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Design optimization of hazardous substance storage facilities to minimize project risk

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ABSTRACT

The storage of dangerous substances is a high risk procedure: a historical analysis revealed that 17% of the major accidents associated with the chemical industry are related to this process. When a storage facility is designed, the investment in safety is not always optimal. The safety measures that are applied are sometimes redundant or ill-maintained. One way to improve safety in a storage facility would be to take advantage of the fact that dividing the mass of dangerous substance results in less catastrophic accidents. In this paper, we present a new method for optimizing the design of storage plants and minimizing the risk by calculating the ideal number of tanks and improving the way in which money is invested in safety. This is achieved by redefining how to estimate risk and by applying the principles of mathematical optimization to quantitative risk analysis. The method is explained step by step. We also present two case studies and a validation of the method using risk analysis software and iso-risk curves.

1. Introduction

The storage of dangerous substances is a process that comprises significant risks. A historical analysis (Casal and Vílchez, 2010) revealed that 17% of the major accidents in the chemical industry happen during the storage process. The National Fire Protection Association (NFPA) reported (Badger, 2010) that in 2009, 13% of the major fire accidents that occurred in the USA happened in storage facilities, causing $69,980,000 in losses. These papers demonstrate that there are still improvements to be made in the storage of dangerous substances, as accidents in this process continue to occur and the losses caused by such events are substantial.

During the design of a project that includes a storage facility, a vast amount of resources are invested in security measures that are meant to prevent a major accident from occurring in the storage units. These measures can make the project significantly more expensive. They include different types of fire protection, pressure relief valves and insulation. Sometimes these protective measures are not applied correctly, and they are occasionally redundant or ineffective. This problem of obtaining the optimum set of protective measures for a plant has been studied by Caputo et al. (2011). At other times, safety equipment, such as fire protection systems, are not maintained properly and therefore cannot prevent accidents. At the time of a major accident, the wrong design, application or maintenance of safety measures results in double loss of money, as the investment in the devices is worthless if they are ineffective. Even when money is spent on the design, purchase and installation of security devices, they may not work as expected, and are often damaged or destroyed during an accident. This adds to the losses caused by the event.

One aspect of the process of storing dangerous substances is usually not taken into account during a project's design phase: the consequences of a major accident are inversely proportional to the mass of substance involved. Therefore, an accident will have less impact if the mass is divided into more containment units. This aspect can be addressed before the previously mentioned security measures are developed and implemented. In fact, we should be able to determine the optimal number of containment units when a storage facility is designed. This optimal way of dividing the mass means that if an accident happens, the cost of the consequences of the event will be lower than the cost of the investment in designing and building the facility, including the security measures that are deemed necessary to ensure the safety of the project.

In this paper, we develop and describe a new way of quantifying the risk associated with a storage facility for dangerous substances. This measure of risk allows us to combine the cost of consequences and the probabilities of different accidents occurring. It can be formulated as a function that depends on the number of tanks used to store the dangerous material. This function can be evaluated for different cases, in which one, two or n units are used to store the mass. As more units are built, the consequences of the most likely accidents will diminish, but there will be more possible accidents, and the overall frequency of occurrences will increase. In addition, the financial investment in the project will increase as more units are used. Thus, a theoretical optimal can be reached, at which the

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Nomenclature

C	concentration of toxic substance (ppm)	n_{ik}	number of injured people (–)
C_E	cost of equipment (€)	n_k	number of fatalities (–)
C_H	cost of accident consequences on human beings (€)	I	thermal radiation intensity (W m^{-2})
C_{Str}	cost of accident consequences on structures (€)	P	probability of independent failure (–)
C_T	total cost of accident (€)	r	risk associated to a project (€/year)
erf	error function (–)	ri	individual risk (fatalities/year)
f	frequency of accident occurrence (year^{-1})	r_{inv}	investment risk (€/year)
n	number of storage tanks (–)	t	time (min or s)
n_{Col}	number of structures that collapse (–)	V	volume of storage tank (m^3)
n_{Dam}	number of structures that suffer structural damage (–)	Y	probit variable (–)
n_f	number of tanks that fail (–)	ΔP	peak overpressure (Pa)

weighted costs of accidents for different designs of the facility are lower than the investment that is required. In other words, the facility will be designed so that the cost of the most likely accidents will never be higher than the investment that is made. A review of previous work developed in the subject is presented, and a new approach to calculating risk is described. Then, the optimization procedure that allows obtaining the minimum risk for a storage facility, depending on its design, is presented. Finally, the method is applied to two case studies and validated through the use of risk analysis software.

2. Design optimization and risk analysis

The combination of mathematical optimization and risk analysis applied to the improvement of the design of industrial processes is a relatively new field of investigation, in which not many articles have been published, most of them having no relation to one another in the methodologies developed, and in the problems addressed. A short review of some of these articles has been carried out.

The problem of applying mathematical optimization to risk analysis in order to find an optimal value between the potential costs of accidents that can occur and the expenses made in some sort of safety measure, to find the optimal design of an installation, has already been approached by Medina et al. (2009); this article is reviewed later on in Section 2.1 in a more detailed level, as it is of great importance to the methodology presented in this communication.

Another interesting contribution in this field was that presented by Young Lee et al. (2005), involving optimization, risk analysis and the study of the domino effect. The main idea of the paper was that it would be possible to develop an algorithm to optimally allocate explosive facilities when designing a chemical process plant, in order to minimize the possibility of domino effect occurrence in the event of a catastrophic accident; the methodology was developed for a case where the facilities have to be placed in a restricted rectangular surface. The objective was to develop a computer programmed module enabling to determine the optimal positioning of explosive facilities to minimize the possibility of domino effect, using nonlinear methods and considering that the domino sequence can occur due to thermal radiation, overpressure and missile impact on equipment. It was considered in this work that the thermal and overpressure effects of an accident are proportional to r^{-2} and that the missile impact is proportional to e^{-r}, where r is the distance between the object that suffers the accident and the surface affected; the height of the facilities is not taken into account. The problem was described as having the n-explosive facilities of the same type, such as storage tanks, in an arbitrary rectangular space in which they have to be placed; the installations have initially defined placement points and the same explosion probability. An objective function was presented that calculates the probability of domino effect as a function of the distance between the facilities; this function will have to be minimized in order to find the optimal solution to the problem. This was achieved by using the gradient descent method. This paper presented a series of numerical experiments in which different numbers of facilities were placed in a rectangular space, and concluded that the module developed can be used as a part of a decision support system to prevent domino accidents.

Another problem that is often found in the risk analysis optimization landscape is "the valve location problem", which objective is to find the optimal location of shut-off valves in an oil pipeline, to minimize the consequences a spill could have on the environment. Pipelines are fitted whit shut-off valves to control oil spills, so every time that a loss of pressure is registered, the valves will automatically shut the line. This means that a possible spill is limited to the volume of the pipe section enclosed between two valves; therefore, it is possible to find an optimal distribution of valves that will minimize the environmental consequences of a loss of containment. This problem has been studied by Grigoriev and Grigorieva (2009) and Medina et al. (2012) using different approaches for the quantification of the cost of environment and the way in which the optimization is solved. Both groups of researchers apply their methods to different case studies and find solutions that optimize the number and positions of shut-off valves across oil pipelines.

Another work that deals with risk analysis and optimization is the previously mentioned paper by Caputo et al. (2011), which proposes a methodology to find the optimal combination of safety measures taking that a unit should be equipped with, taking into account the possible accidents that can occur in it.

Risk analysis can also be used to optimize a process in regards to the land use planning of the zone in which the plant will be located, to define threat and affectation zones of major accidents and comply with the legislation of the country in which the installation will be located. This point is more broadly discussed in Section 8, in which the synergy between land use planning and the methodology is addressed.

The optimization of chemical processes and plants from the point of view of risk analysis is a field in which there is many room for improvement, and that can have a direct impact in the way in which process design is currently carried out. It can be used to take into account the negative impact that an installation could have on different vulnerable elements, whether human, environmental or material, during its design, to optimize it, so that this impact is