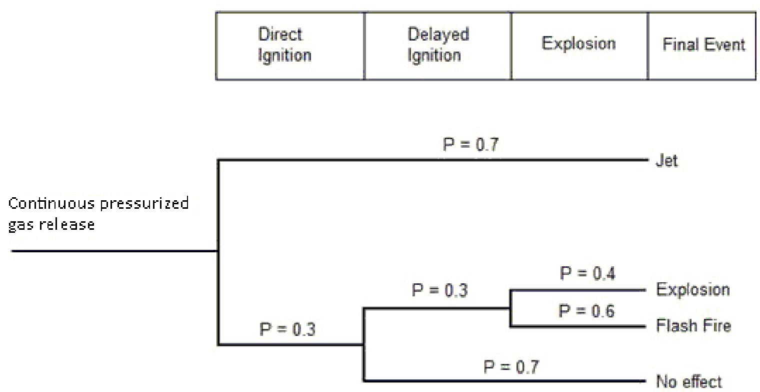


Figure 2: Event Tree for the Continuous Release of a Pressurized Flammable Gas



The event trees in figures 1 and 2 are for a source term superior to 10,000 kg for the instantaneous and to 100 kg/s for the continuous release.

Once the initial accidents that might occur and their frequencies are determined, the next step to define the domino sequence is to calculate the effects these accidents will have on the units that are surrounding the tank that suffers the first event, to know if they suffer damage, and what accidents might happen as a consequence of the initial one. To define the way in which other equipment might be affected, the same LOCs as for the original accident were used, combined with threshold values that allow knowing what type of release occurs in the affected units; for example, if a continuous release that leads to an explosion occurs in a tank, and the overpressure wave that a second unit receives as a result from the initial accident is higher than a certain threshold value, another release, instantaneous or continuous, depending on the magnitude of the wave will occur on the second tank, which might lead to more accidents. The threshold values used for the model are presented in table 3.

Table 3. Threshold values and associated accidents used in the model

Accident	Effect	Threshold	Consequence on Pressurized Tanks
BLEVE	Thermal Radiation (kW/m^2)	≥ 100	G.3 type release
		< 100	No consequence
VCE	Overpressure Wave (kPa)	≥ 109	G.1 type release
		$80 < \Delta P \leq 109$	G.2 type release
		$30 \leq \Delta P \leq 80$	G.3 type release
		$\Delta P < 30$	No consequence
Jet	Jet length Duration of jet (min)	$d_j \geq d$	G.1 type release
		$d_j < d$ & $t_j \geq 10$	G.3 type release
		$d_j < d$ & $t_j < 10$	No consequence
Flash	-	-	No consequence
Pool	Thermal Radiation (kW/m^2) Pool duration (min)	$I \geq 40$ & $t_p \geq 10$	G.1 type release
		$20 \leq I < 40$ & $t_p \geq 10$	G.2 type release
		$8 \leq I < 20$ & $t_p \geq 10$	G.3 type release
		$I < 8$	No consequence
d_j = jet length; d = distance between tanks; t_j = duration of jet; t_p = pool duration			

Flash fires are not considered to have significant effects or consequences on other equipment, because of their short duration, even though the radiation they emit might be high. Jet fires have been evaluated for domino potential according to their length and duration time; then, if a tank suffers a BLEVE, and a surrounding unit receives more than 100 kW/m^2 of thermal radiation, a second release of the complete contents, or the mass released in a maximum time of 30 min, of the affected unit through a 10 mm effective diameter hole will occur, which might result in another one of the final events shown in figure 2, unleashing new accidents in other equipment. Projectiles were not included in the calculations because there are no models that can be applied to accurately describe their trajectory or radius of effect. One of the vital aspects to modeling the domino effect is the frequency of occurrence of the accidents, which will eventually allow calculating the risk and stopping the sequence of events at a certain point. The domino sequences in this model are arranged as event trees in which the probabilities of accidents are dragged through every level, so that the next one will have a lower probability as more levels are generated. If the example given takes place, and a G.3 release occurs in a tank, resulting from a G.1 release in another, the event tree of the G.3 scenario will drag the probabilities of the initial one, and the frequency of the first release; when an accident down the domino sequence occurs with a probability lower than $1 \cdot 10^{-8}$ it is no longer taken into account as a possible initiator of other accidents.

Finally, the model in which the domino sequences are generated, only consists of two steps, the first one is to define the initial accidents that might occur, and the second, which will be repeated until all the equipment are affected, or the accidents have a frequency lower than $1 \cdot 10^{-8}$, is to calculate how the surrounding equipment are affected by the previous event.

To implement this methodology a program was developed in MATLAB, in which the installation is defined by setting the number of tanks, their coordinates and the substance and quantity that will be stored; the program then calculates the distance between the units, and starts generating domino scenarios. It will calculate the possible sequences by starting all the possible LOCs in each one of the units and following the accidents until there are no more units to be affected, or the frequency of the accidents becomes too low. The main advantage of programming this methodology is that it generates all the sequences in a short time, and allows the occurrence of multiple accidents, so the failure in one of the tanks might affect various tanks at the same time, or only some of them, depending on their positions. Then, it is obvious that an intelligent positional design, regarding safety distances and containing dikes for pools must be introduced every time the program is used, as the domino sequences, and therefore, the risk, will depend on the positions of the units.

2.2 Risk associated to the installation

The risk calculated in this methodology must take into account the frequencies and consequences of all the possible accidents that might occur in the domino sequences that are generated after each one of the initial release events take place. The risk will be evaluated for each of the tanks, using all the possible initial types of releases; the risk associated to the installation will be the sum of the maximum risks obtained for the initial releases.

$$\mathrm{r} = \sum_{\mathrm{G}=1}^{3} \max\left((\mathrm{f} \cdot \mathrm{C}) : \mathrm{i} = 1 \cdots \mathrm{n}\right) \quad \text{[Eq. 1]}$$

Where ***G*** represents each one of the possible initial LOCs, ***f*** and ***C*** are the frequencies and economic costs of the possible accidents and ***n*** is the number of tanks.

The frequencies of accidents have already been discussed. To estimate the cost of an accident, its effects and consequences over humans, the environment, equipment and other material values have to be determined. In this paper, the following models were used to estimate the effects of accidents: solid flame model for effects of fire, TNT equivalent mass for explosion blasts and the ALOHA code for atmospheric releases of gases. The consequences of accidents on human life have been calculated using probit analysis, while the consequences on the environment have not been taken into account; the consequences on other equipment after an accident occurs are defined using threshold values, as is discussed in the previous section. Only BLEVE, explosions and flash accidents have effects on people, while all of the accidents, except the flash, can affect other equipment.

The estimation of the cost of human life is a delicate subject; it has been decided to assign an economical value to the death or injury of a person based on the numbers suggested by the Spanish legislation for traffic accidents. The cost of the consequences of an accident on human life will be:

$$C_H = 219{,}000\ N_k + 103{,}000\ N_{ik} \quad \text{[Eq. 2]}$$

Where:
N_k is the number of people that die due to the accident.
N_{ik} is the number of people that result injured from the accident.

The economic value of a tank is estimated using a power law:

$$C_E = 85{,}165 \left(\frac{V}{5}\right)^{0.53} \quad \text{[Eq. 3]}$$

Where:
V (m^3): volume of the tank.

2.3 Design Optimization

The objective function of the optimization will be the risk associated to the installation; the optimization consists on calculating this risk for different decisions, like using one, two or any possible number of tanks to store the mass, and check which one of these decisions represents the lower risk, while complying with an individual risk constraint; the design that is chosen has to have and individual risk lower than $1 \cdot 10^{-6}$. The individual risk is calculated as the overall risk, but instead of using the product of frequency and cost, only the number of fatal victims caused by the accident is used.

$$R_i = \sum_{G=1}^{3} \max\,(n_k\colon i = 1 \cdots n) \quad \text{[Eq. 4]}$$

3. Case Study

The example case deals with the design of an LPG storage installation with an area of 1,200 m^2, where 50,000 kg of propane will be stored. There are three nearby areas where people can be affected if an accident occurs in the installation; the first one, located at a distance of 403 m, where 40 persons can be affected, the second one, at 430 m, where there are 30 people, and the third one, at a distance of 302 m, where there are another 30 people. It is necessary to determine the optimum design of the installation. The storing and atmospheric conditions are presented in table 4.

The program developed in MATLAB during this work was used to solve the problem, calculating the risk associated to the installation for different designs: from using one tank to store all the mass, to divide the substance in six units. In every design, safety measures like containment dikes were taken into account; also, the tanks were located as far from each other as possible. The risk results are shown in figure 3.

Table 4. Case study storage and atmospheric conditions

Temperature (K)	298.15
Relative humidity (%)	70
Atmospheric stability class	D
Wind velocity (m/s)	5
Ground roughness coefficient (cm)	10
Tank pressure (bar)	9.51
Tank temperature (K)	298.15

The minimum risk is achieved when the mass is stored in 5 tanks. The risk associated to the instantaneous release (G.1) decreases as more tanks are built, becoming nearly asymptotic at 4 tanks; the significant decline in risk for this release, from 1 to 2 and 3 tanks is due to the fact that the consequences of the accidents become less severe as more units are built; however, the possibility of risk due to domino effect also increases as more tanks are used to store the mass, which is the reason why the curve stops decreasing at a certain point.

Figure 3: Number of Tanks vs. Risk

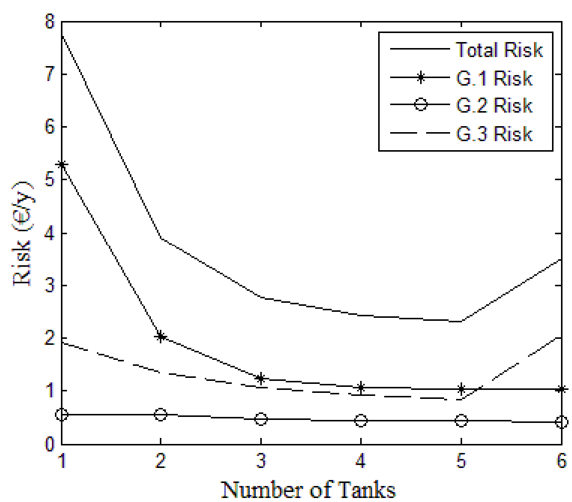
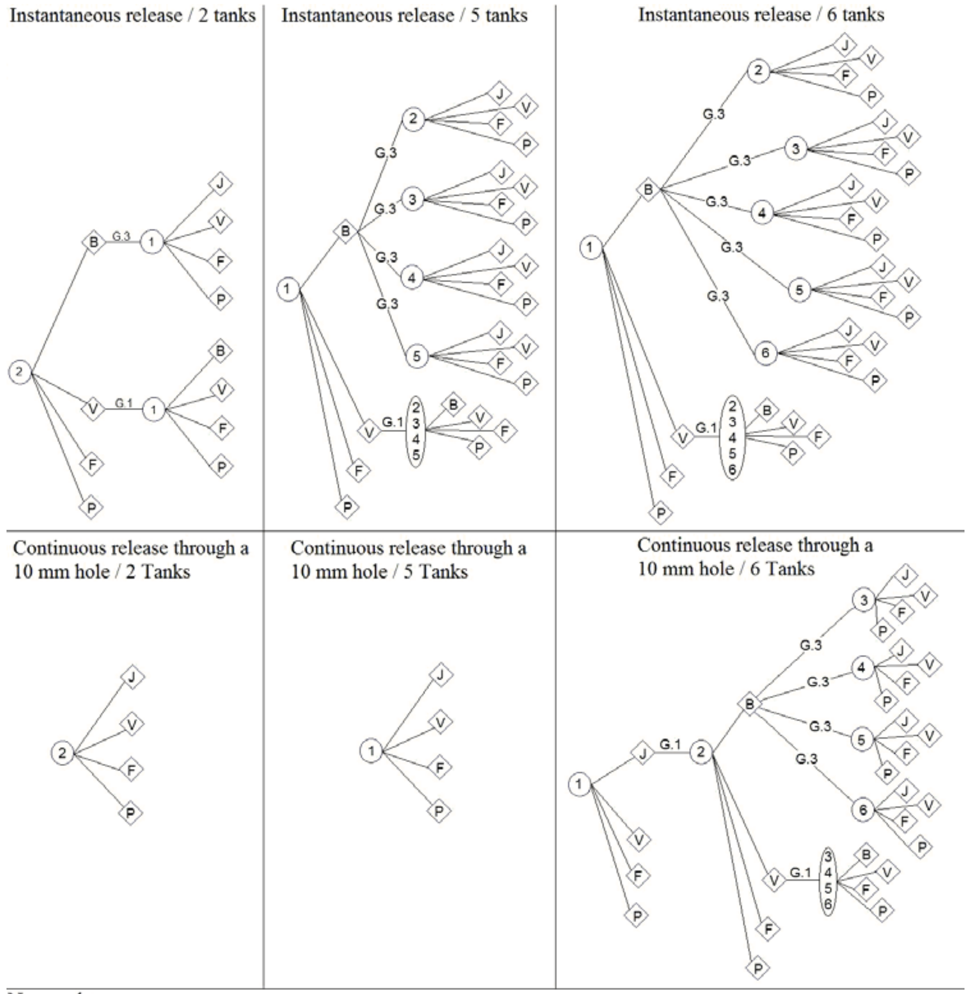


Figure 4 shows how the domino sequences change when using 2, 5 or 6 tanks to store the mass for the G.1 and G.3 releases. The circles represent tanks that suffer LOCs, while the diamonds represent accidents that can occur after said events. The circle from which all the sequence expands is the tank that suffers the initial release. The sequences showed represent the highest risk for the decisions.

For the instantaneous release, when using 2 tanks, there are many less possible accidents than when 5 or 6 tanks are used, but with more significant consequences and higher frequencies of occurrence, which is why the risk for this type of release is higher when using a pair of units. Comparing the accident propagation diagrams that result from using 5 or 6 tanks, it is noticeable that they are very similar, as also are the values of risk; when using 6 tanks, one more unit can suffer damage resulting from previous accidents, however, as more tanks are used their individual cost will decrease, this is the reason why the risk for this type of release remains steady when using 5 or 6 units.

Figure 4: Domino Effect Sequences



Nomenclature:

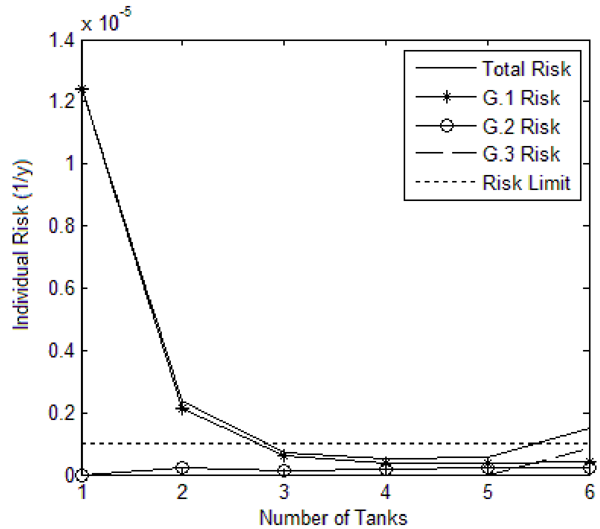
J: Jet fire; B: BLEVE accident; V: Vapour Cloud Explosion; F: Flash Fire; P: Pool Fire

The G.2 scenario is not as relevant for the decision as the other ones, as the risk does not suffer significant changes no matter how many tanks are used. This type of release has a lower risk value than the instantaneous because the BLEVE scenario, which represents a grave danger to the people, does not appear as one of the accidents that can occur after the initial release. Also, the frequency of this type of release is very low compared to the G.3 type, which makes it less hazardous. The combination of low frequency of occurrence, and less significant consequences on the population for the possible initial accidents make this type of release less hazardous than the other two.

The continuous release through a 10 mm hole represents, for many of the decisions, the second most hazardous type of discharge, due to its high frequency of occurrence (two orders of magnitude above the other releases frequencies) even though its effects and consequences are a lot less significant than those of the G.1 and G.2 discharges. As more tanks are built the risk decreases, except for the 6 tanks design, that has a very high risk value, even superior to that of the instantaneous release. This is a direct consequence of the domino effect; as can be seen in figure 4, for 2 and 5 tanks the G.3 scenario does not present domino effect, no further accidents are caused by the initial release; however, when 6 units are used to store the mass a domino effect occurs, as a jet originated in tank 1 may impact tank 2, leading to an instantaneous release in this equipment, and to further releases and accidents in other tanks. The domino effect occurs because the distance between the tanks becomes smaller as more units are used, and its occurrence, coupled to the high initial frequency of this type of release, results in a high risk value.

To reach the final decision, the individual risk analysis must be performed. As figure 5 shows, the decisions that comply with the restriction are the use of 3, 4 or 5 tanks to store the propane.

Figure 5: Number of Tanks vs. Individual Risk

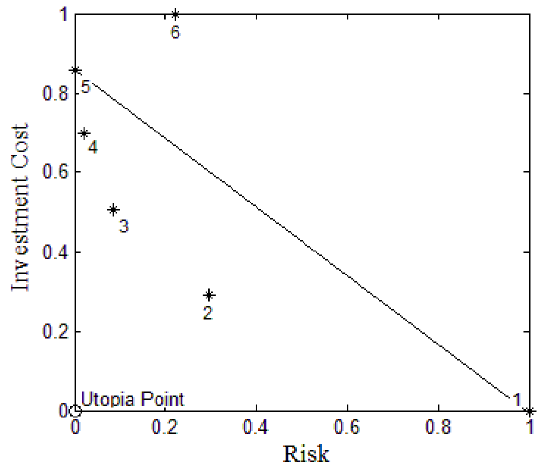


2.2 *Including the economic investment factor in the optimization*

Using five tanks to store the propane would be the optimal solution from a risk point of view; however, in engineering projects, various factors, one of them being the economics of the project, have to be taken into account.

It is clear that the decrease in risk between using 3 or 5 tanks is not very significant, but the investment made to build the facility might be. Then, a multi-objective optimization can be performed to find which decision optimizes both the risk and the investment. This second objective will be estimated as the double of the cost of the tanks. The result of this optimization is shown in figure 6. In this graphic, a normalization of both objectives is represented; the points inside the graph represent different decisions, accompanied by their respective number of tanks; the point in the origin of the axis is the utopian point, which represents the minimization of both objectives, and the decision that is more close to this point will be the one that minimizes both objectives.

Figure 6: Normalized Risk vs. Investment Cost



The closest decision to the utopian point in figure 6 is 2 tanks, but it cannot be used due to the individual risk restriction; therefore, the optimal solution for this problem is to use 3 tanks to store the propane.

4. Conclusions

The results obtained in this work demonstrate that the optimum number of units used to store a hazardous material can be found, and that quantitative risk analysis can be paired with mathematical optimization to form a powerful design tool for this type of process.

A new methodology that allows modeling the domino effect has been developed; it is simple and easy to use, and it is based on highly used concepts of risk analysis, like event trees. Of course, more investigation should be made regarding this phenomenon, which has many more dimensions than those addressed in this paper. It is a highly complex occurrence that can impact the design of an installation, and the risk associated to it in a very significant way. Another conclusion that can be gathered, is that when more equipment are built in less space, the risk associated to the project can increase greatly, not because of the more spectacular accidents like fireballs and explosions, but because of a small release, that can later escalate to cause more serious accidents and losses of containment; this occurs in the case study when the possibility to use 6 tanks inside the limited space of the installation is evaluated.

The methodology presented helps proving the fact that performing risk analysis in the initial stages of a project can help saving lives and resources, and that it is necessary to integrate risk analysis into all the design stages of engineering projects.

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