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Equipment vulnerability assessment (EVA) and pre-control of domino effects using a five-level hierarchical framework (FLHF)

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Abstract

The primary event, damage vector, escalation scenario and escalation network are the fundamental components of any domino effect, and in literature, quantitative risk assessment (QRA) is the main topic of investigation. However, the QRA's implementation and application are complicated, and its results are currently not very useful in industrial practice for implementing prevention, protection and control measures. In this paper, the use of an equipment vulnerability assessment (EVA) focusing on the probability of escalation-scenario occurrence is suggested, which could provide a deep understanding at the elemental level, while QRA is used at the system level. Specifically, the outline, methods and programme for EVA are discussed. In addition, a five-level hierarchical framework (FLHF) is proposed to prevent and control domino accidents comprehensively and systematically, which includes Level 1 – Prevention of loss of containment (LOC); Level 2 – Safety distance, safety inventory and layout optimization; Level 3 – EVA and safety design, safety improvement; Level 4 – Reengineering of layer-of-protection analysis (LOPA); and Level 5 – QRA of the

domino effect. The quantification and implementation of each level are also discussed in detail.

Keywords

Domino effect; Equipment vulnerability assessment; Quantitative risk assessment; Loss of containment; Safety distance; Layer-of-protection analysis

Acronyms

BLEVE	boiling-liquid expanding-vapour explosion
EVA	equipment vulnerability assessment
FLHF	five-level hierarchical framework
IPL	independent protection layer
LOC	loss of containment
LOPA	layer-of-protection analysis
PDSO	probability of domino-scenario occurrence
PFD	probability of failure on demand
QRA	quantitative risk assessment
VCE	vapour-cloud explosion

1 Introduction

Domino effects become more important in process plants and chemical clusters as the scales of storage and process installations increase and the density of population grows. Many research studies of accident statistics (Abdolhamidzadeh et al., 2011; Darbra et al., 2010; Gómez-Mares et al., 2008; Hemmatian et al., 2014; Hemmatian et al., 2015; Kourniotis et al., 2000) have proved the high possibility and extreme consequences of domino effects. Statistics (Zhang and Zheng, 2012) indicate that a domino accident occurred in case of 13.2% of fixed facilities and in case of 9% of hazmat transportation in China from 2006 to 2010.

This term was initially proposed in the first report of The Control of Major Hazards, which was prepared by the Health and Safety Commission in the UK (1976).

Historically, the major fire and series of explosions that occurred at the PEMEX LPG terminal in Mexico City in 1984 (Mannan, 2005) was the turning point. Since this incident, many scientific and technical works emerged on this topic. A ‘domino effect’ was officially described in Europe in Article 8 of the Seveso-II (Directive 96/82/EC, 1996). The domino effect legislation was even strengthened in the latest European Seveso-III (Directive 2012/18/EU, 2012). The widely used quantitative risk-assessment (QRA) guideline of CCPS (2000) and the TNO ‘purple book’ (Uijt de Haag and Ale, 2005) also suggest some simple techniques to address domino effects. A recent all-encompassing volume by Reniers and Cozzani (2013) presents a number of excellent sub-topics, from modelling to prevention and management.

In this paper, the use of an equipment vulnerability assessment (EVA) focusing on the probability of an escalation scenario possible occurring, is suggested to definitively and formally study on domino-effect phenomenon. It could be a powerful tool to prevent and control domino effects, in addition to the prevention of loss of containment (LOC) for primary events and the use of a safety distance to weaken damage vectors on target equipment. EVA is applied on the elemental level while QRA is applied on the system level, thus, a deeper understanding of the knock-on phenomenon can be gained. The outline, methods and programme for EVA are discussed in detail. In addition, a five-level hierarchical framework (FLHF) is proposed to integrate the prevention of LOC, safety distances, EVA, layer-of-protection analysis (LOPA) and QRA tools. The quantification and implementation of FLHF are also discussed. Section 2 reviews the domino-effect phenomenon, including definition, risk assessment and pre-control

measures. EVA and FLHF are discussed in Section 3 and Section 4, respectively.

Section 5 concluded this paper.

2 Domino effect

2.1 Definition and principles

As Reniers and Cozzani suggest (2013; Alileche et al., 2015), the key elements of the domino effect are *propagation* (a primary unwanted event propagates) and *escalation* (resulting in more severe consequences). Therefore, three elements should be clearly assessed:

- (i) *The primary event (that is, the accident scenario of concern and its final outcome expressed in terms of physical effects – thermal radiation, overpressure, fragments, etc.);*
- (ii) *The possible significant secondary scenarios that may be triggered by propagation of the primary event (for example, the secondary scenarios triggered by the damage to pieces of equipment, causing the release of hazardous substances, resulting in final outcomes that escalate the primary scenario);*
- (iii) *The relevant secondary targets (pieces of equipment that may be damaged by the primary event and that, if damaged, have the potential to cause final outcomes that escalate the primary event).*

Table 1 lists the primary scenarios and their damage vectors (Alileche et al., 2015). Fire impingement could ignite the flammable substances in the target equipment, while thermal radiation might cause decreased tensile strength of the shell-wall material, increased internal pressure, high local thermal stress, and/or the melting of the non-metallic parts. Blast overpressure can result in buckling, collapse, rupture and shift of target vessels, fracture of connected pipelines and failure of installed safety devices.

Blast fragments can penetrate vessels, cut off supporting structures and pipelines, and ignite or heat substances if at high temperature. Generally, toxic release cannot directly lead to secondary scenarios, but may cause human errors.

Table 1. Primary scenarios and damage vectors (Alileche et al., 2015)

Primary scenarios	Damage vectors
Pool fire	Radiation, fire impingement
Jet fire	Radiation, fire impingement
Fireball	Radiation, fire impingement
Flash fire	Fire impingement
Mechanical explosion	Fragment projection, overpressure
Confined explosion	Fragment projection, overpressure
BLEVE	Fragment projection, overpressure
VCE	Overpressure, fire impingement
Toxic release	--

Note: BLEVE, boiling-liquid expanding-vapour explosion, and VCE, vapour-cloud explosion.

2.2 Risk assessment

Risk assessment has become a specific methodology for contemporary safety science. Domino effects are no exception in this regard. The QRA guideline of CCPS (2000) notes that either of two approaches can be used:

- (i) *Increase the consequences of a given incident at a fixed frequency to allow for larger consequences due to domino effects (modifying the outcome in an event-tree context), or*
- (ii) *Increase the failure frequency of a given incident at fixed consequences to allow for domino-effect contribution (treating the domino as an external event in a fault-tree context).*

However, no matter which approach is chosen, the damage probabilities of target equipment items exposed to fire thermal radiation, blast overpressure and blast fragments are required. Furthermore, a generally agreed upon definition of domino scenario is also needed if the escalation network is complex. Fig. 1 shows the

conceptual schema for domino risk assessment. Table 2 compares the different domino risk methods used in literature.

Fig. 1. Conceptual schema for domino risk assessment

Table 2. Comparison of different domino risk methods used in literature

Sources	Domino risk and domino scenario	Damage probabilities
Bagster and Pitblado (1991); Mannan (2005)	$\sum_{\text{route}} P_e \{ (i, X) \xrightarrow{k} j \}$ <ul style="list-style-type: none"> Increase the failure frequency. PDSO represents domino risk. Domino scenario is defined as the sum of escalation routes. Five possible escalation scenarios of unit i are considered. Method can be extended to cover high orders. 	$P_d = \left(1 - \frac{r}{r_{th}} \right)^2$ <ul style="list-style-type: none"> The uniform ratio method is used for P_r, P_b and P_f.
Khan and Abbasi (1998)	$f_p \cap (P_r \cup P_b \cup P_f)$ <ul style="list-style-type: none"> Increase the failure frequency. PDSO represents domino risk. Domino scenario is defined as the first-order escalation. Synergistic effect of the different damage vectors is considered. 	$P_r = \frac{P_2 - P_{\text{relief}}}{P_{\text{relief}}} \cup \frac{E_{y\max}}{E_y}$ $P_{r_b} = -23.8 + 2.92 \ln[(1 + C_d)p^0]$ $P_f = \frac{ps - h}{ps} \cup \frac{P_2 - P_{\text{relief}}}{P_{\text{relief}}} \cup \frac{V}{V_e}$

Cozzani et al. (2005); Cozzani et al. (2014)	$f_p \left(1 - \sum_i \sum_m P_e^{(l,m)} \{i \rightarrow j\} \right)$ <ul style="list-style-type: none"> • Increase the consequences. • Individual and societal risks represent domino risk. • Domino scenario is defined as all combinations of escalation scenarios. • Concurrence of multiple units of j is considered. • Method can be extended to cover high orders. 	$Pr_r = 9.25 - 1.85 \ln(ttf)$ $\begin{cases} \ln(ttf) = -1.13 \ln I - 2.67 \times 10^{-5} V + 9.9, & \text{Atmospheric} \\ \ln(ttf) = -0.95 \ln I + 8.845 V^{0.032}, & \text{Pressurized} \end{cases}$ $\begin{cases} Pr_b = -18.96 + 2.44 \ln(p^o), & \text{Atmospheric} \\ Pr_b = -42.44 + 4.33 \ln(p^o), & \text{Pressurized} \\ Pr_b = -28.07 + 3.16 \ln(p^o), & \text{Elongated} \\ Pr_b = -17.79 + 2.18 \ln(p^o), & \text{Auxiliary} \end{cases}$ $P_{f,imp} = \frac{\Delta \theta}{4\pi} \int_{\Delta \varphi} \cos \varphi d\varphi$
Abdolhamidzadeh et al. (2010); Rad et al. (2014)	$f_{p,j} + \sum_{\text{route}} f_{p,i} P_e \{ (i, X) \xrightarrow{k} (j, Y) \}$ <ul style="list-style-type: none"> • Increase the failure frequency. • PDSO represents domino risk. • Domino scenario is defined as the sum of escalation routes. • High orders, multiple scenarios of unit i and j and synergistic effect of the same damage vectors are considered. • Monte-Carlo simulation and random sampling of escalation scenarios and damage probabilities. 	<ul style="list-style-type: none"> • The basic methods for P_r and P_b are Probit models. The sampled probabilistic values are compared with the Probit values. • P_f is not considered.
Kadri et al. (2013)	<ul style="list-style-type: none"> • Based on Cozzani et al.' method. • Synergistic effect of the different damage vectors is considered. 	<ul style="list-style-type: none"> • P_f is calculated by Monte-Carlo simulation on the projectile-trajectory equation.
Zhang and Chen (2013)	<ul style="list-style-type: none"> • Increase the consequences. • Individual and societal risks represent domino risk. • Calculate the escalation probability by solving a set of linear equations. • High orders and synergistic effect of the different damage vectors and the different units of i are considered. 	<ul style="list-style-type: none"> • P_r is based on Khan & Abbasi's method. • $P_b = (p^o - P_2)/p_{th}^o$ • P_f is calculated by Monte-Carlo simulation on the projectile-trajectory equation.
Bernechea et al. (2013)	<ul style="list-style-type: none"> • Increase the failure frequency. • Individual and societal risks represent domino risk. • Event tree is extended and integrated into the general QRA. • High orders and multiple scenarios of unit i and j are considered. 	<ul style="list-style-type: none"> • Escalation scenarios are determined by thresholds. • P_f is not considered.
Khakzad et al. (2013); Khakzad (2015)	<ul style="list-style-type: none"> • Increase the consequences. • PDSO represents domino risk. • PDSO of each order is calculated by 	<ul style="list-style-type: none"> • P_r and P_b are calculated using the Probit models. • P_f is not considered.

	Bayesian network.	
	<ul style="list-style-type: none"> • High orders, multiple scenarios of unit i and j, synergistic effect of the same damage vectors and dynamic process are considered. 	
Zhou et al. (2016)	<ul style="list-style-type: none"> • Only for the first-order escalation of fire. • Conditional probability of emergency events represents domino risk. • Event-sequence diagram and Monte-Carlo simulation. • The key is emergency intervention and the dynamic process is considered. 	<ul style="list-style-type: none"> • Conditional probability of emergency events is equivalent to P_r. • Random sampling of states and time cost of emergency event.
Non-probabilistic methods	<ul style="list-style-type: none"> • Tugnoli et al. (2008) and Cozzani et al. (2009), index methods. • Khakzad and Reniers (2015), method based on graph theory. • Ni et al. (2016), relative risk model. 	

Note: $P_e\{(i,X) \xrightarrow{k} (j,Y)\}$, escalation probability that the occurrence of source i in scenario X results in the occurrence of target j in scenario Y , in the order k ; $\sum_{route} P_e$, sum of escalation routes; $P_e^{(l,m)}$, PDSO of the m -th domino scenario defined by l escalation scenarios; f_p , frequency of LOC; P_d , damage probabilities; P_r , P_b , P_f , damage probability of fire thermal radiation, blast overpressure, blast fragments; Pr_r , Pr_b , Probit of P_r , P_b ; $P_{f,imp}$, probability of fragment hitting target; r , distance between i and j ; r_{th} , maximum impacting distance; P_2 , internal pressure of vessels; P_{relief} , set pressure of safety valves; $E_{y,max}$, allowable strength of the shell-wall material in high temperature; E_y , shell-wall stress produced by P_2 ; p^0 , blast peak overpressure; C_d , blast drag factor; p_{th}^0 , blast threshold; ps , fragment penetration; h , shell-wall thickness; V , target volume; V_e , hemisphere volume with radius of r ; ttf , time to failure; I , fire thermal-radiation intensity; $\Delta\theta$, intersection angle of two tangent lines from blast source in horizontal plane; φ , projective angle in vertical plane; and $\Delta\varphi$, intersection angle of two projective trajectories in the vertical plane of which one hits the front side of the target and the other hits the back side.

Some comments about domino risk assessment are the following:

- (i) The selection of a domino scenario or its definition should be agreed upon so that the evaluated objects are consistent.
- (ii) The damage probabilities of target equipment items exposed to fire thermal radiation, blast overpressure and blast fragments are very important and fundamental. Even though the Probit models are light and concise, they are not precise and customized because of the diversity of process equipment and the different damage patterns. This work, named equipment vulnerability assessment (EVA), should be conducted independently and achieved through the cooperation of the safety department with production people.

- (iii) The presentation or visualization of domino risk is not agreed upon. Actually, the probability of domino-scenario occurrence (PDSO) is more suitable to be defined as the domino risk than individual and societal risks, due to the difficulty in linking the Probit models of individual fatality with the complex escalation network.

2.3 Prevention, protection and control measures

In a certain sense, QRA is a specialized method for the pre-control of domino effects. However, its performance is limited. Thus, some other measures are discussed in literature. The most intuitive and inherently safe method is the safety distance, which is determined by consequence models and thresholds. Its inverse is safety inventory, which can be managed dynamically, while safety distance is usually achieved in the layout-design stage. However, some constraints of chemical processes and/or land-use planning and uncertainties of consequence models and thresholds still exist, making the use of safety distance undesirable. For example, with reference to the blast-overpressure effect, two aspects seem important (Alileche et al., 2015): (i) the complete lack of indications of the specific characteristics of targets, and (ii) the ambiguities in the definitions of damage and/or loss. A relatively comprehensive and detailed research work on safety distance was published by Cozzani et al. (2006; Alileche et al., 2015). Another measure related to safety distance is layout optimization, for which the key aspects are the definition of objective functions and the development of optimization algorithms. PDSO or domino indexes can be defined as the objective function and two typically employed algorithms are the gradient-descent method (Lee et al., 2005; So et al., 2011) and mixed-integer nonlinear programming (de Lira-Flores et al., 2014; Jung

et al., 2011; Lopez-Molina et al., 2013).

Protection layers and safety barriers are generalized approaches to decrease the probability of occurrence of the primary scenario and/or reduce its physical effects on targets. An existing technique that uses this philosophy is LOPA (CCPS, 2001). However, its performance and configuration for preventing and controlling domino effects are not clearly defined. Landucci et al. (2015) investigated the availability and probability of failure on demand (PFD) of safety barriers preventing fire-induced domino scenarios. Janssens et al. (2015) developed a meta-heuristic algorithm to position safety barriers rationally. Fire thermal insulations and coatings to prevent or delay BLEVE are more specific and well-researched implementations of this philosophy (Landucci, Molag and Cozzani, 2009; Landucci, Molag, Reinders and Cozzani, 2009; Tugnoli et al., 2012).

Safety and security management also take important roles. Reniers et al. (2008; 2009; 2010; 2012; Reniers and Audenaert, 2014; Reniers and Dullaert, 2007, 2008) researched safety and security management in depth, and used game theory to support investment decisions between multiple enterprises and proposed a prioritization approach by considering installations as nodes and linking them with damages. In terms of emergency response and management, Zhou et al. (2016; Zhou and Reniers, 2016) simulated and evaluated the emergency events intervening in fire domino scenarios using event-sequence diagrams and Petri networks.

3 Equipment vulnerability assessment (EVA)

The comments on domino risk assessment in Section 2.2 suggest that EVA should be performed independently to provide a more accurate and customized damage probability. Actually, EVA can be generalized to cover more damage vectors, e.g., natural hazards. These damage vectors and the associated damage probabilities of specific target equipment exposed to them, share the same evaluation methodology. This methodology can provide a universal and uniform approach to evaluate and manage damage vectors quantitatively and comparably. The key aspects are the development of various vulnerability models and their validation and popularization.

3.1 Basic concepts

In general, vulnerability expresses the propensity of an element or a set of elements organized in a system exposed to hazards to suffer damage. A conceptual schema for EVA is shown in Fig. 2. Three main parts are included: (i) damage vectors; (ii) definition of damage to equipment, which consists of damage patterns, intensities and criteria related to both damage vectors and equipment characteristics; and (iii) vulnerability models and methods used to plot vulnerability curves and/or surfaces, including the empirical statistical method based on regression models and the theoretical-analysis method based on structural-reliability models. For the vulnerability curve, it is a probability result of EVA, as shown in Fig. 3, and when two coupled damage vectors impact simultaneously, vulnerability surfaces are presented.

Fig. 2. Conceptual schema for equipment vulnerability assessment (EVA)

Fig. 3. Sketch of equipment vulnerability curve

3.2 Methods for plotting vulnerability curves

3.2.1 Empirical statistics based on regression models

The regress data may come from accident cases and/or experiment research and contain at least the damage-vector intensities, damage states (either binary classes or multiclass; a binary class simply distinguishes whether the equipment is damaged, while a multiclass strictly defines the damage intensity) and characteristic parameters of the equipment. Logistic and Probit regression models are widely used and the difference between them is not large. For binary-class regression, the Logistic and Probit models can be expressed as follows (Wang and Guo, 2001).

$$\ln\left(\frac{P}{1-P}\right) = \alpha + \sum_i \beta_i \cdot VI_i + \sum_j \gamma_j \cdot CP_j \quad (1)$$

$$\Phi^{-1}(P) = \alpha + \sum_i \beta_i \cdot VI_i + \sum_j \gamma_j \cdot CP_j \quad (2)$$

where P is the damage probability, VI is the damage-vector intensity, CP is the characteristic parameter of the equipment, α , β_i and γ_j are the regress coefficients, and $\Phi^{-1}(\cdot)$ is the inverse of the cumulative normal-distribution function.

For multiclass regression, the cumulative Logistic-regression model is

$$\ln\left(\frac{P_k}{1-P_k}\right) = \mu_k - \left(\alpha + \sum_i \beta_i \cdot VI_i + \sum_j \gamma_j \cdot CP_j \right) \quad (3)$$

where P_k is the cumulative damage probability that the defined damage intensity of the equipment is not more than k -th level, and μ_k is an undetermined coefficient that can be merged with α .

For the estimation of the regress coefficients, the maximum-likelihood method can be employed. After the regression model is established, some quality evaluations are necessary, e.g., test of goodness of fit. Then, the statistics of the population can be inferred. The damage-probability models of fire thermal radiation and blast overpressure in the QRA of Cozzani et al. (2005; 2014; Cozzani and Salzano, 2004; Landucci, Argenti, Tugnoli and Cozzani, 2009; Zhang and Jiang, 2008) are applications of this approach.

3.2.2 Theoretical-analysis method – I. Static-reliability models

The empirical statistical method relies strongly on the quality of the regress data. However, most of the data samples are limited and of low quality because of the high cost and danger of experimenting on large vessels, which are usually accompanied by

complex conditions and uncertain damage patterns. Thus, structural-reliability methods are employed, which can be divided into three types: static, dynamic and systemic. The static one is suitable for static and stable systems for which the effect of the accumulation of damage vectors over time on target equipment is not strong, e.g., blast overpressure and seismic oscillation. First, a response function of the damaged equipment should be defined:

$$R = f(VI, CP) \quad (4)$$

where R is the response variable and a critical variable.

Then, the limit-state equation is constructed according to the defined damage criterion:

$$g(R, S) = 0 \quad (5)$$

where S is the strength variable and the other critical variable.

The equipment vulnerability can be expressed as

$$P(vi) = P[g(R, S) > 0 | VI = vi] \quad (6)$$

Generally, $P(vi)$ needs to be calculated by discretizing VI . When $g(\cdot)$ is in explicit form, the first-order reliability method can be used, otherwise, the response-surface method or Monte-Carlo simulation should be employed (Zhang, 2008). In addition, if there is a single extreme point of the dynamic system, this approach can be applied as well.

3.2.3 Theoretical-analysis method – II. Dynamic-reliability models

For general dynamic systems for which the effect of the accumulation of damage vectors over time is strong and/or the number of extreme points is unclear, the dynamic-reliability models are more suitable and the time duration is also a damage vector, e.g.,

the system of pressure vessels exposed to fire. The key aspects are treating damage vectors and response variables as stochastic processes and employing the first-passage failure theory (Gardiner, 1996; Zhu, 1998, 2003). If the damage vector is composed of Gaussian white noise and the system is of a single degree of freedom, a model assuming that the response is a Poisson process, can be used. An example in which the damage vector is assumed to be stationary and of zero-mean is the following (Zhu, 1998).

$$\begin{cases} P(t) = 1 - \exp\left[-\int_0^t \lambda(\tau) d\tau\right] \\ \lambda(\tau) = v_a^+ = \frac{1}{2\pi} \frac{\sigma_{\dot{R}}}{\sigma_R} \exp\left(-\frac{a^2}{2\sigma_R}\right) \end{cases} \quad (7)$$

where $P(t)$ is the dynamic damage probability, $\lambda(\tau)$ is the intensity of the Poisson process, v_a^+ is the expectation of the ratio of $R(t)$ passing through the single threshold of a , $\dot{R}(t)$ is the time derivative, and σ_R and $\sigma_{\dot{R}}$ are the standard deviations.

Another model that assumes that the responses are diffusion processes has relatively fewer restrictions (Zhu, 2003):

$$\begin{cases} P(t|\mathbf{x}_0) = 1 - P\{\mathbf{X}(s) \in \Omega, s \in (0, t] | \mathbf{X}(0) = \mathbf{x}_0 \in \Omega\} \\ \frac{\partial P}{\partial t} = \sum_i a_i(\mathbf{x}_0) \frac{\partial P}{\partial x_{i0}} - \sum_{i,j} \frac{1}{2} b_{ij}(\mathbf{x}_0) \frac{\partial^2 P}{\partial x_{i0} \partial x_{j0}} \end{cases} \quad (8)$$

where $P(t|\mathbf{x}_0)$ is the conditional dynamic damage probability, $\mathbf{X}(t)$ is the stochastic response vector, Ω is the safety domain, and $a_i(\mathbf{x}_0)$ and $b_{ij}(\mathbf{x}_0)$ are the drift and diffusion coefficients of the corresponding Ito stochastic differential equation.

Actually, the parabolic partial differential equation in formula 8 is the Kolmogorov backward equation, which can be solved by using the finite-difference method.

3.2.4 Theoretical-analysis method – III. Systemic-reliability models

Systemic-reliability models, e.g., event- and/or fault-tree analysis, reliability block

diagrams, Bayesian networks, event-sequence diagrams, Petri networks, etc., are mainly used for complex systems. In other words, the damage patterns should be defined as system failures, e.g., safety-device and emergency-response failures. It is difficult to describe the structure and scope of the system very correctly, so this approach should be applied carefully.

3.3 EVA programme and key issues

A programme for carrying out an EVA was developed and is given in Fig. 4.

Fig. 4. Programme for equipment vulnerability assessment (EVA)

The steps of the programme are:

Step 1 – Choose equipment to be evaluated: Some selection rules should be followed, e.g., those items for which the consequences of failure might be very large, major hazards, Class-III pressure vessels, etc. Otherwise, there will be a huge workload involving some meaningless analysis.

Step 2 – Identify possible damage vectors and randomize them: In the same area of the plant, the damage vectors of natural hazards impacting on different target

equipment should be the same, obviously. However, the damage vectors of fire thermal radiation, blast overpressure and blast fragments should be different, evidently. According to the identified primary scenarios and their consequence models, the damage vectors are quantitatively and randomly processed, which mainly involves calculating the means and variances or intervals of the damage-vector intensities.

Step 3 – Calculate damage probabilities and plot vulnerability curves: Peeling off all protection layers, calculate damage probabilities and plot vulnerability curves of all selected equipment exposed to all damage vectors by a one-by-one selection or by developing capable vulnerability models based on the methods described in Section 3.2.

Step 4 – Analyse coupled damage vectors: Two types of coupled damage vectors should be distinguished: synchronous and asynchronous. The coupled damage vectors occurring synchronously can be applied according to the probabilistic logical-operation rules, while those occurring asynchronously can only be sorted among all combinations of damage vectors. The logic and sorting operations could assist in the management of multiple damages, optimization of safety resources and design of emergency plans.

Step 5 – Guide safety design, improvement and protection-layer settings: The results of EVA can guide the safety design and improvement of equipment quantitatively. Furthermore, detailed demands for protection-layer settings can also be obtained (see also Section 4.3).

4 Five-level hierarchical framework (FLHF)

The pre-control of domino effects is a complicated system-engineering problem. The dependence of safety on a single measure is impossible and impractical. QRA is a relatively high-level approach, and the currently implemented measures (discussed in Section 2.3) are disorganized. In addition, the prevention of primary scenarios plays an important role in preventing domino effects, and has already been carefully considered in the ordinary activities of process safety. Thus, a good systematic macro-design is needed to organize the related measures to avoid the overlap and excess of safety activities. Fig. 5 shows the proposed five-level hierarchical framework (FLHF). The quantification and implementation of each level are further discussed in detail.

Fig. 5. Five-level hierarchical framework (FLHF) for pre-control of domino effects

4.1 Level 1 – Prevention of LOC

- **Objective:** mainly to prevent the primary scenarios related to dangerous liquids and gases. Other topics, e.g., building fires, run-away reactions, dust explosions, etc., are not specifically considered here but should be considered in other safety activities.

- **Quantification:** frequency of LOC and its modification.
- **Implementation:** the key is to integrate different techniques, e.g., hazard and operability analysis (HAZOP), risk-based inspection (RBI), structural integrity (SI), process-safety management (PSM), etc. The modification of the frequency of LOC is suggested as follows (GB/T 26610.4, 2014).

$$F = F_G \times F_E \times F_M \times F_L, \quad (9)$$

where F is the modified frequency; F_G is the statistical frequency of similar equipment; and F_E , F_M and F_L are the modification coefficients of the equipment itself, the management system and the excessive defects; the corresponding modifying factors to be considered are listed in Table 3.

Table 3. Factors used to modify frequency of LOC (adapted from GB/T 26610.4, 2014)

Items	Factors	
Equipment itself	Technologies	Wall thinning; Stress-corrosion cracking; High-temperature hydrogen attack; Furnace-tube damage; Mechanical fatigue; Equipment-lining damage; External damage; Brittle fracture
	Conditions	Plant operation; Cold climate; Seismicity
	Mechanical	Structural complexity (equipment and pipeline); Fabrication code; Life cycle; Safety factor (operating pressure and temperature); Vibration monitoring
	Processes	Process continuity (planned and unplanned shutdown); Process stability; State of safety valve (Maintenance; Dirt; Corrosion; Cleanliness)
Management system	Safety-responsibility system; Process-safety information; Process-hazard analysis; Safety check; Change management; Operating procedure; Safe operation; Personnel training; Inspection and maintenance; Safety check before servicing; Emergence response; Accident investigation; Subcontract management; Evaluation of safety-management system	
Excessive defects	If time-related degradation mechanism does not exist, determine according to periodic inspection, fitness-for-service assessment and safety factor. If time-related degradation mechanism exists, determine according to service conditions (High temperature; Fatigue; Special medium; Environment), damage mechanisms (Room temperature: Fatigue; Fatigue + Corrosion; Special medium stress-corrosion cracking. High temperature: Creep; Fatigue; Material degradation; Special medium corrosion), planned time to servicing, and remaining life.	

4.2 Level 2 – Safety distance, safety inventory and layout optimization

- **Objective:** achieve inherent safety of target equipment.
- **Quantification:** deterministic safety distances and safety inventories.
- **Implementation:** as discussed in Section 2.3, safety distance and safety inventory, determined by consequence models and thresholds, are inherently safer methods to prevent and control domino effects. The recommended values for the threshold and safety distance are listed in Table 4 (Alileche et al., 2015). If the listed safety distances are not exhaustive and/or some other uncertainties exist, layout optimization can be employed.

Table 4. Recommended values for threshold and safety distance (Alileche et al., 2015)

Scenarios	Damage vectors	Modalities	Target categories	Damage thresholds	Escalation thresholds	Safety distances
Flash fire	Heat radiation	Fire impingement	Floating roof tanks	Damage unlikely	Flame envelope	Maximum flame distance
			All other units	Damage unlikely	Escalation unlikely	--
Fire ball	Heat radiation	Flame impingement	Atmospheric	$I > 100 \text{ kW} \cdot \text{m}^{-2}$	$I > 100 \text{ kW} \cdot \text{m}^{-2}$	Maximum flame distance
			Pressurized	Damage unlikely	Escalation unlikely	--
		Distant radiation	Atmospheric	$I > 100 \text{ kW} \cdot \text{m}^{-2}$	$I > 100 \text{ kW} \cdot \text{m}^{-2}$	Maximum flame distance
			Pressurized	Damage unlikely	Escalation unlikely	--
Jet fire	Heat radiation	Fire impingement	All	Flame envelope	Flame envelope	--
		Stationary radiation	Atmospheric	$I > 15 \text{ kW} \cdot \text{m}^{-2}$	$I > 15 \text{ kW} \cdot \text{m}^{-2}$	50 m from flame envelope
			Pressurized	$I > 45 \text{ kW} \cdot \text{m}^{-2}$	$I > 45 \text{ kW} \cdot \text{m}^{-2}$	25 m from flame envelope
Pool fire	Heat radiation	Flame impingement	All	Flame envelope	Flame envelope	--
		Stationary radiation	Atmospheric	$I > 15 \text{ kW} \cdot \text{m}^{-2}$	$I > 15 \text{ kW} \cdot \text{m}^{-2}$	50 m from pool border
			Pressurized	$I > 45 \text{ kW} \cdot \text{m}^{-2}$	$I > 45 \text{ kW} \cdot \text{m}^{-2}$	20 m from pool border
VCE	Overpressure	Blast wave interaction	Atmospheric	$P > 7 \text{ kPa}$	$P > 22 \text{ kPa}$	$R = 1.75 \text{ (ME); } 1.50 \text{ (BS)}$
			Pressurized	$P > 20 \text{ kPa}$	$P > 20 \text{ kPa}$	$R = 2.10 \text{ (ME); } 1.80 \text{ (BS)}$
			Elongate (toxic)	$P > 14 \text{ kPa}$	$P > 20 \text{ kPa}$	$R = 2.10 \text{ (ME); } 1.80 \text{ (BS)}$
			Elongate (flammable)	$P > 14 \text{ kPa}$	$P > 31 \text{ kPa}$	$R = 1.35 \text{ (ME); } 0.85 \text{ (BS)}$
	Heat radiation	Fire impingement	See flash fire	See flash fire	See flash fire	See flash fire
Confined explosion	Overpressure	Blast wave interaction	Atmospheric	$P > 7 \text{ kPa}$	$P > 22 \text{ kPa}$	20 m from vent
			Pressurized	$P > 20 \text{ kPa}$	$P > 20 \text{ kPa}$	20 m from vent
			Elongate (toxic)	$P > 14 \text{ kPa}$	$P > 20 \text{ kPa}$	20 m from vent
			Elongate (flammable)	$P > 14 \text{ kPa}$	$P > 31 \text{ kPa}$	20 m from vent
Mechanical explosion	Overpressure	Blast wave interaction	Atmospheric	$P > 7 \text{ kPa}$	$P > 22 \text{ kPa}$	$R = 1.8$
			Pressurized	$P > 20 \text{ kPa}$	$P > 20 \text{ kPa}$	$R = 2.0$

BLEVE	Missile projection	Overpressure	Blast wave interaction	Elongate (toxic)	$P > 14 \text{ kPa}$	$P > 20 \text{ kPa}$	$R = 2.0$
				Elongate (flammable)	$P > 14 \text{ kPa}$	$P > 31 \text{ kPa}$	$R = 1.2$
				All	Fragment impact	Fragment impact	300 m (prob. $< 5 \times 10^{-2}$)
				Atmospheric	$P > 7 \text{ kPa}$	$P > 22 \text{ kPa}$	$R = 1.8$
				Pressurized	$P > 20 \text{ kPa}$	$P > 20 \text{ kPa}$	$R = 2.0$
				Elongate (toxic)	$P > 14 \text{ kPa}$	$P > 20 \text{ kPa}$	$R = 2.0$
				Elongate (flammable)	$P > 14 \text{ kPa}$	$P > 31 \text{ kPa}$	$R = 1.2$
				All	Fragment impact	Fragment impact	300 m (prob. $< 5 \times 10^{-2}$)
				Atmospheric	$P > 7 \text{ kPa}$	$P > 22 \text{ kPa}$	--
				Pressurized	$P > 20 \text{ kPa}$	$P > 20 \text{ kPa}$	--
Point-source explosion	Missile projection	Overpressure	Blast wave interaction	Elongate (toxic)	$P > 14 \text{ kPa}$	$P > 20 \text{ kPa}$	--
				Elongate (flammable)	$P > 14 \text{ kPa}$	$P > 31 \text{ kPa}$	--
				All	Fragment impact	Fragment impact	300 m (prob. $< 5 \times 10^{-2}$)

I , heat-radiation intensity; P , maximum peak static overpressure; R , energy-scaled distance; ME, multi-energy method; and BS, Baker-Strehlow method.

4.3 Level 3 – EVA and safety design, safety improvement

- **Objectives:** according to EVA results, (i) achieve safety evaluation, safety design and improvement of target equipment; and (ii) raise quantitative demands for protection-layer settings.
- **Quantification:** vulnerability curves and/or surfaces.
- **Implementation:** the achievements of Level 1 and Level 2 of FLHF are relatively easy based on mature techniques. However, Level 3 is new and much research and work in practice are still needed. Level 3 mainly focuses on the possibility of an escalation scenario occurring, and can be complementary to the prevention of primary scenarios. First, the development of various vulnerability models and their validation are the foundation, as discussed in Section 3. The safety design and improvement of target equipment based on EVA are more reliable than the use of protection-layer settings in terms of preventing escalation scenarios, and can be achieved and evaluated in order to make the vulnerability as low as possible. For example, the parameters of a safety valve can be adjusted to ensure that the dry-wall

temperature of an LPG tank exposed to fire is much lower than the critical temperature of the wall material, so that the probability of BLEVE occurrence is as low as possible. If both safety design and safety improvement are either incapable or insufficient, protection-layer settings constitute an addition effort, and EVA results could suggest a quantitative demand.

4.4 Level 4 – Reengineering of LOPA

- **Objective:** evaluate and guide settings of additional safety measures.
- **Quantification:** probabilities of failure on demand (PFDs) of independent protection layers (IPLs).
- **Implementation:** as discussed in Section 2.3, the performance and configuration of LOPA for preventing and controlling domino effects are not clearly defined. Thus, a reengineering of LOPA is needed to consider domino effects. The key is to distinguish between the abilities of protection layers to either prevent the primary scenarios or control the escalation scenarios, or both. The PFD values of some typical IPLs are listed in Table 5, these values can be used to evaluate the performance of LOPA to prevent and control domino effects (CCPS, 2001).

Table 5. PFD values for some typical IPLs (adapted from guideline of CCPS, 2001)

IPLs		Comments	PFDs
Inherently safer design		If properly implemented, can significantly reduce the frequency of consequences associated with a scenario.	$1 \times 10^{-1} \sim 1 \times 10^{-6}$
Basic process-control system (BPCS)		Can be credited as an IPL if not associated with the initiating event being considered.	$1 \times 10^{-1} \sim 1 \times 10^{-2}$
Critical alarms and human intervention	Human action with 10-minute response time.	Assuming adequate documentation, training and testing procedures.	$1.0 \sim 1 \times 10^{-1}$
	Human response to BPCS indication or alarm with 40-minute response time.		1×10^{-1}

	Human action with 40-minute response time.			$1 \times 10^{-1} \sim 1 \times 10^{-2}$
Safety instrumentation systems	Safety integrity level (SIL)	SIL 1	See IEC 61508 and IEC 61511.	$1 \times 10^{-1} \sim 1 \times 10^{-2}$
		SIL 2		$1 \times 10^{-2} \sim 1 \times 10^{-3}$
		SIL 3		$1 \times 10^{-3} \sim 1 \times 10^{-4}$
Physical protection	Safety valves		Prevent system from exceeding specified pressure. Effectiveness of these devices is sensitive to service and experience.	$1 \times 10^{-1} \sim 1 \times 10^{-5}$
	Rupture discs			$1 \times 10^{-1} \sim 1 \times 10^{-5}$
Post-release protection	Dikes		Will reduce the frequency of large consequences.	$1 \times 10^{-2} \sim 1 \times 10^{-3}$
	Underground drainage systems			$1 \times 10^{-2} \sim 1 \times 10^{-3}$
	Open vent (no valve)		Will prevent overpressure.	$1 \times 10^{-2} \sim 1 \times 10^{-3}$
	Fireproofing		Will reduce rate of heat input and provide additional time for depressurizing, firefighting, etc.	$1 \times 10^{-2} \sim 1 \times 10^{-3}$
	Blast-walls/ bunkers		Will reduce the frequency of large consequences by confining blasts and protecting equipment, buildings, etc.	$1 \times 10^{-2} \sim 1 \times 10^{-3}$
	Flame/ detonation arrestors		If properly designed, installed and maintained, should eliminate the potential for flashback through a piping system or into a vessel or tank.	$1 \times 10^{-1} \sim 1 \times 10^{-3}$
	Remote emergency cut-off valves		Will reduce the amount of substances involved in a scenario.	$1 \times 10^{-1} \sim 1 \times 10^{-2}$

4.5 Level 5 – QRA of domino effect

- **Objectives:** (i) identify the protection and/or control priorities of units to assist with safety management and optimization of safety resources; and (ii) control the societal risk by protecting high-occupancy areas.
- **Quantification:** defined domino risk.
- **Implementation:** a QRA for domino effects is the last step of FLHF, which sometimes relies on the results of the other 4 levels. This approach is relatively complicated, as discussed in Section 2.2. When the equipment nodes and their damage linkages increase, the defined domino risk will become less sensitive to the node-parameter variations such that the protection and control measures and their

effectiveness are difficult to evaluate on the node level. Thus, prioritization of units and controlling societal risk are the main objectives and, for both objectives, an agreement on the QRA method first needs to be reached. Zhang and Chen's (2011) discretizing isolated-island model is an implementation of prioritization of units. In terms of controlling the societal risk, the most effective way is by protecting high occupancy areas, e.g., staff quarters and office buildings, since most effort has been made to decrease the PDSO from Level 1 to Level 4. The QRA results could support decision-making in this regard.

5 Conclusions

In this paper, the domino-effect phenomenon was first reviewed, including its definition, principles, risk-assessment methods and pre-control measures, and some comments about domino risk assessment were presented as well. Following the comments, an approach called 'equipment vulnerability assessment (EVA)' was suggested and discussed in detail, including the outline, methods and programme. The key aspects are the development of various vulnerability models and their validation and popularization. Finally, a five-level hierarchical framework (FLHF) for pre-control of domino effects was proposed, and the quantification and implementation of each level were discussed.

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