The Quantitative Risk Assessment of domino effect on Industrial Plants Using Colored Stochastic Petri Nets

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Abstract: The accidents caused by the domino effect are those that cause the most catastrophic damage. The consequences of the damage caused are at various levels and may not only affect the industrial sites (activities, importance), but also people, environment and economy. The fire is among the most frequent primary accidents for a domino effect sequence, due to the installations/equipments under pressure, and the storage of flammable and dangerous substances, storage areas being the most probable starters of a domino effect. Heat radiation generated by fire is one of major factor leading to domino effects on industrial/storage sites and likely to lead to damage and serious consequences for equipments, facilities, staff, buildings, and environment. In the last decade, the available methodologies for the assessment of domino effects are mainly based on the probit models. This paper develops a new methodology for the quantitative assessment of domino effect caused by heat radiation to process equipments and/or storage vessels in industrial sites using a Colored Stochastic Petri Nets model.

Keywords: Domino effect, Risk assessment, Stochastic Petri Net, Storage areas.

1. Introduction

The accidents caused by the domino effect are those inducing the most catastrophic consequences. These consequences are at various levels and may not only affect the industrial sites, but also people, environment and economy. The potential risk of the domino effect is widely recognized in the legislation since the first "Seveso-I" European Community Directive (82/501/EEC), and the second "Seveso-II" Directive (96/82/EC).

Over the period 1992 to 2009, the ARIA data base has recorded 33 142 events in the European Union. In France, the same data base has recorded 1073 technological accidents from January to December 2008, and 1477 others from January to December 2009, where more than 60% of accidents are caused by fires, followed by the release of hazardous materials and explosions.

Recently, an inventory of the past domino accidents [1], reveals that explosions are the most frequent cause of domino effects (57%), followed by fires (43%). A study of 225 accidents involving domino effects [2], shows that storage areas are the most probable starters of a domino effects (35%), followed by process plant (28%) and transportation of hazardous materials (19%). Also, the most frequent accident sequences are explosion → fire (27.6%), fire → explosion 27.5% and fire → fire (18%).

Heat load generated by fire is one of major factor leading to domino effect on industrial plants and storage areas [3]. It may affect the surrounding units. If the affected targets are damaged, these latter may also explode and generate other threats to other surrounding units and so on. This chain of accidents may lead to catastrophic consequences on industrial plants.

A review of methodologies and software tools used in the literature to the study of the cascading events [4], shows that, in the last decade, the available methodologies for the assessment of domino effects are mainly based on the probit models. In the framework of domino effect analysis, the failure of the affected target unit is not instantaneous; it depends not only on the dynamical characteristics of the physical effects (escalation vectors) but also on the intervention time. So, it is necessary to determine the failure time and the intervention time of each affected target by the physical effects.

In this article, a new methodology for the quantitative risk assessment of domino effect caused by heat load on industrial plants is proposed. This methodology is based on a Colored Stochastic Petri Nets model and physical models, which allows quantifying the effect of the escalation vectors (physical effects), taking into account deterministic and probabilistic aspects of the physical models, the reliability and the availability of the intervention/mitigation system. After this introduction, the analysis of the previous works identified in literature, definition and main features of Stochastic Petri Net approach are presented. The next section, details the main steps of the developed methodology. Then, the fourth section deals with a case study to show and comment some significant results. And finally, the paper is completed by a conclusion and perspectives.

2. ANALYSIS OF PREVIOUS WORKS

2.1. Bases of domino effect analysis

A domino accidental event is defined as an accident in which a primary event propagates to nearby equipment, triggering one or more secondary events resulting in overall consequences more severe than those of the primary event [5].

The analysis of the technical literature shows that all the accidental sequences where a relevant domino effect took place have three common features [6, 7]:

(a) A primary accidental scenario, which initiates the domino accidental sequence;

(b) The propagation of the primary event, due to an escalation vectors, generated by the physical effects of the primary scenario, that results in the damage of at least one secondary target;

(c) One or more than one secondary accidental scenarios or events, involving the same or different plant units causing the propagation of the primary event.

Although several studies were dedicated to the detailed analysis of fire and/or explosion damage to process equipment, only few simplified models are available for the assessment of equipment damage by fire in the framework of domino effect [8, 9, 10]. A quantitative study of domino effect has been made by [11]. They have described possible approaches for quantifying the consequences of domino effects resulting from events rising the thermal radiation.

A simplified model has been proposed by [5, 12, 13, 14], based on the probit approach developed by [15]. They have analyzed and reviewed the existing models to develop a probabilistic model for damage to specific categories of industrial equipments. The damage probability proposed by [12] takes into account four categories of industrial equipments: atmospheric vessels, pressurized vessels, elongated vessels, and small equipment.

To estimate the time to failure (*ttf*) of industrial equipments exposed to fire. A simplified model proposed by [16] is based on the probit approach. The authors have built a specific probit function which links the time to failure (ttf) to the probability of escalation:

$$Y = a + b \times ln(ttf) \tag{1}$$

Where Y is the probit function for exposed equipment, ttf is the time to failure (sec), a and b are the probit coefficients (a = 12.54 and b = -1.847 for atmospheric and pressurized vessels respectively). Table 1 presents the thresholds and damage probability models of two categories of equipment.

Table 1: Damage probability models and threshold values for the heat radiation, where *ttf* is the time to failure (sec), V is the vessel volume (m^3) and I is the amount of heat radiation received by the target vessel (kW/m^2) [16].

Equipment category	**Threshold**	**Correlation**
Atmospheric vessels	15 kW/m^2, $t \geq$ 10 min	ln(ttf)= - 1.128ln(I) -2.66710^{-5}V + 9.887
pressurized vessels	50 kW/m^2, $t \geq$ 10 min	ln(ttf)= - 0.947ln(I) +8.835$V^{0.032}$

The intensity of heat radiation received by a target unit (system) is very important for the quantification of domino effects in industrial plants/storage areas. Different formulas are used to quantify the heat radiation generated by a fire. The radiation on a receptor body located at a distance r from the center of a fire ball or pool fire may be expressed by the following equation [17]:

$$I(r) = \frac{\tau F_s D^2 m_\infty H_C}{16.r^2} \tag{2}$$

Where: $I(r)$ is the heat radiation flow (kW/m^2), F_s is the fraction of the generated heat radiated from the flame surface (between 0.13 and 0.4), m_∞ is the combustion velocity per unit surface area of the pool $[kg/(m^2.s)]$, τ is the atmospheric transmissivity coefficient (usually between 0.2 and 0.8), H_C is a combustion heat (kJ/kg), D is the pool diameter (m) ($D_{max} = 5.8\times\ m_t^{\frac{1}{3}}$, m_t is the total mass of the fuel in kg).

2.2. Stochastic Petri Nets

The Stochastic Petri Nets have been introduced in 1978 by Florin in the aim to model certain problems involving random phenomena. They have been used in different systems for modeling random phenomena [18]. This concept has attracted many researchers [19, 20].

The Generalized Stochastic Petri Nets (GSPN) have two types of transitions; immediate transitions and temporized transitions [21]. The Petri nets are used for dynamic systems specification, description and verification in a wide range of applications. The SPN is also widely used for risk analysis, accident modeling and safety [22, 23].

3. METHODOLOGY

In the framework of domino effect analysis, the failure of a target unit depends on the dynamic characteristics of the escalation vectors (physical effects), threshold values, category of the target unit, the characteristics of the substance stored or manipulated, and the robustness of the mitigation/intervention systems.

3.1. Representation of system states (state of each unit)

An industrial system is composed of several subsystems or units $(U_1, U_2, ..., U_n)$. In the framework of domino effect analysis, each unit can be characterized by the following three main states:

$$U_i = \begin{cases} State1, & \text{Running state,} \\ State2, & \text{Affected state,} \\ State3, & \text{Failure state.} \end{cases} \tag{3}$$

(a) State 1: In normal operation, the output values induced by the input parameters of the system are less than the threshold values respectively. In this state, the unit may be affected by the escalation vector(s) generated by a primary event(s).

(b) State 2: The intensity or the value(s) of escalation vector(s) is equal to its corresponding threshold value, the unit is affected. The unit is possible and depends on its time to failure. This ttf is dependent on the nature or category of the unit, the amount of present danger or threat and intervention/mitigation system. In this state, the time to failure is greater than the intervention delay.

(c) State 3: The value of the escalation vector(s) is greater than its corresponding threshold value. In this state, time to failure is less than the intervention delay.

3.2. Transition between system states

Considering two units, the transitions may take place from the state 1 to state 2 and/or state 3, between the two units, from the failed state of the primary unit to the affected state and/or the failed state of the second unit.

To study the sequence of domino effect, one can take as starting point, the failure of at least one unit as initiating event. Based on the assumption, there is at least one failed unit. Figure 1 represents the possible transitions states in the case of two units.

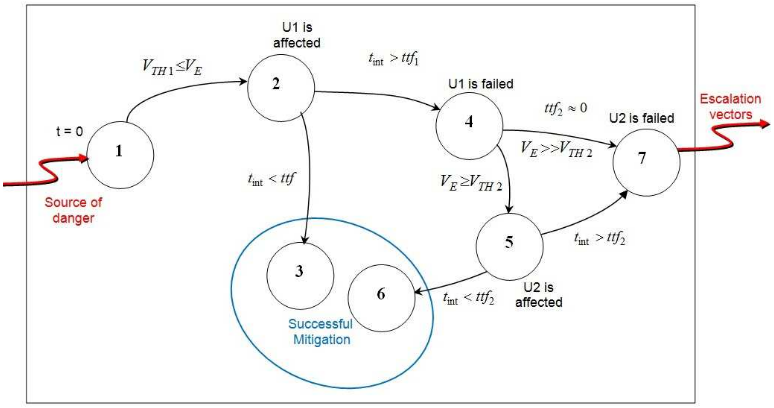

Figure 1: Transition states in the case of two units, where ttf is the time to failure, t_{int} is the intervention time, V_E is the estimated value of physical effect and V_{TH} is the threshold value.

- State 1: is the initial state (both U1 and U2 are in normal operation). In this state, at $t = 0$, we consider that a primary incident have occurred, it may affect or cause the failure of the two target units.
- State 2: it is a state in which U1 is affected by the primary event, and U2 is in normal operation.
- State 4: knowing that U1 is affected, this step represents the state in which the unit (U1) is failed ($t_{int} > ttf$). The failure of U1 may generate other threats to other and may affect and/or cause the failure of U2.
- State 5: represents the state where U2 is affected by the physical effects generated by the failure of U1 ($V_E \geq V_{TH2}$). If the emergency assistance does not intervene, the target U2 may become failed.
- State 3 and State 6: These states represent the state in which the mitigation is successful ($t_{int} < ttf_1$) and ($t_{int} < ttf_2$) and/or the threat is stopped or removed. In this case, the escalation is stopped at this state.

- State 7: In this state, U1 and U2 are failed. This state may generate other escalations vectors that may affect other surrounding targets and so on.

3.3. Simplified Colored Stochastic Petri Nets (CSPN) Model

3.3.1. Domino scenario principle

A system is composed of four units (U_1,...,U_4), assuming that U1 is failed, and the escalation vector(s) generated after the failure of the U_1 possibly affect the surrounding units (U_1, U_2, U_3). The ttf_i for each affected target and its corresponding t_{int_i} can be estimated. In this example, this estimation facilitates the study of the domino scenarios, only the time to failure ttf_i is taken into consideration.

The case where another target fails (for example U_3) is considered. Consequently, its escalation vectors add to those of U_1, and this sum leads to affect U2 and U4. So, the new ttf_2 and ttf_4 taking into account of the intensity of the escalation vector(s) $I_{12} + I_{14}$ and $I_{32} + I_{34}$ have to be updated, and so on (see Figure 2).

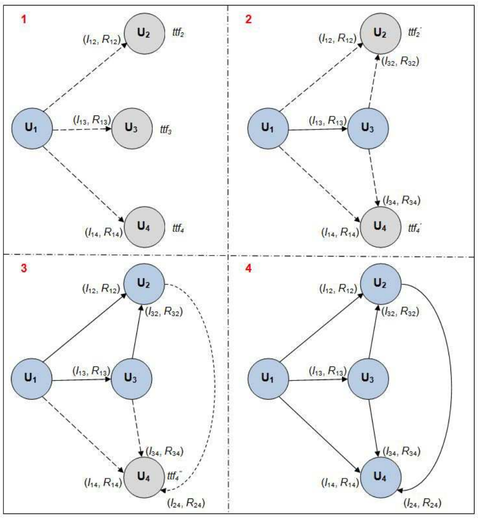

Figure 2: Domino scenario principle

For example, the actual time to failure (ttf) of the unit U_2 may be estimated by the following equation:

$$ttf_2 = ttf_3 + min(ttf_{12} + ttf_{32}) \tag{4}$$

Where ttf_3 is the time to failure of the unit U_3, ttf_{12} is the time to failure of the unit U_2 caused by the rupture (explosion) of the unit U_1 and ttf_{32} is the time to failure of the unit U_2 caused by the rupture of the unit U_3.

In general case, one assume that we have n units, where k units are failed ($k < n$) which may affect the j^{th} target unit. So, the time to failure of the j^{th} unit may be estimated as follow:

$$ttf_j = ttf_{AFT} + min(ttf_1, ttf_2, ..., ttf_k) \tag{5}$$

where, ttf_j is the time to failure of the j^{th} unit, ttf_{AFT} is the time to failure of the last failed target (actual failed time).

3.3.2. Unit States

According to the previous steps, each unit can be characterized by a state graph represented by a basic (elementary) Stochastic Petri Nets. Each unit state is represented by a colored token. The place P_1 contains the units in normal operation. The place P_2 contains the affected units. The place P_3 contains the mitigated units. The place P_4 contains the failed units, this place represents the source of danger for the surrounding units (see Figure 3).

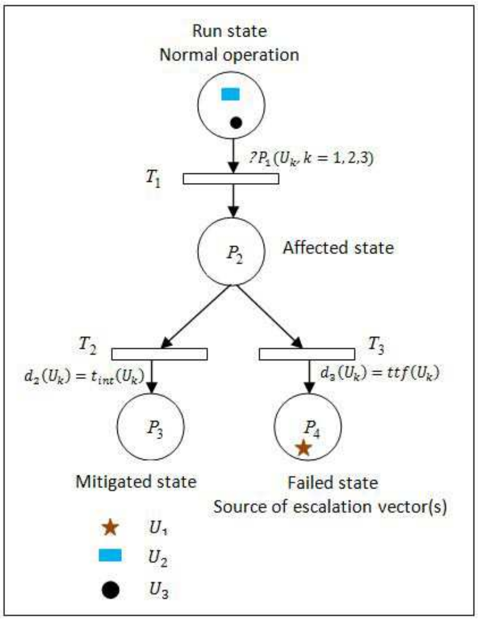

Figure 3: Basic Stochastic Petri Nets for unit states

The mitigated states differs from the failed states by the fact that the estimated time to failure (*ttf*) exceeds the intervention time (t_{int}) according to the intensity of the escalation vectors.

3.3.3. Firing conditions

According to the previous steps, a primary scenario has caused the catastrophic failure of one unit, this latter possibly generating a heat radiation that may affect the other surrounding units. The system behavior evolution is simulated by the firing of transitions, a transition firing corresponding to the occurrence of an event. In the same way, an event affects the system state, and leads to transition fires, and finally modification of the Stochastic Petri Net marking.

(a) T_1: the transition is fired if the estimation of the intensity of the escalation vector ($V_E(t)$) is greater than its corresponding threshold value. In the case of heat radiation, ($V_E(t)$) may be estimated using the Eq.(2). If $V_E(t) \geq \mathrm{V}_{TH}$, then the firing condition is true.

(b) T_2: the transition is fired if $t_{int} < ttf$, where the ttf is estimated by using the results of the table 1 and the t_{int} is obtained by another Petri Net describing the intervention system. An approximate distribution of time for the arrival of emergency teams and the start of the chain of emergency [24], has been estimated recently; only 10% of cases, the chain of emergency can start in less than 5 minutes, and 90% of cases, the chain of emergency can start in less than 20 minutes.

(c) T_3: the firing condition of the transition T_3 is $t_{int} > ttf$ (T_2 doesn't fire).

If U is the units ensemble, N the total number of units in the normal state (normal operation), A the number of affected units, M the number of mitigated units, and F the number of failed units, then:

$$U = N + A + M + F \tag{6}$$

where $N = P_1$, $A = P_2$, $M = P_3$, $F = P_4$. If $U_k \in F$, each unit from F may affect (cause the damage or the failure of) the units from N and A ($U_{k'} \in N$; $k' \neq k$, $U_{k''} \in A$; $k'' \neq k$ and $k'' \neq k'$).

3.3.4. Failure probability/mitigation probability

According to the figure 3, the failure probability (P_{U_i}) for each unit may be calculated as the firing probability of the transition T_3. The mitigation probability of the unit U_i is the firing probability of the transition T_2 knowing that the transition T_1 is fired.

3.3.5. Domino scenario probability

While failure probability, P_{U_i} is known for each unit, the probability of domino effect may be evaluated for the whole system. The probability of each domino scenario (domino sequence) may be calculated as follows:

$$P_{DO_i} = \prod_{j=1}^{n} P_{U_j} \tag{7}$$

Where, n is the number of the failed unit involving in the domino sequence, the probability of domino sequence i, P_{DO_i}, is the joint probability that each unit from sequence i fails.

4. CASE STUDY

The above defined methodology was used in the case-study in order to assess domino effect in the case of LPG storage area. The lay-out considered in the analysis is shown in Figure 4. The type of equipments and their inventory are shown in the Table 2. We assume that a primary scenario has caused the failure of one tank. The latter can generate three escalation vectors, and may affect the surrounding units. Some simplifications are used in the present study, only the heat effects of heat radiations has been considered and all tanks are spherical.

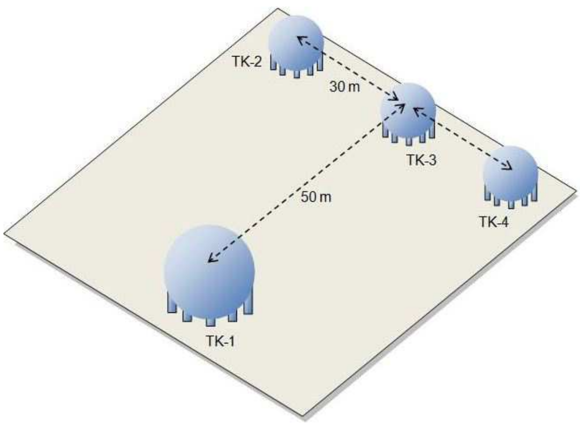

Figure 4: Lay-out used for the case-study.

Table 2: Equipment considered in the case-study.

Tank	**Type**	**Substance**	**Content** (m^3)
TK1	Pressurized tank	LPG	1600
TK2-TK4	Atmospheric tank	Ethanol	400

4.1. Effects on surrounding equipments without intervention

In the case-study, the catastrophic failure of the unit or TK1 is considered as the primary event. The influence parameters used in this study are presented in the table 3. The radius of the zones affected by the heat radiation resulting from the catastrophic failure of TK1 are represented in the figure 5.

According to this figure, we can define three types of zones: i) zone of certain destruction, ii) zone of possible destruction, and iii) safety zone. One remarks that whole process equipments that are in the area limited by the radius of 841 m have failed with failure probability $P_F = 10^{-6}$.

Table 3: The influence parameters used in the case of heat radiation, where $\mu = 0.5\times\ln(2\mathrm{R}\times D_{max})$ $\sigma = 0.26\times\ln(\frac{D_{max}}{2R})$ and R is a spherical tank rayon.

Random parameters	**Probabilistic distribution**	**Deterministic parameters**
τ: Atmospheric transmissivity	$\tau \sim U(0.2,\ 0.8)$	$H_{C_{LPG}}$= 46.333 (MJ/Kg)
F_s: Fraction of the generated heat	$F_s \sim N(0.265{,}0.0821)$	$m_{\infty_{LPG}}$= 0.099 $[Kg/(m^2.s)]$
D: Pool diameter	$D \sim N(\mu,\ \sigma)$	$H_{C_{Ethanol}}$= 29.7 (MJ/Kg)
t_{int}: intervention time	$t_{int} \sim N(12.5,\ 5.814)$	$m_{\infty_{Ethanol}}$= 0.015 $[Kg/(m^2.s)]$

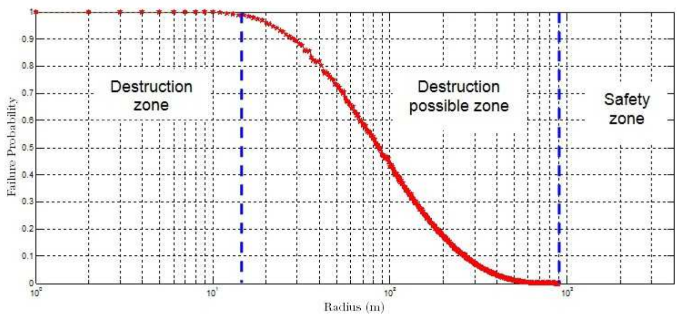

Figure 5: The failure probability and the affected zones resulting from the rupture of TK1.

4.2. Effects on surrounding equipments with intervention

One assume that, the probability of the initiating event (the catastrophic failure of the TK1, $P_{f_{tk1}} = 10^{-6}$). The domino sequence probability, P_{DO_i} for each domino scenario is tabulated in the table 4.

The influence parameters used in this study have great influence on the failure probability and the damage radii. The domino sequences probabilities in function of the pool diameter are represented in the figure 6 below.

Table 4: The probability of each domino scenario, with $D = 2.5 \times D_{min}$ $\tau = 0.5932$, $F_s = 0.307$, $t_{int} \sim N(12.5, 5.814)$.

Scenario	Domino sequence	Domino sequence probability P_{DO_i}
1	TK1-TK3	1.76×10^{-7}
2	TK1-TK3-TK2	3.28×10^{-9}
3	TK1-TK3-TK2-TK4	3.49×10^{-9}

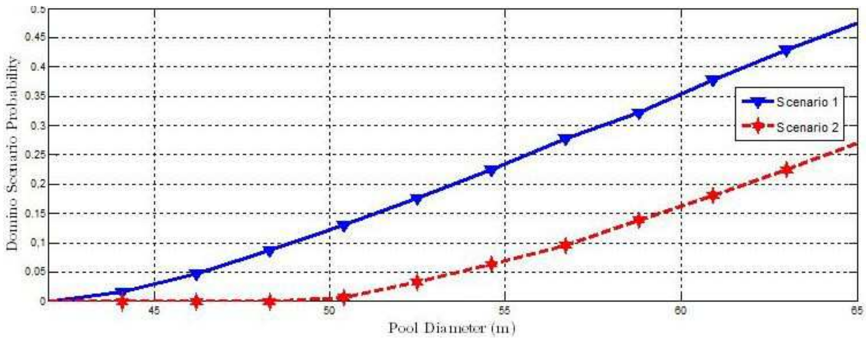

Figure 6: Domino sequence probability in function of the pool diameter, $\tau = 0.5932$ $F_s = 0.307$, and $t_{int} \sim N(12.5, 5.814)$.

5. CONCLUSION

A quantitative method for the assessment of domino effects in industrial sites has been developed in this paper. This methodology is based on the Colored Stochastic Petri Nets model coupled with the physical models. It allows quantifying the effect of the escalation vectors (heat radiation) in industrial plants taking into account deterministic and probabilistic aspects of the physical models and the intervention system.

Based on this method, we can assess the time to failure (ttf) for each unit which depend on the intensity of the escalation vectors, the category of the equipment and the robustness of the intervention system (t_{int}). Then, the failure probability for each unit affected by the physical effects may be obtained. After that, the probability of the possible domino scenarios (domino sequences) may be assessed for the whole site.

In the study of the cascading events in industrial plants, we must analyze the reliability and the availability of the safety system and emergency assistance. For a better estimation of the failure probability and ttf of the target unit, we must assess the failure probability of the target due to the three escalation vectors (heat load, overpressure and fragments). These are being modeled for a forthcoming paper.

The analysis above shows the importance of domino effect assessment in the framework of risk analysis. Hence, it shows that must much more importance be attached to the study of this phenomenon.

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