Journal of Loss Prevention in the Process Industries 26 (2013) 887–894

Contents lists available at SciVerse ScienceDirect

Journal of Loss Prevention in the Process Industries

journal homepage: www.elsevier.com/locate/jlp

An approach for domino effect reduction based on optimal layouts

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ARTICLE INFO

Article history:
Received 5 October 2012
Accepted 5 November 2012

Keywords:
Probit function
Layout
Domino effect
Risk reduction
Explosion
Overpressure

ABSTRACT

An approach to reduce the probability of producing a domino effect in process industry is developed in this work. It is assumed that optimal layouts should include appropriate analysis to reduce risk during the process design stage. The model developed for this approach combines the estimation of probability of damage due to overpressure, proposed by Mingguang and Juncheng (2008), and escalation threshold values defined by Cozzani, Gubinelli, and Salzano (2006). These equations are combined with other typical layout constraints as well as bounding the probability constraint, which has resulted in a highly non-linear MINLP problem. Solving a case study used by other authors provides evidence for reliability of the developed approach. In this way, layouts are designed to reduce the escalation probability yielding safe distributions.

1. Introduction

Given the continuous worldwide population increase, the needs of food, raw materials and energy continue increasing every day. Several industrial plants for processing and storage are, and more will be, installed to satisfy these needs. The inherent problem is the amount of hazardous materials handled in these installations and their sudden releases of hazardous material may affect health of people, structures and the environment. In many cases, an initial accident may damage nearby equipment to produce what is known as a "domino effect". The most commonly used definitions of domino effect have been summed up in Abdolhamidzadeh et al. (Abdolhamidzadeh, Abbasi, Rashtchian, & Abbasi, 2011). In this work, the domino effect is defined as the accident in which a process unit is affected in a primary scenario and its damage affects at least another process unit (Cozzani, Gubinelli, & Salzano, 2006b). Statistical studies show that the number of domino effects continues growing particularly in developing countries (Kourniotis, Kiranoudis, & Markatos, 2000). Much of the research on domino effect are aimed to evaluate consequences, probability of damage to equipment, to prevent domino accidents by inherent safety designs, and to implement active and passive protection barriers (Antonioni, Spadoni, & Cozzani, 2009; Cozzani & Salzano, 2004b, 2004a, 2004c; Cozzani, Gubinelli, & Salzano, 2006; Cozzani, Gubinelli, Antonioni, Spadoni, & Zanelli, 2005; Cozzani, Tugnoli, & Salzano, 2007; Cozzani, Tugnoli, & Salzano, 2009; Gubinelli, Zanelli, & Cozzani, 2004; Khan & Abbasi, 1998b; Mingguang & Juncheng, 2008; Salzano & Cozzani, 2005; Salzano & Cozzani, 2006). Other authors have developed software to assess the likelihood of damage and consequences in cascaded accidents (Cozzani, Antonioni, & Spadoni, 2006; Khan & Abbasi, 1998a; Reniers & Dullaert, 2007). Some work has been focused in developing strategies to evaluate the domino effect not only inside the industrial areas but also to prevent external effects (Reniers, 2010; Reniers, Dullaert, Ale, & Soudan, 2005, 2008, 2009). An interesting assessment tool in domino effects by indexing inherent safety appeared recently (Tugnoli, Khan, Amyotte, & Cozzani, 2008a, 2008b).

Nowadays many chemical plants are operating with a high probability of domino effect since its possibility was not analyzed during their design step. In most of these cases, actions could be taken to just mitigate this effect through safeguards. Safeguards such as bunds, fire walls, blast wall, gas detectors, etc. are intended to mitigate loss of containment accidents to avoid domino escalation mechanisms. These mechanisms include thermal radiation, propagation of fire, overpressure, etc. Then the possibility of domino effect depends on the safeguards effectiveness. On the

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http://dx.doi.org/10.1016/j.jlp.2012.11.001

other hand, domino effects can be prevented during the layout design stage of new plants. For instance, new designs should consider safe separation distances among process units, segregation policies, and designs of robust security systems including both passive and active devices.

Experience indicates that facility siting plays a very important role in risk reduction and consequences of accidents as well as in plant costs (Mannan, 2005; Mannan, West, & Berwanger, 2007; Mecklenburgh, 1985). The main purpose for layout or facility siting aims to find the best allocation for each process unit within an installation, as well as the temporary or permanent allocation of buildings such as control rooms and administrative offices. Earlier layouts were intended to just minimize the occupied area and interconnection costs since experience has indicated that piping cost can typically be as much as 80% of the total purchase of units (Peters, Timmerhaus, & West, 2003), whereas 15–70% of the total operation cost depends on the layout (Tompkins et al., 1996). A review of the work done for the facility siting problem, including modeling and methodologies for solution, has been already presented somewhere else (Singh & Sharma, 2006). Unfortunately the layout design had omitted the safety point of view, since the rules were mainly based on industrial practice and simple guidelines or empirical rules from operational issues. Tables containing conventional segregation distances for various process units are traditionally used in this regard (CCPS, 2003). More recently, some authors have developed solutions to the layout problem based on safety issues (Díaz-Ovalle, Vázquez-Román, & Mannan, 2010; Penteado & Ciric, 1996; Patsiatzis, Knight, & Papageorgiou, 2004; Vázquez-Román, Lee, Jung, & Mannan, 2010). However, none has included the possibility of reducing the domino effect during this layout design step.

It is now clear that the plant layout plays an important role in the safety of chemical plants. Therefore, it is considered here that all previous layout approaches should be extended to include related methodologies to prevent domino effects and thus produce real optimal layouts. This work presents an approach to produce inherently safer layouts by including the probability of domino effect by explosion in a model, which is consequently optimized. The proposed model combines the estimation of probability of damage due to overpressure, proposed by Mingguang and Juncheng (2008), and escalation threshold values defined by Cozzani et al. (Cozzani, Gubinelli, et al., 2006).

2. Estimation of probability of damage

Historical data have shown that overpressure is an important factor to produce domino effect in process units (Jacobson, Hujo, & Molinero, 2010; Kletz, 2009). Overpressure is produced when an explosion occurs. Several authors have developed proposals to assess the probability of damage due to excess pressure (Cozzani & Salzano, 2004b; Khan, Asad, & Abbasi, 2001). Most stochastic approaches involving safety issues are based in the probit model such as the one applicable to damage due to overpressure:

$$Y_{i,j} = a_k + b_k \ln\left(\Delta P_{i,j}\right) \tag{1}$$

where $Y_{i,j}$ is the probit variable to estimate the damage on process unit j having a k-unit type due to the overpressure produced by explosion of unit i, $\Delta P_{i,j}$ is the peak static overpressure (Pa), and a_k and b_k are coefficients of the model.

The probit model is well known and it has been applied to assess human response to different scenarios not only due to overpressure but also due to thermal radiation and toxic effects. Overpressure analysis used here is included in the assessment of damage to equipment. The coefficients of the probit function are obtained after statistical treatment of data, which comes from historical records of accidents and scaling data from experiments. The first improvements to the model in this direction were made by Khan and Abbasi (1998a), who proposed to assess the likelihood of damage with the total pressure, i.e. the sum of the static pressure and dynamic pressure. Subsequently, Cozzani and Salzano (2004b) gave a classification of the process units and assigned levels of damage with very good results. Latter, Mingguang and Juncheng (2008) proposed a new classification of data and damage levels to produce a better fit. Some probit features and suggested threshold values of chemical process units, reported by these authors, have been used in this work, Table 1. However, it should be clear that having any structural damage does not necessarily cause a scenario scaling. To avoid an escalation, the percentage of damage must be substantial. Cozzani et al. (Cozzani, Gubinelli, et al., 2006; Salzano & Cozzani, 2006) have defined threshold escalation values for different units intended to represent the sufficient percentage of structural damage to produce escalation. The probability of damage could be estimated by solving:

$$P_{D_{i,j}} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Y-5} \exp\left[-\frac{V^2}{2}\right] dV \tag{2}$$

where V is the random variable.

The above equation has been numerically approximated (Vilchez, Montiel, Casal, & Arnaldos, 2001). Yet the resulting equation is highly non-linear and introduces numerical difficulties to produce optimal solutions. In this work, the equation proposed by Mingguang and Juncheng (2008) is used for the sake of simplicity to easy the optimization job:

$$P_{D_{i,j}} = \frac{1.005}{1 + e^{-\left(\frac{Y_{i,j} - 5.004}{0.6120}\right)}} \tag{3}$$

Equation (3) yields a fitting error in the order of 1.0×10^{-3}, which is not substantially high in comparison to the 1.6×10^{-3} produced in an analytical estimation (Vilchez et al., 2001).

3. Overpressure estimation

An explosion represents an instantaneous release of a large amount of energy, which manifests itself in the form of heat, blast wave, light, and emission of gases in a reduced time interval. Explosions can be of various types: condensed phase explosions such as explosive charges, confined explosions such as dust and gas explosion within equipment or buildings, boiling-liquid expanding-vapor explosions (BLEVE), runaway reaction explosions, physical explosions such as bursting of overfilled vessels, unconfined and partially confined vapor clouds (VCE) (Cozzani & Salzano, 2004b). All explosive phenomena produce blast waves around their occurrence. Blast waves damaging process units are related to the incident static overpressure (ΔP), to the positive impulse and to drag forces on bodies, which in turn are strongly depending on

Table 1
Probit function and suggested thresholds values of process vessels.

Type of vessel	Probit function	Threshold values of 30% damage (kPa)	Threshold values of 70% damage (kPa)
Atmospheric	$Y = -9.36 + 1.43\ln(\Delta P)$	15	33
Pressurized	$Y = -14.44 + 1.82\ln(\Delta P)$	32	58
Elongated	$Y = -12.22 + 1.65\ln(\Delta P)$	24	46
Small	$Y = -12.42 + 1.64\ln(\Delta P)$	29	56