A Methodology Based on Fault Tree Analysis to Assess the Domino Effect Frequency

Antioco López-Molina, Richart Vázquez-Román, Efraín Quiroz Pérez, Instituto Tecnológico de Celaya, Departamento de Ingeniería Química. Av. Tecnológico y A.G. Cubas s/n, Celaya, Gto. CP 38010, Mexico

M. Guadalupe Félix-Flores, Unidad Académica de Ciencias Químicas, Universidad Autónoma de Zacatecas, CU-Siglo XXI, Edificio 6, km 6 Carr. Zacatecas-Guadalajara s/n, Ejido La Escondida, Zacatecas 98160, Zac., Mexico

Several tragic industrial accidents have produced domino effects in their occurrences and, hence, several approaches have been presented to estimate the probability of their effects. Some of these approaches are focused on estimating the damage probability due to fire or explosion whereas others apply Monte Carlo simulations to predict the domino frequency. In this work an easy to perform methodology has been developed to predict the occurrence frequency of the domino effect. The methodology considers the failure frequency for each unit process, the damage probability due to escalation vectors, and the use of active and passive safeguards. This methodology is based on the fault tree analysis framework. The approach can be used into the QRA analysis without any extra effort, since all aspects are previously assessed by the procedure. A case study is presented to show the application of this approach.

Keywords: Domino effect; Frequency Analysis; Fault Tree Analysis; QRA

Introduction

Common accidents into the chemical industries include explosions, fires and toxic emissions; however, the largest consequences are produced during a domino effect. A risk analysis can help to prevent any kind of accident. There are several tools to apply a risk analysis strategy and a typical procedure is the quantitative risk analysis (QRA). The objective for a QRA is to assess the risk associated to any process unit through consequence-frequency estimations in a set of possible accidents. The success of QRA into the industrial practice is based on the detailed analysis and the amount of information used about the analyzed process. It can be applied in almost any project stage, making it a powerful tool to estimate risk for almost any probable accident. Nevertheless, the QRA has a weakness: the domino effect has not been considered in detail.

A domino accident has being defined as: *the accident in which a primary event is propagated to nearby equipment, triggering one or more secondary events with overall consequences more severe than the first accident* (Cozzani et al. 2006). Statics studies proves that domino effect is still appearing in recent decades and showing a rise tendency (Abdolhamidzadeh et al. 2011). Both frequency and severity for domino effect justify the effort to develop more strategies for their consequence assessment, prevention and frequency estimation. Several methods have been published to assess accident damages (CCPS 1998; Eggen 1998; Gledhill et al. 1998; CCPS 1999; CPR14E 2005; Mannan 2005; Cozzani et al. 2006; Casal 2008), and a minor number of approaches have appeared related to domino effect prevention (Reniers et al. 2005; Reniers et al. 2005; Cozzani et al. 2007; Zhang et al. 2011; López-Molina et al. 2013). To estimate the domino effect frequency, the Lee’s book (Mannan 2005) only dedicates two pages to describe the method by Bagster and Pitblado (1991). Khan and Abbasi proposed the DEA (Domino Effect Analysis) methodology to assess the domino effect probability, where a set of models are included to estimate damage probabilities due to escalation vectors, radiation, overpressure and missiles (Khan et al. 1998). The DEA methodology was incorporated into the computational software named DOMIFFECT. The application of this software was presented by the authors to solve a case study (Khan et al. 2001). Cozzani *et al*. (2005) have also proposed a methodology to consider the events combination to assess the domino effect probability. An application of those methodologies in an industrial complex was carried out by Antonioni *et al*. (2009). Abdolhamidzadeh *et al.* (2010) proposed the FREEDOM (FREquency Estimation of DOMino accident) methodology: a complex algorithm based on Monte Carlo simulations, to improve the accuracy of the domino effect frequency estimation. More recently, Bernechea *et al.* (2013) have presented a methodology focused on storage facilities to assess the domino effect frequency based on an events tree analysis

All above described methodologies have introduced relevant contributions to analyse the domino effect problem. These approaches are based on calculating the damage probability for the second process unit by analysing the escalation vectors. However, none of them has included important aspects such as active and passive safeguards, and probability of ignition source. The current work propose a new methodology to assess the frequency of domino effect occurrence considering the failure frequency for each unit process, damage probability due to escalation vectors and presence of safeguards.

The domino effect has been responsible of most tragic industrial accidents. According to recent statistics analysis, 80% of domino accidents has occurred in fixed installation, 41.8% in storage facilities and 33.7% on processing installations. The remaining accidents have occurred in transportation and transfer activities. Petroleum products are among the most common substances to cause domino, 53.8%, followed by hydrocarbons, 20.8%. The domino accidents occurred in developed countries is 71.1 % whereas 28.9% took place in developing countries, but the accidents occurred in developing countries have risen to 52.9% during 2000s (Kourniotis et al. 2000; Darbra et al. 2010; Abdolhamidzadeh et al. 2011; Chen et al. 2012). In spite of having higher rate of frequency in developed countries, the number of fatalities became higher on developing countries due to a poor legislation about safety and badly trained operators (Chen et al. 2012). Explosions and fires have been the most common primary accidents with a rate of 57% and 43%, respectively.

A methodology to assess the domino effect frequency

The domino effect is manifested by different accidents sequences: explosion → fire, fire → explosion→ fire, fire → fire, mainly (Kourniotis et al. 2000; Darbra et al. 2010; Chen et al. 2012). Irrespective of the sequence of accidents involved into domino effect, all domino accident can be framed in a general sequence of events. The sequence start with a failure of any process or storage unit: loss of control operation or loss of containment. If the item is equipped with control devices and at least one does not respond to avoid the emission or release of dangerous material, then a dangerous material release will occur. Once the emission has occurred, a question merges related to whether the cloud can get a fire or explosion and factors such as atmospheric conditions, confinement, and safety measures should be considered into the ignition source probability. When an explosion or fire may occur, the following probable event is the damage escalation, which is function of the amount of released material and separation distances among process units. If a second process unit is close enough to the primary event and its passive safeguards fail, then the domino effect occurs. Figure 1 shows the general sequence of the domino effect. This events sequence is the guide for this methodology. The methodology is based on performing a fault tree analysis (FTA) as described in next section. The general procedure follows the next order: 1) Build the domino fault tree, 2) Collect information about base events, 3) Define the number of dangerous process units and its scenarios, 4) Fix a process unit as a secondary unit (target unit) while the remaining units are considered as primary events (trigger units), 5) Assess the scenarios and estimate the damage probability on target unit, 6) Assess the domino frequency for target unit using the domino fault tree, and 7) Estimate the overall frequency when all dangerous process units have been evaluated, Figure 2.

Domino fault tree construction

Since the domino effect has been described by a fault tree, then it is used to estimate its occurrence frequency, Figure 3. In the fault tree, the domino effect on the second dangerous *i*-process unit (*i*-SDPU) has been defined as a top event. According with historical data, fires and explosions are the main cause of domino effect. Then fire and explosion become a part for the next two branches of the fault tree to represent the two possible accidents on nearby *j*-dangerous process units (NDPU) which could damage the *i*-SDPU. It has to firstly be developed the analysis on the branch corresponding to damage of *i*-SDPU because of fire on *j*-NDPU. Then it follows the development of the branch corresponding to damage of *i*-SDPU due to explosion on *j*-NDPU.

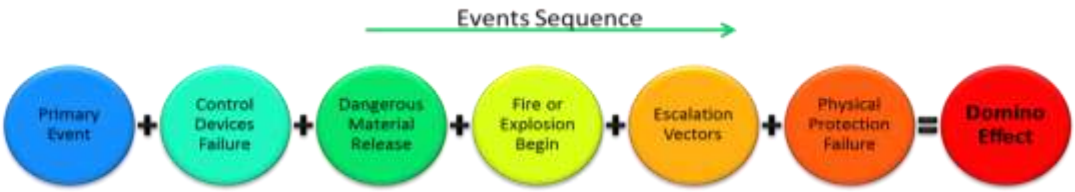

Figure 1. Domino accident sequence

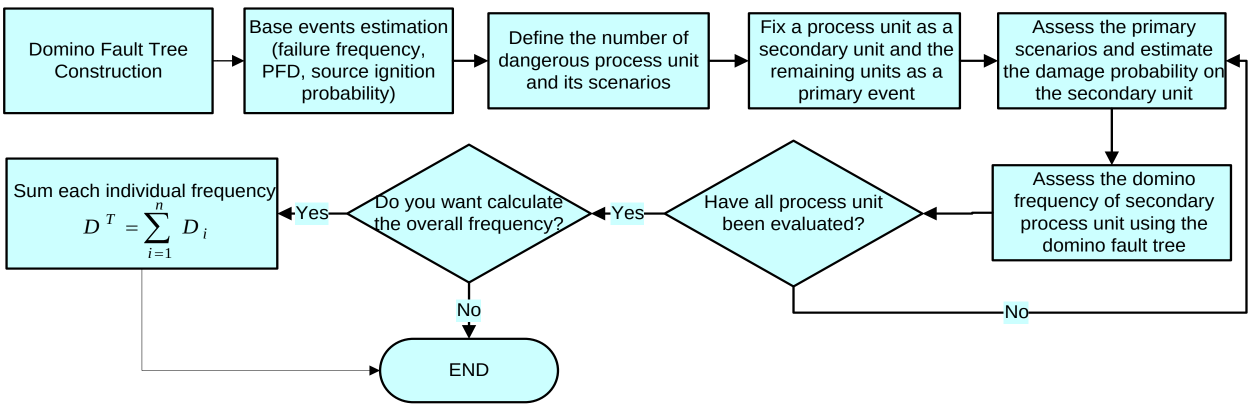

Figure 2. General methodology

Damage due to fire

Three events must be combined when a *i*-SDPU can be damage by fire as a result of radiation effect: a fire scenario on any *j*-NDPU, high radiation damage probability from *j*-NDPU to *i*-SDPU and failure of physical protection installed on *i*-SDPU. Two conditions must be satisfied to get a fire: a dangerous material release (DMR) from any *j*-NDPU and having an ignition source. A DMR could come from a failure in any *j*-NDPU so that each of them must be included. The failure of any *j*-NDPU is a consequence of two basic events: the probability of failure in the unit itself and the probability of failure on demand (PFD) on its installed control devices. The next necessary event to produce damage due to fire is the high radiation damage probability. Two aspects have been considered to perform this evaluation. It is firstly considered that the thermal radiation is the unique escalation vector of the fires and it can come from any kind of fire, pool fire, jet fire and fire ball so that each of them is included into the analysis. It is secondly considered here that, depending on process conditions, all the *j*-NDPU may develop one or more risk scenarios and hence the damage probability of each scenario must potentially include all *j*-NDPU, Figure 4. The last condition refers to the physical protection installed on the *i*-SDPU, which has no more branches, as indicated in the diagram. The assessment of the basic events will be described in the next section.

Damage due to explosion

The structure described above is similar to the damage due to an explosion where the only difference is the damage probability assessment. Thermal radiation is considered as the unique escalation vector for fires; however, explosions have two main escalation vectors which are overpressure and missiles. Both overpressure and missiles damages probabilities must be assessed for all potential j-NDPU having potential for an explosion. The explosion scenarios considered were VCE and BLEVE. The others sub branches are equal to the damage due to a fire branch.

Domino frequency assessment procedure

A detailed assessment should be conducted for all basic events as a first step to get the total domino frequency. It includes equipment failure frequency, probabilities of failure on demand (PFD) for passive or dynamics protections and probability of ignition source. Two situations should be considered for failure frequency: historical failure data of the plant should be used to determine the basic event value when the assessment is in installed plants and bibliographic references can be used to make the first estimation when the assessment is for a new project. A long list for failure frequency in different units is found in the OREDA handbook (OREDA 2002), as well as in other associations or industries such as the International Association of Oil & Gas (OGP 2010) and DNV report (DNV 2006). The PFD is a measure for effectiveness of protection devices and its values are estimated via fault trees. Values for weakest protections are around $1x10^{-1}$, and for strongest protections range $1x10^{-4}$ – $1x10^{-5}$ (CCPS 2001). A methodology to predict and model more accurately the PFD in protection layers, considering many variables into a fault tree structure, has been recently proposed (Rathnayaka et al. 2011; Rathnayaka et al. 2011). Though evaluating the probability of ignition source is very difficult since it depends on many variables, the International Association of Oil & Gas has published a report on ignition probabilities (OGP 2010) and an algorithm to predict it has been also developed (Moosemiller 2011; Rathnayaka et al. 2011).

Once probabilities for all basic events are estimated, the next step is to define the number of dangerous process unit (DPU) with theirs scenarios to detect all DPU as second unit and remaining units with primary events, assessing the primary events and estimating the damage probability for the second unit. The damage probability must be assessed for all escalation vectors (radiation, overpressure and missiles) and it can be done through probit models. There are several probit models reported on bibliography, but the models used in this work were taken from Antonioni and coworkers and Gubinelli and coworkers (Gubinelli et al. 2004; Antonioni et al. 2009). The damage probability was approximated using the Vilchez's equation (Vilchez et al. 2001).

In the next step, the domino frequency is estimated based on the domino fault tree. The domino fault tree is resolved using Boolean algebra, Figure 3. The resultant equations for each event is described from bottom to top of the tree, starting with the damage due to fire branch and subsequently the damage due to explosion. The first event to assess is the equipment failure frequency, f_j, represented by,

$$f_j = f_j^{fail} \cdot PFD_j^{CD} \tag{1}$$

where, f_j^{fail} is the itself failure frequency of j-NDPU, and PFD_j^{CD} is the probability of failure on demand of control devices installed on j.

The dangerous material release frequency, f^E, is calculated by,

$$f^E = \sum_{j=1}^{n} f_j^{fail} \cdot PFD_j^{CD} \tag{2}$$

The fire scenario frequency, f^F, on j-NDPU is estimated as follows,

$$f^F = f^E \cdot P_I^S \tag{3}$$

where P_I^S is the probability of ignition source.

The domino frequency due to fire, D^F, is estimated with three events using the fire scenario frequency, radiation damage probability, P_R^D, and probability of failure on demand for physical protections, PFD^{pasive}. The domino frequency and the radiation damage probability are represented as follows:

$$D^F = f^F \cdot P_R^D \cdot PFD^{pasive} \tag{4}$$

$$P_R^D = \sum_{j=1}^{n} P_{Pool\,j}^D + \sum_{j=1}^{n} P_{Jet\,j}^D + \sum_{j=1}^{n} P_{Ball\,j}^D \tag{5}$$

where P_{Pool}^D is the radiation damage by pool fire, P_{Jet}^D is the radiation damage by jet fire and P_{Ball}^D is the radiation damage by fire ball. All these fire scenarios come from the j-NDPU, j, to the i-DPU.

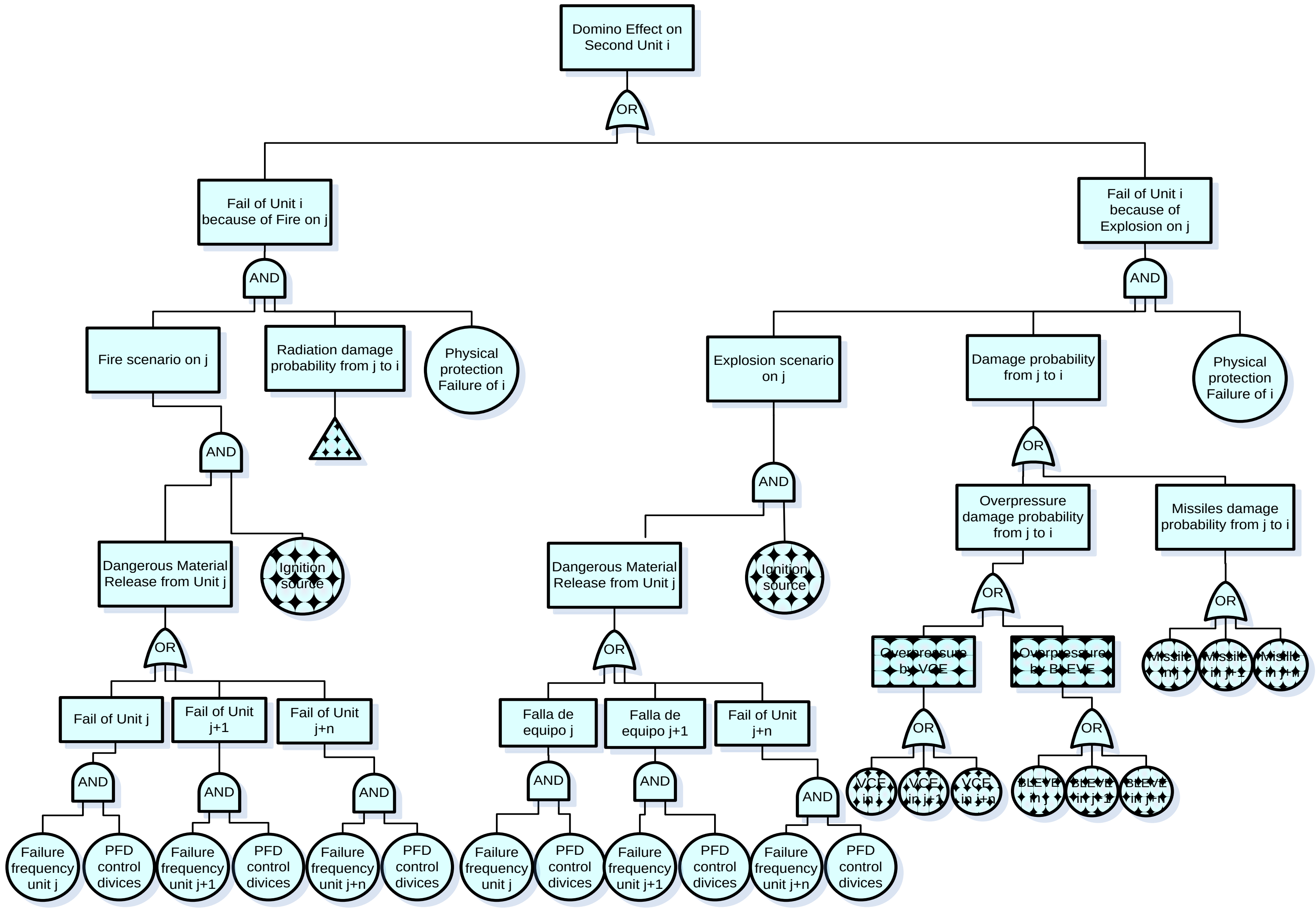

Figure 3. Domino fault tree

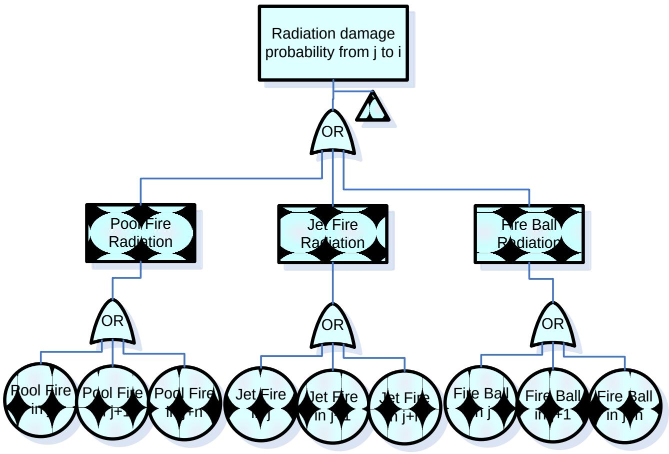

Figure 4. Extension of domino fault tree

The estimation of domino frequency damage due to explosion, D^{Ex} , is similar to the damage due to fire:

$$D^{Ex} = f^{Ex} \cdot (P_O^D + P_M^D) \cdot PFD^{pasive} \tag{6}$$

where PFD^{pasive} is the probability of failure on demand in passive devices installed on i.

Then equation (1) and (2) are applied in the same way. The explosion scenario frequency, f^{Ex}, is assess by:

$$f^{Ex} = f^E \cdot P_I^S \tag{7}$$

The total damage probability due to overpressure, P_O^D, represents the sum of all possible VCE and BLEVE scenarios from all *j*-NDPU,

$$P_O^D = \sum_{j=1}^{n} P_{VCE}^D + \sum_{j=1}^{n} P_{BLEVE}^D \tag{8}$$

The total damage probability due to missiles, P_M^D is defined by the sum of all damage because of missiles from any *j*-NDPU,

$$P_M^D = \sum_{j=1}^{n} P_{M_j}^D \tag{9}$$

Finally, the top event is the domino effect on a second unit, D_i, because of fire or explosion represents the link of these two branches:

$$D_i = D^F + D^{Ex} \tag{10}$$

The above described domino fault tree procedure is used to assess the domino occurrence frequency of a second dangerous equipment, i; affected by all *j*-NDPU, Figure 5a. However, the total domino frequency has to consider all possible interactions among all dangerous equipment, Figure 5b. Then, the fault tree for the total domino frequency is showed on Figure 6, and it is solved by,

$$D^T = \sum_{i=1}^{n} D_i \tag{11}$$

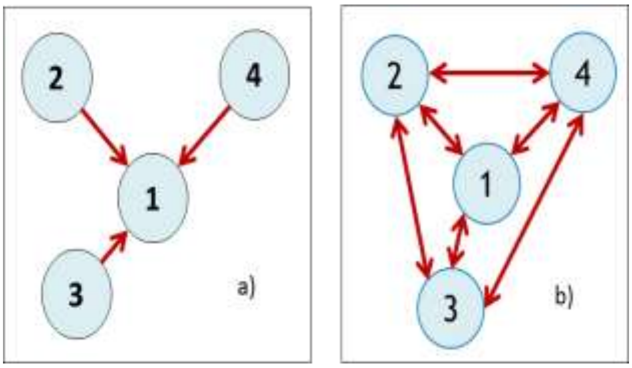

Figure 5. Process units interaction

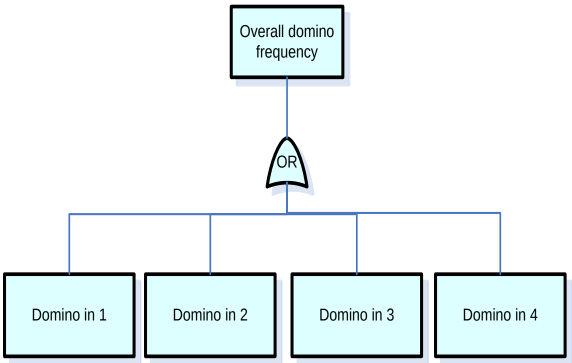

Figure 6. Overall domino frequency

Case study

A storage area, introduced in (Cozzani et al. 2005), is used here to illustrate the domino frequency estimation procedure. However, several assumptions are introduced to allow the assessment. Figure 7 shows the layout used and Table 1 summarizes the possible scenarios for each process tank, as well as relevant characteristics of the units considered in the plan layout. Additional information about PFD and failure frequency of the equipment is given in Table 2. The PFD for dynamics and physical protections were taken from others (CCPS 2001; Crowl et al. 2002; Rathnayaka et al. 2011). For the sake of simplicity, a single scenario was associated to each process tank, and it was considered as the only possible primary and/or secondary event, excepting the LPG sphere, TK10, which was considered with two primary events. Credible accidents on process tank were defined as scenarios, Table 1. The study was mainly focused on determining the domino effect frequency and the severe scenarios considered were BLEVEs, VCEs, fire ball or pool fire involving the entire catch basin and the complete tank inventory. Those models described in the “yellow book” were used for the consequences assessment (CPR14E 2005).

Results and discussion

The case study has nine process tanks, eight of them were atmospherics and one pressurized, Figure 6. The primary and secondary events for atmospheric tanks were pool fire. On other hand, the pressurized thank had as primary events both fire ball and VCE. The results after calculating the occurrence frequency procedure are summarized in Table 3. As expected, a lower overall domino frequency is obtained when the process units were equipped with some kind of safety devices. Values of $1.3\text{x}10^{-9}$ and $1.58\text{x}10^{-7}$ were obtained when process units were protected and when they were unprotected, respectively.

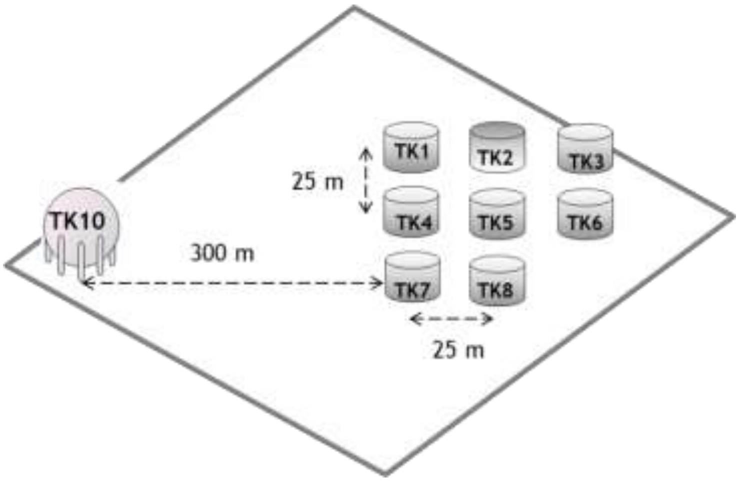

Figure 7. Pressurized and atmospheric thanks layout

Table 1. Units description and primary scenarios

Unit	Type	Substance	Content (ton)	Type of released	Quantity released	Primary scenario	Escalation vector
TK1	Atmospheric	Ethanol	2000	Instantaneous	All inventory	PF	Radiation
TK2	Atmospheric	Ethanol	2000	Instantaneous	All inventory	PF	Radiation
TK3	Atmospheric	Ethanol	2000	Instantaneous	All inventory	PF	Radiation
TK4	Atmospheric	Ethanol	2000	Instantaneous	All inventory	PF	Radiation
TK5	Atmospheric	Ethanol	2000	Instantaneous	All inventory	PF	Radiation
TK6	Atmospheric	Ethanol	2000	Instantaneous	All inventory	PF	Radiation
TK7	Atmospheric	Ethanol	2000	Instantaneous	All inventory	PF	Radiation
TK8	Atmospheric	Ethanol	2000	Instantaneous	All inventory	PF	Radiation
TK10	Pressurized	LPG	1400	Instantaneous	All inventory	FB	Radiation
TK10	Pressurized	LPG	1400	Total 10 min	All inventory	VCE	Overpressure

Table 2. PFD and failure probability

Unit	f_j^{fail}	PFD_j^{CD}	PFD^{pasive}
TK1	$3.25x10^{-8}$	0.1	0.1
TK2	$3.25x10^{-8}$	0.1	0.1
TK3	$3.25x10^{-8}$	0.1	0.1
TK4	$3.22x10^{-8}$	0.1	0.1
TK5	$3.25x10^{-8}$	0.1	0.1
TK6	$3.25x10^{-8}$	0.1	0.1
TK7	$3.25x10^{-8}$	0.1	0.1
TK8	$3.25x10^{-8}$	0.1	0.1
TK10	$5.40x10^{-8}$	0.01	0.1

Table 3. Domino frequency of case study two

Unit	f^E	f^F	$P^D_{Pool\,j}$	$P^D_{Ball\,j}$	P^D_R	P^D_O	D^F	D^{Ex}	$D_i^{protected}$	$D_i^{unprotected}$
TK1	$2.33x10^{-8}$	$3.26x10^{-9}$	$3.28x10^{-5}$	0.007	$7.0x10^{-3}$	0.564	$2.41x10^{-12}$	$1.84x10^{-10}$	$1.86x10^{-10}$	$2.25x10^{-8}$
TK2	$2.33x10^{-8}$	$3.26x10^{-9}$	$4.93x10^{-5}$	0.007	$7.05x10^{-3}$	0.478	$2.16x10^{-12}$	$1.56x10^{-10}$	$1.58x10^{-10}$	$1.90x10^{-8}$
TK3	$2.33x10^{-8}$	$3.26x10^{-9}$	$3.28x10^{-5}$	0.006	$6.03x10^{-3}$	0.391	$1.92x10^{-12}$	$1.27x10^{-10}$	$1.29x10^{-10}$	$1.56x10^{-8}$
TK4	$2.33x10^{-8}$	$3.26x10^{-9}$	$4.93x10^{-5}$	0.007	$8.0x10^{-3}$	0.575	$2.45x10^{-12}$	$1.87x10^{-10}$	$1.90x10^{-10}$	$2.29x10^{-8}$
TK5	$2.33x10^{-8}$	$3.26x10^{-9}$	$6.59x10^{-5}$	0.007	$7.07x10^{-3}$	0.488	$2.19x10^{-12}$	$1.59x10^{-10}$	$1.61x10^{-10}$	$1.94x10^{-8}$
TK6	$2.33x10^{-8}$	$3.26x10^{-9}$	$3.30x10^{-5}$	0.006	$6.03x10^{-3}$	0.4	$1.94x10^{-12}$	$1.31x10^{-10}$	$1.32x10^{-10}$	$1.6x10^{-8}$
TK7	$2.33x10^{-8}$	$3.26x10^{-9}$	$3.28x20^{-5}$	0.007	$8.0x10^{-3}$	0.578	$2.45x10^{-12}$	$1.89x10^{-10}$	$1.91x10^{-10}$	$2.3x10^{-8}$
TK8	$2.33x10^{-8}$	$3.26x10^{-9}$	$3.30x10^{-5}$	0.007	$7.03x10^{-3}$	0.491	$2.19x10^{-12}$	$1.60x10^{-10}$	$1.62x10^{-10}$	$1.96x10^{-8}$
TK10	$2.60x10^{-8}$	$3.64x10^{-9}$	$1.47x10^{-55}$	0	$1.47x10^{-55}$	0.0	$5.36x10^{-65}$	0.00	$5.36x10^{-65}$	$5.36x10^{-63}$

The consequences analysis is done using the methods described in the "yellow book". Probit models were used to assess both radiation and overpressure damage probability. In this case, it can be observed that safeguards devices play an important role in the final domino frequency value. After performing the assessing suggested here, it becomes easier to identify which nits are the most vulnerable. In this case, it can be observed that tank 10 has the biggest influence in the frequency value. The immediate explanation is that its consequence is higher than the remaining tanks. The case study shows the simplicity and versatility of this methodology, giving a fast and trusted evaluation for the overall and individual domino effect frequency.

Conclusions

A new methodology to assess the domino frequency has been presented in this work. The methodology is considerably simpler than all previous approaches; however, the reliability accuracy of this approach depends on the quality of source data. This methodology is based on the fault tree analysis and it takes into account important aspects affecting the frequency estimation such as ignition source probability and probability of failure on demand for active and passive devices. The application of this methodology does not require extra effort on the QRA analysis. It can be applied for storage and process facilities in both new and installed plants. This methodology can be a useful tool in the QRA analysis since it improves the domino frequency accuracy and, thereby, the domino effect prevention.

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