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# Domino Effect Analysis and Assessment of Industrial Sites: A Review of Methodologies and Software Tools

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## ABSTRACT

In the field of risk analysis, the accidents caused by the domino effects are those inducing the most catastrophic consequences. The consequences of these latter are at various levels and may affect not only the industrial sites, but also people, environment and economy. The probability of the domino effects is increasingly high due to development in industrial complexes, the proximity of such industrial plant, the storage of dangerous substances and the transportation networks. The diversity of these factors is even more critical that they are often related to the emergence of new threats that exploit the malicious acts and human error. Although the literature abounds in several studies on domino effects, it is necessary to deepen their analysis, and pay more attention to their modeling. This article presents the main existing methods and software tools for analysis and modeling of domino effects. A conclusion and perspectives are also proposed.

**Keywords:** Domino effect, Cascading events, Risk assessment, software tools, Explosions, Fires.

## I. INTRODUCTION

In the field of risk analysis, domino effect has been documented in technical literature since 1947. The accidents caused by the domino effects are those inducing the most catastrophic consequences. The consequences of these latter are at various levels and may affect not only the industrial sites (activities, importance ...), but also people, environment and economy. The probability of the domino effect is increasingly high due to the development in industrial plants, their proximity to such establishments, and their inventory of dangerous substances. The probability of domino effects is increasingly high due to development in industrial plants, the proximity of such establishments, their inventories of dangerous substances and the transportation of the dangerous substances. The potential risk of the domino effect is widely recognized in legislation since the first "Seveso-I" Directive (82/501/EEC), which required the assessment of domino effects in the safety analysis of industrial sites whose activities are subject to this directive. Furthermore, the "Seveso-II" extended these requirements to the assessment of domino effects not only within the site under consideration, but also to nearby plants [1].

Recently, an inventory of the past domino accidents [2], reveals that explosions are the most frequent cause of domino effect (57%), followed by fires (43%). A study of 225 accidents involving domino effects made by [3], shows that storage areas are the most probable starters of a domino effect (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%).

The objective of this paper is to present the related works and the main existing methods and software tools for domino effect analysis. The second section of this paper is devoted to the definition of the domino effect and some major accidents involving domino effects identified in literature. Next, the potential sources of domino effects, propagation process and escalation vectors are also studied. The fourth section, presents the main existing methods and software tools for analysis and modeling of this phenomenon, and finally the paper ends with a conclusion and perspectives.

## II. DEFINITION OF DOMINO EFFECTS

There is no generally accepted definition of what constitutes domino effects in the context of accidents in the chemical processing industry, although various authors have provided suggestions. An overview of some definitions identified in a review of the relevant documents is as follows.

Lees (1980, 1996), gave two definitions, the first one was in 1980, he defined the domino effects as a factor to take into account of the hazards that can occur if leakage of a hazardous material can lead to the escalation of the incident [4]. The second one in 1996, he defines a domino accident as an event whose consequence causes a separate event in a separate unit [5].

Bagster and Pitblado (1991) defined the domino effect as a loss of containment of a plant item which results from a serious incident on a nearby plant unit [6].

In Europe, the basic guidelines for preventing major accidents are stipulated in the "Seveso-II" [1]. Article 8 of this directive uses the term domino effects to denote the existence of establishments or groups of establishments where the likelihood and the possibility or consequences of a major accident may be increased because of the location and the proximity of such establishments, and their inventories of dangerous substances.

Delvosalle (1996), defined domino effect as a primary accident in a primary installation (this event might not be a major accident), inducing one (or more) secondary accident(s), concerning secondary installation(s). This (these) secondary accident(s) must be a major one(s) and must extend the damage caused by the primary accident. Therefore, the domino effects act in a chain, involving a number of installations [7].

Gledhill and Lines (1998), proposed the following definition in terms of the regulations of the European Union's Committee on Control of Major Hazards (COMAH). A domino event is defined as a loss of containment incident on a major hazard installation which has resulted either directly or indirectly from a loss of containment incident at an adjacent or nearby major hazard installation [8]. Khan and Abbasi (1999), defined domino effect as the occurrence of a cascading chain of events when the fire, explosion, missile projection, etc., generated by an accident in one process unit causes secondary accidents in other units is a likely scenario in many major industrial plants and has the potential for catastrophic consequences [9].

The AIChE-CCPS [10], defined domino effect as an incident which starts in one item, and may affect nearby items by thermal, blast or fragment impact, causing an increase in consequence severity or in failure frequencies.

A recent definition is given in [11], that a domino accidental event will be considered 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.

## **II.1. Domino effect and escalation**

We can call domino event, every event of the chain of events (accident scenarios) that contributes to the domino effect. The concept of escalation is a process that promotes the degradation of property (materials, equipments, systems industrials, ecosystems) and injury to people during development of the domino effect, that is, which tends to increase damages. Thus, in the industrial field, we consider that any event spreading from equipment or industrial unit to another or from one site to another site should be classified as a domino event.

The analysis of the technical literature and of case histories concerning past accidents, shows that all the accidental sequences where a relevant domino effect took place have three common features [12]:

- A primary accidental scenario, which initiates the domino accidental sequence;
- 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;
- One or more than one secondary accidental scenarios or events, involving the same or different plant units causing the propagation of the primary event.

## **II.2. Review of some major accidents involving domino effect**

It may be pertinent to review some major accidents involving the domino effect before describing its main characteristics. In this section, we present a few case studies which involve a series of accidents. Various types of accidents involving a domino effect in a complex industrial site have been identified in literature. For example, at Feyzin (France), on January 4, 1966, eleven storage tanks were destroyed, 1475 constructions were affected [13,14], fragments, which cover a distance of 800 meters around the site and debris until around Vienna located at 18 Kilometers from Feyzin. The accident caused 18 deaths and 84 injured. The Mexico accident (1984) is one of the most important involving domino effects. This accident caused 550 deaths, 7200 were injured, and 200 000 were evacuated [15].

On September 14, 1997 a huge fire and explosions devastated the terminals and storage tanks at the refinery of HPCL (Hindustan Petroleum Corporation Limited) unit at Vishakhapatnam in India [16]. More than 55 people were killed and dozens of others were seriously injured. Two bodies were found on the upper storey of the administrative block which had collapsed, while three more were seen in the debris underneath by a team of reporters who ventured in later in the evening. This accident is considered as one of the most catastrophic accidents in the chemical industries in the world [17]. Recently, studies of the past domino accidents made by [2], the authors identified several domino accidents involving the industrial plants in the last decade. These accidents caused much material damage, human, and economic losses. These examples of accidents show the importance of consequences of accidents involving the domino effect. Indeed, in each case, the number of structures concerned is considerable. Moreover, the kinetics and the chain of events of the complete accident is complex. Despite the destructive potential of domino accidents, and the risk that many industries all over the world face from their likelihood, this phenomenon has received much less attention than other aspects of risk assessment.

## **III. POTENTIAL SOURCES OF DOMINO EFFECTS**

Potential sources of domino effects are of different nature and are also linked to various initiating events. In general, they are distinguished by the nature of risks, from natural or anthropogenic. In the latter category, there are technological and organizational risks (unintentional) and the risks of malevolence (intentional),

knowing that the purpose of study of domino effects takes into account the combination of these two risks. It is therefore possible to propose the decomposition (not disjoint) of the nature of risks and, therefore, the classification of initiating events as follows:

**a) Natural origins** (geological origins and/or atmospheric mainly) [18, 19, 20]:

- Climate origin: forest fires, runoff and floods, avalanches, hurricanes and tornadoes, storms;
- Geological origin: landslides and earthquakes, tsunamis, volcanic eruptions and other natural emissions (gas, etc.).

**b) Human origins** (organizational and malevolence) [21, 22, 23]:

- Organizational origin: Humans failures (incorrect human action, lack of human action), defects in design, procedures and/or organizational;
- Malevolence origin, thefts, sabotage and/or revenge action, damage of any kind attacks. These actions may touch or affect the material, but also the personal or sensitive information.

**c) Technological origin** (fire, explosion and toxic releases):

- Fire: pool fire, flash fire, fireball and jet fire;
- Explosion: confined vapor cloud explosions (CVCE), boiling liquid expanding vapor explosion (BLEVE), vented explosion, vapor cloud explosion (VCE), dust explosion and mechanical explosion;
- Toxic chemicals release: from process or storage sites and transportation accidents.

These risks can be combined which significantly complicates the analysis. Sometimes, the very different nature of risks involves varied propagation processes. This also leads to the exploitation of different analysis methods (deterministic, probabilistic and quantitative methods).

### **III.1. The propagation process**

The propagation processes are directly related to the potential source and the initiating event, but also to its immediate environment (field of danger). It is described by a physical-chemical process, but also informational whose evolution conditions are guided by features such as: physical (atmospheric, geological, hydrological) and material (buildings, sites, facilities, roads ...), ecological (vegetation, animals), informational (detections and observations, information systems) and human (individual behavior, organization and logistics, local demography). For more detailed about the propagation of danger from potential source to a potential target and the concepts of "source" and "target" [24, 25] can be referred. For readers interested in systemic approaches, it is advisable to refer to references [26].

## III.2. Domino effects modeling

An industrial site contains different installations under pressure, including tanks that store flammable liquids. The risk of explosion and fire characterized by the possibility of an accident at an industrial site likely to lead to damage and serious consequences for staff, people, goods and environment. They can generate four main events (escalation vectors); these escalation vectors are defined as physical effects of the primary events [27, 28, 29]:

- Overpressure/blast waves;
- Heat load;
- Projection of fragments (missiles);
- Toxic release.

Several models were developed for the assessment of domino effects in industrial plants caused by fires and explosions; therefore, we find in literature several models trying to deal with this phenomenon. We find models that are used to assess: i) domino effect generated by heat load and overpressure, and ii) domino effect caused by projection of fragments.

### III.2.1. Domino effect caused by fire and overpressure

#### a) The first models

The more simple approach proposed for the assessment of damage to equipment caused by fires and explosions. Several authors propose to consider zero probability of damage to equipment if the physical effect is lower than a threshold value for damage, and to assume a probability value of one if the physical effect is higher than a threshold value for damage [30, 31, 32].

In 1991, the authors [33] described an approach for the estimation of domino accident frequencies. This was developed on the principle of treating the domino event as an external event in a fault tree context. The same team defined a damage probability function based on the distance from the center of the explosion [34]:

$$F_d = 1 - \frac{r}{r_{th}^2} \quad (1)$$

Where  $F_d$  is the damage probability,  $r$  is the distance from explosion center (m) and  $r_{th}$  is the distance from explosion center at which a threshold value of static overpressure is reached (36 kPa).

A quantitative study, however, of the domino effect has been made by [35]. They have described possible approaches for quantifying the consequences of domino effects resulting from events giving rise to thermal radiation. A first approach evaluating the frequency accidental explosions was proposed by [36]. They provided a methodology for predicting domino effects from pressure equipment fragmentation.

A simplified model proposed by [37] assesses the damage probability of process equipment, caused by a blast overpressure. The authors defined the "probit function» to relate equipment damage to the peak static overpressure:

$$Y = a + b \times \ln(P^0) \quad (2)$$

Where  $Y$  is the probit function for equipment damage,  $P^\circ$  is the peak static overpressure (Pa),  $a$  and  $b$  are the probit coefficients ( $a = -23.8$  and  $b = 2.92$ ).

The authors [38] proposed a probit function similar to the model proposed by [37] (Eq.(2)), but substituting the static overpressure by the total pressure (the sum of static and dynamic pressure).

The major drawback of this model is that the value of pressure is very high, and they have been applied to all industrial equipments, without taking into account the categories of equipments and other characteristics. Also, the authors kept the same probit coefficients ( $a$  and  $b$ ) for probit function.

The drawback with these aforementioned models is that, they remain statistical and qualitative. These works were limited to only mentioning some aspects of domino effects and the methods are based on very simplistic assumptions. Finally, these methods can calculate the probability of damage for only one unit of an industrial site without considering the rest of the site and surrounding systems.

### b) Advanced models and associated tools

The probit approach was followed by [11, 39, 40, 41, 42], the authors published a series of articles in which they analyzed and reviewed the existing models to develop a probabilistic model for damage to specific categories of industrial equipments.

The damage probability model proposed by the authors takes into account four categories of industrial equipments (atmospheric vessels, pressurized vessels, elongated vessels, and small equipments). The probit coefficients for overpressure damage probabilities for four equipment categories are represented in the table 1.

Table 1: Probit coefficients for different equipment categories [39]

Equipment category	a	B	Threshold
Atmospheric vessels	- 18.96	+ 2.44	22 kPa
Pressurized vessels	- 42.44	+ 4.33	16 kPa
Elongated equipment	- 28.07	+ 3.16	31 kPa
Small equipment	- 17.79	+ 2.18	37 kPa

To improve these models, specific thresholds for domino effects were obtained for the different escalation vectors, taking into account the characteristics of different categories of industrial equipments.

To estimate the time to failure  $t_{ff}$  of industrial equipments exposed to fire. A simplified model proposed by [43, 44, 45] is based on the probit approach. The authors proposed a damage probability model that takes into account the categories of industrial equipments. Table 2 presents the thresholds and probit models for two equipment categories.

Table 2: probability models and threshold values for the heat radiation,  $Y$  is the probit function,  $ttf$  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 ( $kW/m^2$ )

Equipment category	Threshold	Correlation
Atmospheric vessels	$15 kW/m^2$ $t \geq 10 \text{ min}$	$Y = 12.54 - 1.847 \times \ln(ttf)$ $\ln(ttf) = -1.128 \times \ln(I) - 2.667 \times 10^{-5}V + 9.887$
Pressurized vessels	$50 kW/m^2$ $t \geq 10 \text{ min}$	$Y = 12.54 - 1.847 \times \ln(ttf)$ $\ln(ttf) = -0.947 \times \ln(I) + 8.835V^{0.032}$

Most of these models use the probit model; the difficulty herein lies in the association of each category of equipment to a specific probit function. Also, the difficulty to classify all industrial equipment to specific categories based on their resistance to physical effects. Studies of past accidents indicated that other events can trigger a chain of cascading events (human error, malicious acts, and natural risk).

### III.2.2. Domino effect caused by projectiles

On industrial sites, the projectiles generated by an explosion of a tanks containing gas or highly pressurized liquids are threats to other surrounding equipment and can lead to successive explosions. Several studies have been done on modeling the impact of projectiles on industrial installations.

The fragments are capable to generate secondary accidents which could cause tertiary ones and etc. The generation of fragments is generally followed by the catastrophic failures of equipment. Two main accident scenarios are responsible for primary accidents resulting in the projection of fragments [28] :

- Internal explosions due to confined deflagrations, and
- BLEVEs (Boiling Liquid Expanding Vapor Explosion).

Returning to the first models, a fundamental approach is described by [46], their model utilize empirical correlations to compute a scaled initial fragment velocity from the scaled internal pressure of the vessel, and then a scaled fragment range from the scaled initial velocity.

Based on previous works, the author of [47,48] presented a methodology to calculate the trajectories of fragments resulting from bursting spherical and cylindrical vessels containing gas at high pressure using analytical solutions of the equations of motion.

A model for the assessment of the impact probability on a given target of fragments generated by an internal explosion of pressure vessel was developed by [49]. The model was based on the analytical solution of the ballistic equations for fragment trajectory, and on the introduction of probability distribution functions for the initial direction of fragment projection. The model needs three uncertain input parameters: mass, shape and the initial velocity. Each fragment generated in the primary event may cause a domino effect with an expected frequency ( $f_{d,F}$ ) given by the following expression:

$$f_{d,F} = f_p \times P_{d,F} \quad (3)$$

Where  $f_p$  is the expected frequency of the primary event and  $P_{d,F}$  is the probability of the above event sequence for a single fragment, which may be expressed as:

$$P_{d,f} = P_{gen,F} \times P_{imp,F} \times P_{dam,F} \quad (4)$$

$P_{gen,F}$  is the probability of the fragment  $F$  (with defined mass, shape and initial velocity) to be generated in the primary event,  $P_{imp,F}$  is the probability of impact between the fragment and the target vessel, and  $P_{dam,F}$  is the probability of target damage given the impact with the fragment.

The weaknesses of these models are that these previous investigations and propositions are based on a single-scenario approach, which does not suffice due to the randomization of other scenarios. Then, the authors [50] proposed a model based on two credible scenarios to quantify the probability of fragments impact on a given target for a particular case of missiles originating from bursting horizontal and cylindrical vessels:

- Scenario 1: impact resulting from projectiles landing within the vulnerable area, and
- Scenario 2: impact resulting from projectiles landing beyond the vulnerable area (but colliding with the target object while in flight before reaching their final destination).

The results show that among the two credible scenarios proposed, the second scenario is more credible than scenario 1, with a contribution of 51% to the impact probability.

The authors of [51,52], developed two approaches, the first one, based on fragmentation patterns to estimate the expected number of fragments and the fragment drag factors in vessel fragmentation events. The authors have based their data on a collection of over 140 vessel fragmentation occurrences. The second one was proposed for the assessment of possible fragmentation modes following the collapse of a process vessel due to a too high internal pressure. A database collecting 121 accidents involving vessel fragmentation and fragment projection in the process industry was developed.

Recently, a new model, that allows to evaluate the penetration depth of metallic projectiles inside metallic targets was developed by [53,54,55]. They proposed an approach to assess the drag factor of fragments generated during an explosion due to an internal pressure and the modes of fragmentation, these modes were defined on the basis of geometric characteristics of vessels categories which are more frequently involved in fragmentation accidents.

After, the same team [56] focused their studies on source terms, where they developed a probabilistic distribution for the source terms. They also proposed a probabilistic approach on the same subject; the latter requires three main steps:

- Probabilistic modeling of source terms: the probability of occurrence of the primary explosion, then the number, mass, velocity, departure angles, the geometric shape, dimensions and construction material properties are described with probability distributions,
- Probabilistic modeling of the target: number of projectiles, speed, angles, energy at the impact, construction materials, dimensions of the targets affected, and depths of penetration are also described with probability distributions, and
- Risk assessment for the second scenario explosion which may have taken place in the affected targets.

## IV. METHODOLOGIES AND SOFTWARE TOOLS

To address the problem posed by the assessment and/or analysis of domino effects in industrial sites, several methods and software tools have been developed. In this section, we present the main existing methods and software tools for analysis and modeling the domino effects.

### IV.1. Methodologies

#### a) DEA methodology:

Domino Effect Analysis (DEA), developed by [13], and some applications in [57,58], include two levels of study, the first level is a detailed analysis to identify units that may be considered as targets. For that the threshold values of different physical effects of industrial equipments (target) are used (an overpressure of 0.7 atm, a heat load of 37 kW/m<sup>2</sup>, and a projectile having a velocity higher than 75m/s. If the estimated values of these parameters at the location of the target unit are higher than the threshold values, a second study (level 2) is performed, in which a detailed analysis must be made to verify the existence of domino effect, using the potential damages of the primary event and the characteristics of the secondary unit. To evaluate all credible accident scenarios in an industrial unit, the same authors, proposed a MCAS methodology (Maximum Credible Accident Scenarios) [59]. This method starts with the development of all plausible accident scenarios in the unit, and it allows evaluating the damage radii for each accidental scenario. Once damage radii and probabilities are known for each damaging event, some factors will be estimated using site-specific information such as population density, and asset density at the industrial plant [60].

#### b) Procedure for domino effect analysis:

A systematic procedure for the quantitative assessment of the risk caused by domino effect to industrial plants has been developed by [12]. This methodology aims to calculate the propagation probability of primary scenarios, the expected frequencies of domino events, and allowed to estimate the contribution of domino scenarios to individuals as well as societal risk.

The strong point of this methodology, is that it takes into account the combination of these events by estimating their probabilities, whereas it's an over simplified technique limited to only assess the primary events without taking into account the probability of escalation of secondary events.

### **c) Methodology for the quantitative risk assessment of accidents triggered by seismic events:**

An analytic methodology for the quantitative assessment of industrial risk due to accidents triggered by seismic events has been developed by [61]. This procedure is based on the use of available data (historical data) to assess the expected frequencies and magnitude of seismic events. Thus, it uses equipment-dependant failure probability models (fragility curves) to assess the damage probability of equipment items. The main objective of this procedure is to:

- Identify the accidental scenarios that may follow a seismic event,
- Evaluate the credibility of the accidental events, and
- Assess the expected consequences of the possible scenarios.

### **d) Procedure for the quantitative assessment of industrial risk caused by lightning:**

Two years after, the same team [62] proposed an approach in the form of a flowchart, this method, allows the assessment of accidental scenarios caused by lightning. Occurrence of lightning may cause damage to industrial equipments/ installations that contain high amounts of hazardous compounds. The main steps of the methodology are:

- Characterization of external event (frequency and severity), the identification of target equipment, damage states, and reference scenarios,
- Estimation of damage probability, consequences calculation for the events, and each combination of events,
- Frequency/probability calculation for each combination and calculation of risk/hazard indices.

### **e) FREEDOM algorithm (FREquency Estimation of DOMino accidents):**

A most recent method for assessing domino effects based on Monte Carlo simulation has been developed by [63], the authors developed a FREEDOM algorithm, which is based on conducting several hypothetical experiments to simulate the actual behavior of a multi-unit system. The system is defined as the combination of equipment present in an industrial unit that may influence the failure of each other. This tool, examines the failure of each equipment in the industrial unit.

FREEDOM algorithm has two inner and outer loops. The inner loop, which is representative of the average lifetime of the equipment, is selected according to the failure rate of equipment. The outer loop, that operates for the iterations or experiments which are performed  $N$  times.

## **IV.2. Software tools**

Some computer-automated tools have been developed for determining the probability of domino effects and to provide a risk assessment after accidents in chemical processing industries and industrial complexes have occurred.

To estimate and prevent the accidents involving toxic releases, explosions, and fires in chemical processing sites, the authors [64,65] developed a computer-automated tool MAXCRED (MAXimum CREDible accident analysis). This has been created is on the Event Tree Method, and Fault tree analysis. The seconde version MAXCRED-II can quantitatively simulate accidents in any chemical process site [64].

Another software tool DOMIFFECTION (DOMIno eFFECTION), developed by the same team [17] for domino effect analysis in chemical processing plants, is based on the deterministic models used in conjunction with probabilistic analysis. The tool is based on a systematic domino method [13]. DOMIFFECTION is a PC-based software with object oriented architecture coded in C<sup>++</sup>. It consists of six main modules Data, Accident scenario, Analysis, Domino, Graphics, and User Interface.

The ARIPAR project attempts to evaluate the risk from several plants, the software developed in the ARIPAR project was used for the calculation of local, individual and social risk due to fixed installation and transportation of hazardous substances [67]. The software, evaluates the corresponding vulnerability of data using probit correlations. The latest version of ARIPAR, implements a probabilistic methodology for assessing the risks of industrial complexes, including the transport of dangerous substances, to obtain a number of different risk measures [68].

The authors [69] have developed the ATLANTIDE software to assess the consequences of accidental events that may occur in storage areas. The application of the tool is appropriate for LPG storage, and processing plants (substances/gas dispersion and other phenomena such as BLEVE and fire ball). The software uses event trees to evaluate all possible scenarios, from the initial accidental event, taking into account the weather, different releases, mode and other features typical of the plant [70].

The DOMINOXL tool developed by [71], aims to enumerate all possible domino effects that can lead to internal and external cascading accidents. For the most dangerous equipment zones in a group of chemical plants, they are determined by adding up the number of primary domino effects per potential hazard leading to a danger factor. Similarly, the most vulnerable equipment zones or pipes are also determined by adding up the number of domino effects for an installation, and then considering a secondary installation for a given protection level. This calculation leads to a vulnerability factor.

In the aim to develop a methodological tool to manage major accidents with the domino effect, the GeOsiris software was developed by [72,743], which simulates industrial accidents involving domino effects. The GeOsiris software identifies the sequence of accidental events and quantifies their consequence in term of effect distances, provide assistance for decision making, as well as to define the means of implementation and reaction time to realize an efficient intervention.

A computer-programmed-module MiniFFECTION (MINImization of domino eFFECTION) developed by [74], allows to determine the position of chemical facilities and the optimal positioning for minimizing the effects of the cascading event using nonlinear programming approaches. MiniFFECTION software shows the position of each facility with cartesian coordinates. It takes into account three major factors of the domino effects: i) heat load, ii) overpressure, and iii) fragments effect.

To determine the domino effects with priority order in an industrial plant, on one or on several levels on the site, the authors [75] proposed a software tool called DomPrevPlanning for the prevention planning of domino effects. This software uses three main documents Instrument Domino Effects (IDE), the Manual for failure frequency Figures, and Guidelines for quantitative risk assessment. This software can perform the analysis of dominos risks, the comparison of installations in industrial facility, and the classification of chemical installations that is likely to cause the escalation effects.

## V. CONCLUSION

In this paper, we identified the main existing methodologies and software tools used to study and analyze domino effects. The review of literature shows that there are four vectors by which a domino effect may be propagated from one unit or plant to another. These escalation vectors are heat load, overpressure/ blast waves, fragments, toxic releases and other hazardous releases.

A few quantitative approaches have been developed to model this phenomenon, and they are still very simplified, and very specific to study only certain escalation vectors without addressing the concepts of dependency between these physical effects and other which can lead to very serious consequences. Therefore, there is no generic model that takes into account the effects of these chains of accidents. The software tools treat only partially the problems of domino effects. So further research is needed to determine what the cause is and how the domino effect can be prevented and/or mitigated.

We observed that, there is a lack of methodologies that take into account natural risk/disasters (flood, seismic, and lightning risk...), human error, and malicious acts, in the study of cascading chains despite their potential danger on industrial facilities, the population, structures, and ecosystems, and the possibility of initiating a chain of accidents in industrial plants.

An important feature of many industrial systems is their dynamic appearance due to changes they support over time, and interactions between their components and or their environment. Each given behavior of the system is defined by the laws of physics, and further more the transition from one behavior to another may be due to several causes: atmospheric condition, human intervention, and action of regulatory organs acting under the influence of physical variables that define the state of the system.

Therefore, these phenomena can be modeled as dynamic systems which, in addition to escalation vectors (physical effects), must take into account the human and organizational factors as parameters that can initiate, influence or aggravate the phenomenon, as well as logistics, and intervention in real time (material and human). To remedy that, we can use models that take into account deterministic and probabilistic aspects, or the coupling of both probabilistic-deterministic methods.

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