Identification and assessment of domino sequences initiated by loss of containment

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Abstract

A Domino Effect (DE) can be initiated by several types of primary accidents, which are often caused by Loss of Containment (LOC). In this paper we clarify the concept of domino effect based on a solid literature research; we quickly go through the latest developments that study and propose to prevent DE. Then we explain our approach based on modelling of accident scenarios triggered by LOC, aimed at DE risk estimation for land use planning purpose.

Keywords: loss of containment, accident, domino effect, risk analysis, land use planning.

1. Introduction

The severity of an accident consequences are increased by the occurrence of domino effect phenomenon leading to a major accident. This is due to the spread of the accident in both space and time, thus leading to the scope extension, with obvious repercussions on the criticality of individual and societal risk.

Taking into account domino effect in hazard studies is required by European Union legislation, in order to protect populations through land use planning in the vicinity of hazardous industrial sites, by means of technological risks control. More precisely, industrial sites falling under requirements of the Directive (96/82/EC) "Seveso II", which has been amended by the Directive (2003/105/EC) "Seveso III", must be able to identify domino scenarios likely to occur at their borders or involving neighbouring facilities, within and outside the establishment.

However the nonexistence of a well-defined procedure, able to prevent the risk of DE accidents, after assessment in all its forms, lets managers powerless against this phenomenon during the preparation of safety reports by companies and their evaluation by authorities. Although attempts on the development of methods have been made to meet the regulatory requirements, they remain ineffective, because of the complexity of this phenomenon, governed by a strong probabilistic propensity.

In this paper we explain our approach to study the propagation of any type of LOC able to spread the incident, and then cause a domino effect, on an industrial area, mostly starting from chemical industrial facilities, where large amount of dangerous substances are stored or handled.

The proposed methodology is implemented on Matlab software package, and uses Visual Basic for Applications (VBA) to enable an easy input procedure and output analysis in Microsoft Excel. It provides all possible accidents propagation paths, and their frequencies.

2. The Domino effect

2.1 Definitions

The term is used in its simplest sense in many fields to describe an event that causes another; the origin of the term comes from the game of dominos toppling. Based on this analogy, the term DE is used to describe an event, usually undesirable, which is responsible for the occurrence of other undesirable events. It's widely used by economists and political scientists to describe the impact of actions that has the propensity to bring about one crisis after another. Several definitions are available in the literature to describe DE in the context of industrial risks assessment, due to the complexity of the phenomenon, and therefore the different evaluations that researchers may have. None has been universally accepted (Abdolhamidzadeh et al. 2011).
However most of them agree on the basic principles, which are the propagation and worsening of the accident consequences. Table I summarizes some definitions, among those found in the literature, especially with reference to process industries.
If we retain the CCPS and Kourniotis et al. definitions for closer analysis, it appears that the second one describes the worsening of consequences caused by DE only for off-site events. This leads us to talk about a restriction in the definition of DE, evoked by Abdolhamidzadeh et al. (2011). This restriction sometimes appears within the European Union, and is due to Article 8 of Seveso-II Directive, while CCPS, without mentioning the consequences of the DE, defines it as a propagation of an accident from one unit to another unit. These two definitions are correct but incomplete. A common definition ought to be chosen by the scientific community to standardize the DE, it must include both the spread and consequences aspects, this initiative is of crucial importance for the past accidents analysis, and for the modelling of this phenomenon.

Table I: Definitions of domino effect.

Author(s)	Domino effect definition
Delvosalle et al. (1996)	A cascade of events in which the consequences of a previous accident are increased by following one(s), as well spatially as temporally, leading to a major accident.
Khan et al. (1998)	A chain of accidents, or situations when a fire/ explosion / missile /toxic load generated by an accident in one unit in an industry causes secondary and higher order accidents in other units.
Kourniotis et al. (2000)	Situations where a chemical accident becomes the initiating event of one or more other accidents, thus, increasing the severity of the off-site consequences.
CCPS (2000)	An incident, which starts in one item and may affect nearby items by thermal, blast, or fragment impact.
Cozzani et al.(2006)	Accidental sequences having at least three common features: (1) a primary accidental scenario, which initiates the domino accidental sequence; (2) the propagation of the primary event, due to “an escalation factor” generated by the physical effects of the primary scenario, that results in the damage of at least one secondary equipment item; and (3) one or more secondary events (i.e. fire, explosion and toxic dispersion), involving the damaged equipment items (the number of secondary events is usually the same of the damaged plant items).
Reniers and Cozzani (2013)	An accident in which a primary unwanted event propagates within an equipment (“temporally”), or/and to nearby equipment (“spatially”), sequentially or simultaneously, triggering one or more secondary unwanted events, in turn possibly triggering further (higher order) unwanted events, resulting in overall consequences more severe than those of the primary event.

Reniers (2010) highlighted the absence of a widely accepted definition, by taking thirteen DE definitions among those encountered in the literature, indicating that this does not constitute an exhaustive list. From these definitions the author proposed a classification of domino events according to the various ways in which they can occur, into four categories, each having two subcategories, namely: type.1 (internal or external), type.2 (direct or indirect), type.3 (temporal or spatial), type.4 (in serial or parallel).

A concept called local domino effect has been proposed by Abdolhamidzadeh et al.(2011) to designate several separate accidents, within the same unit, with a time interval significant enough for emergency responses to be set in motion (one minute or more).

The last definition given in table I (Reniers and Cozzani 2013) seems to be the more comprehensive one, since it encompasses all specific aspects found in most definitions of domino events, including the four categories cited below and the concept of local DE as well.

2.2 Scientific approaches and existing methodologies

Two main approaches are being followed by researchers in an attempt to assess and control the risk due to domino accidents. The first is the analysis of past accidents, which is essential for the second: the development of analysis or prevention methods for DE.

2.2.1 Past accident analysis

From the study of past accidents involving the phenomenon, important lessons and conclusions can be drawn; on the one hand this first approach allows having feedback to exploit it, in order to know what would be the best approach to develop methods for analysing, and preventing the risk. And secondly it allows obtaining the required input data, such as the initiating events, their frequencies and the most recurrent accident sequences etc. To be able to model this phenomenon, to reproduce it by numerical simulation and thus understand it further for better control.

It is important to note that the primary accidents (explosion, fire etc.), which may result in a DE, are due either to internal initiating events at source, such as corrosion, wear, construction defects, failure; or they can also be due to external initiators events, which can be classified into three categories according to their origin:

- Human: terrorism, malevolence, human errors.
- Accidents in neighbouring industrial facilities or transportation incidents of hazardous materials in all its forms: by roads, rivers, and railway or pipeline networks.
- Natural causes: earthquake...

According to Liu et al. (2012), accidents tending to cause DE are essentially explosions and fires, and this position is supported by many other researchers, and confirmed by experience feedback. Explosions are divided into four types in the process industry:

- Confined/Unconfined vapour cloud explosions (CVCE/UVCE);
- Boiling liquid expanding vapour explosions (BLEVE);
- Dust explosions.

We could add physical explosions, and condensed phase explosions. Following an explosion, physical effects are mainly missile projection effects (fragment ejection), overpressure effects (shock waves) and thermal effects (heat radiation). Furthermore, fires in the chemical industry are also divided into four types, named: pool fires, flash fires, fireball and jet (spray) fires. The main physical effect caused by fires is the heat flux.

2.2.2 Development of analysis and risk prevention methods

Several approaches have been proposed to study this phenomenon, and to this end researchers use different tools and models, depending on the purpose of their study. Some aim at risk prevention in industrial areas, while others tend more towards a more accurate quantification of consequences, and therefore are limited to one type of primary accident likely to generate a DE. Among the methods that were proposed, some are time consuming and require involvement of experts, with diversified skills (highly qualified staff in diverse fields); while others are limited to the first scenario level. This does not undermine the efforts of research teams working on the subject, but highlights the complexity of the DE, both physically and organizationally, as the phenomenon may involve several companies, and therefore the risk assessment should be done in consultation and collaboration between neighbouring industrial sites, which is difficult to implement because of the confidentiality constraints.

The complexity of the phenomenon obliges researchers to address the subject with some simplifying assumptions; as a consistent approach to risk management should include several steps that researchers must follow one by one, from the analysis of the DE risk to it prevention and control, hence the diversity of the presented work by scientists. In the following some relevant examples of the proposed methods are separately mentioned according to their objective.

2.2.2.1 Quantification methods

A systematic procedure for the quantitative risk analysis caused by DE has been developed by Cozzani et al. (2005). They have introduced a simplified technique for the analysis of both the consequences and the relevance of domino scenarios. This model provides threshold values for damage caused to equipment due to different effects. A method based on probit function has been proposed to estimate the probability of an accident escalation. The methodology has been implemented in the ARIPAR software to calculate risk indexes (individual and societal risk, potential loss of life), and it has been applied to several case studies, including domino effect studies within an extended industrial area.

Liu et al. (2012) have proposed a model for area risk assessment based on DE. The model was built in order to carry out a quantitative assessment of global risks in chemical parks, to provide a scientific basis to support decision making regarding safety management.

2.2.2.1 Prevention methods

Reniers et al. (2005) have developed a method that intends to prevent the risk of external DEs, named Hazwim, using several methods and simple tools such as HAZOP and What-if analysis for hazard identification and risk matrix for their evaluation. The method can reach the purpose for which it was designed, but to the detriment of a certain level of complexity, and it implementation requires the involvement of experts in the HAZOP, What-if analysis and risk matrix.

The DomPrevPlanning software, was proposed by Reniers et al. (2007), meant for the prevention planning of DEs, by providing help in decision making concerning the application of preventive and protective measures to minimize the risk in industrial areas, including chemical plants.

The DominoXl was developed by Fievez et al. (2002) in order to enumerate all chains of accidents that could be caused by DEs. From the most dangerous equipment, and for each installation of the chemical cluster, the software examines the possibility of a primary accident leading to a secondary accident in another installation in the area.

3. Proposed methodology

The approach followed is composed of two main steps, the first one is the design of a database that lists the required information for the development of the method, which includes the equipment types considered by the model, the annual frequencies of losses of containment, a classification of hazardous materials stored or handled within the units, etc. The second step is the modelling of domino scenarios: modelling the LOCs consequences and their propagation**;** given that DE analysis is an extension of the hazard identification, primary accident scenarios are modelled first and then their possible propagation to the nearby units and establishments are then assessed, taking into account the repression systems if they exist.

3.1 The modelling of accident scenarios

LOCs can be considered as the main recurrent initiating event of accident sequences in the chemical industry. They cause hazards that vary according to several parameters (type of leakage and its height if continuous leak, characteristics and equipment type, phase and substance category, weather conditions, etc.). The researchers define and classify losses of containment depending on the purpose of their work and the type of facility concerned. In this study, the classification of the Purple Book is used; leaks are classified in three classes defined below:

- G1: Instantaneous release of the complete inventory (catastrophic rupture).
- G2: Continuous release of the complete inventory in 10 minutes at a constant rate of release.
- G3: Continuous release from a hole with an effective diameter of 10 mm.

The approach focuses on these three types of leakage, by treating them separately to obtain at first the consequences of each leak, on the unit where the failure occurred; and secondly, to study the propagation of the effects within and outside the establishment.

3.1.1 <u>The modelling of primary accident scenarios</u>

As consequences from LOCs, the possible scenarios are multiple and could vary according to the parameters previously mentioned. To determine the outcomes (primary accidents) of these accident scenarios and their likelihood of occurrence, on the equipment where the release occurred; based on the existing event trees in the scientific literature, such as in the Purple Book, Delvosalle et al. (2006) and Vílchez et al. (2011). We have drawn up twenty event trees in which each branch represents an accident scenario.

Event trees are assigned to suitable LOCs, depending on the assumed conditions of the releases and equipment. As the number of possible cases (combinations of the releases conditions and equipment type) is very high, since modifying one parameter concerning the release conditions, or the equipment type, could completely change the accident scenarios and consequently the outcomes. We have used Matlab® to perform the calculations related to the LOCs modelling. This was achieved by encoding the twenty event trees in Matlab® in order to call each one as a function, when its conditions are fulfilled.

We assume that this twenty event trees represent all the possible cases of LOCs, which could lead to DE in a chemical park. The toxic character of substances is neglected in this first step, and the risk of toxic dispersion is not considered in this work; for the reason that, we aim to study the primary accidents propagation, to nearby installations, through analysing the consequences of their physical effects.

However, the toxic dispersion cannot spread the accident to another unit, except in special cases. Nevertheless, this aspect can easily be added to the methodology to calculate the consequence on humans, and estimate the individual and social risk, in a Quantitative Risk Analysis (QRA) context. Using the results obtained for the outcome: toxic dispersion; and then by means of a human vulnerability model, the risk indexes could be calculated.

When calculating the frequencies of occurrence of the primary accidents, repression systems and meteorological conditions are taken into account. This is done by multiplying the frequency of the event by the probability of failure on demand (PFD) of the existing repression systems and the weather conditions probability if relevant for the scenario. In process plants, there are many kinds of safety barriers, which could act on the events leading the outcome, for example: blocking systems, water spray barriers to limit the release amount and its spread, in the case of gas releases, or the use of foam to limit the evaporation of a pool etc. In some cases the branch representing the accident scenario on which a control safety barrier exist, could be cut from the event tree, for example: a separate containment vessel or catch-tank for gas release/ underground drainage system for liquid spill.

3.1.2 The modelling of accident propagation

Once an event tree is attributed to a loss of containment, all the possible outcomes (primary accidents) are known. The next phase consists of modelling the propagation, in order to determine which installations in the vicinity of the installation source, will be affected by these incidents, and propagates the accident in turn. This is made possible by following four steps explained hereafter:

Step.1: Calculation of each outcome consequences, using existing consequence models. The physical effects considered are the heat radiation, overpressure and missiles projection effects. This amounts to calculate the effect distances, and compare them to the real distances. Equipment for which effect distances exceed real distances, are selected for an accurate calculation of the intensity of the physical effect involved, at the real distance separating them from the equipment source.

Step.2: Comparison of the obtained values from step1, to the escalation thresholds; at this point, we obtain a qualitative propagation model, by determining the potential target equipment. If the value of one of the physical effects calculated for the primary accident is greater than the escalation threshold values given by Cozzani et al. (2006), we consider the installation as a potential target.

Step.3: Estimation of the escalation probability, for the equipment considered as potential targets from the previous step, using the vulnerability models by means of probit function; different functions are used depending of the physical effects studied, and the type of equipment. Table II, shows the different probit function used (Landucci et al 2009, and Mingguang and Juncheng 2008)

Table II: Models for damage probability considered by the methodology

Physical effect	**Target equipment**	**Vulnerability models**
Head radiation	Atmospheric	$\ln(\text{ttf}) = -1.13 \cdot \ln(I_{i,j}) - 2.67\ 10^{-5}\ \text{V} + 9.9$ $Y_{i,j} = 12.54 - 1.847 \cdot \ln(\text{ttf})$
	Pressurised	$\ln(\text{ttf}) = -0.95 \cdot \ln(I_{i,j}) + 8.845\ \text{V}^{0.032}$ $Y_{i,j} = 12.54 - 1.847 \cdot \ln(\text{ttf})$
Overpressure	Atmospheric	$Y_{i,j} = -9.36 + 1.43 \ln(\Delta P_{i,j})$
	Pressurised and Elongated (toxic)	$Y_{i,j} = -14.44 + 1.82 \ln(\Delta P_{i,j})$
	Elongated (flammable)	$Y_{i,j} = -12.22 + 1.65 \ln(\Delta P_{i,j})$

$I_{i,j}$, radiation intensity on the target equipment, (kW/m^2). $\Delta P_{i,j}$, peak static overpressure on the target equipment, (kPa). V, equipment volume (m^3). $Y_{i,j}$ Probit function. ttf, time to failure(second).

Regarding the missile projection effect, as no accurate model (vulnerability models) exist for the estimation of the damage caused on the target, we only give a qualitative propagation model provoked by this effect, and so we don't consider it further in the study.

For the estimation of the escalation probability, we use equation (1). In terms of domino effect frequencies, equation (2) is used, where safety barriers, which can limit the effects of a primary accident (after its occurrence) are included in the computation, by multiplying the probability of escalation by their PDF, for example if an escalation is possible due to the spread of a fire and a fire protection systems (sprinklers) exist. We don't include the probability of meteorological conditions, since they are already involved in the estimation of the frequency of the primary accidents for which they are relevant.

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

$$F_{ed} = f_{ep} \times P_{i,j} \times PFD_{Repsyst} \qquad (2)$$

$P_{i,j}$: Likelihood of the equipment *j* possibly damaged following an accident in the equipment *i*.

$Y_{i,j}$: Calculated probit value.
V: Equipment volume (m^3).
f_{ep}: Frequency of occurrence of primary accident ($year^{-1}$).
F_{ed}: Frequency of occurrence of domino effect ($year^{-1}$).
$PFD_{Repsyst}$: Probability of failure on demand of repression system which acts on the accident considered.

Step.4: If the probability of escalation exceeds a predetermined value, named cut-off level, it is estimated that the escalation is possible and then we affect an appropriate event tree to the target equipment, in order to determine the primary escalation scenarios with their different outcomes.
Repeating this four steps, allows to determine the probability of escalation to the second level (three equipment affected by two consecutive accidents), and so on.

4. Conclusion

Domino scenarios are among the more complex accidental events that may take place in the process industry. The use of past accidents coupled to event tree analysis of primary events may lead to a methodology for the assessment and the management of risk due to such events. The application of the procedure described in this paper, for all equipment of an industrial zone, provides all possible accident sequences due to loss of containment. So as to reduce the risk at source; equipment involved in the propagation of the accident and therefore found in several sequences, must be ranked in order, according to their number of appearance and the expected frequencies, then central equipment to the security (which in case of a LOC propagate the incident and significantly aggravate the consequences) will be identified.

The Methodology proposed can be used as a decision support tool, in order to allow security managers to have a clear idea of equipment dangerousness according to their propensity to cause or propagate domino effect.

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References

Abdolhamidzadeh, B., Abbasi, T., Rashtchian, D., Abbasi, S.A., (2011). *Domino effect in process-industry accidents – An inventory of past events and identification of some patterns*. Journal of Loss Prevention in the Process Industries 24, 575–593.

Cozzani, V., Gubinelli, G., Antonioni, G., Spadoni, G., Zanelli, S., (2005). *The assessment of risk caused by domino effect in quantitative area risk analysis*. Journal of Hazardous Materials 127, 14–30.

Cozzani, V., Gubinelli, G., Salzano, E., (2006). Escalation thresholds in the assessment of domino accidental events. Journal of Hazardous Materials 129, 1–21.

Delvosalle, C., (1996), Domino Effects Phenomena: Definition, Overview and Classification. First European Seminar on Domino Effects. Leuven.

Delvosalle, C., Fievez, C., Pipart, A., Debray, B., (2006). ARAMIS project: A comprehensive methodology for the identification of reference accident scenarios in process industries. Journal of Hazardous Materials 130, 200–219.

Genserik Reniers, Valerio Cozzani, (2013). Domino Effects in the Process Industries Modelling, Prevention and Managing.

Genserik L.L. Reniers, (2010). Multi-Plant Safety and Security Management in the Chemical and Process Industries.

Kourniotis, S.P., Kiranoudis, C.T., Markatos, N.C., (2000). Statistical analysis of domino chemical accidents. Journal of hazardous materials 71, 239–252.

Khan, F.I., Abbasi, S.A., (1998). Models for domino effect analysis in chemical process industries. Process Safety Progress 17, 107–123.

Liu A, Wu C, Peng X. (2012) Research on Area Risk Assessment for Chemical Park based on Domino Effect Model. Procedia Engineering 45, 47–52.

Landucci G, Gubinelli G, Antonioni G, Cozzani V. (2009). The assessment of the damage probability of storage tanks in domino events triggered by fire. Accident Analysis & Prevention 41, 1206–1215.

Mingguang Z, Juncheng J. (2008). An improved probit method for assessment of domino effect to chemical process equipment caused by overpressure. Journal of Hazardous Materials 158, 280–286.

P.A.M. Uijt de Haag, B.J.M. Ale, (2005). Guidelines for quantitative risk assessment, THE COLOURED BOOKS.

Vílchez, J.A., Espejo, V., Casal, J. (2011). Generic event trees and probabilities for the release of different types of hazardous materials. Journal of Loss Prevention in the Process Industries 24, 281–287.