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How to investigate and assess combination of hazards

Keywords

hazards, domino effect, cascade effect, multi-hazard, assessment

Abstract

Operating experience from different types of industrial installations has shown that combinations of different types of different hazards occur during the entire lifetime of the installations. Typically site specific occurring hazards cause or induce other hazards to occur. In particular, natural hazards rarely happen alone. Thus, it is very important to note that almost any event combination of hazards is possible and that it is necessary to identify these interactions and find ways to mitigate the effects of hazard combinations. Therefore, it is a basic task to investigate and assess the relevant combination of hazards not only for a single installation but for the respective site/industrial park. In that context domino effects and cascade effects pose particular challenges for risk management to prevent industrial accidents.

1. Introduction

The complexity of domino and cascade effects requires the application of a proper risk assessment methodology. In the common practice, the risk evaluation is performed for independent events where single risk indexes are determined.

However, when considering domino and cascade effects which are often induced by external hazards, the resulting risk indices may be higher than the simple aggregation of single risk indexes. For this reason multi-risk assessments should be carried out taking into account all possible interactions of risks due to cascade effects.

Multi-hazard assessment has to be performed to determine the probability of occurrence of different hazards either occurring at the same time or shortly following each other, because they are dependent from one another or because they are caused by the same triggering event or hazard, or merely threatening the same elements at risk without chronological coincidence.

In order to investigate and assess the whole risk from several hazards, taking into account possible hazards and vulnerability interactions a multi-risk approach has to be chosen which entails a multi-hazard and multi-vulnerability perspective. A detailed literature review of the most important initiatives on multi-hazard and multi-risk assessment is provided in [12].

It should be mentioned that different terminologies were used in the practice of risk evaluation when addressed to the concept of chain reaction effects.

The term domino effect is mainly applied in studies of accidents in the chemical and process industry triggered by technological or natural disasters [9], [42], while the term cascade effect is mainly used in studies of natural disasters triggered by natural disasters in the context of multi-risk assessment [36].

In this paper the following definitions are used according to [12]:

- The domino effect is a cascade of events in which the consequences of a previous accident are increased by following one(s), as well spatially as temporally, leading to a major accident,
- The cascade effect is the situation for which an adverse event triggers one or more sequential events.

Quantitative risk analyses considering cascade effects require a clear identification of possible scenarios of cascade events and approaches to quantify probabilities associated to each scenario.

Furthermore, the effects of time dependent mitigation actions have to be included into the concept model throughout the definition of decision nodes.

2. Framework of analysis for combinations

The assessment and mitigation of the impacts of hazardous events considering cascade effects require innovative approaches which allow comparison and interaction of different risks for all the possible cascade events.

A multi-risk approach is aimed to solve a problem of the interaction among different threats and to establish a ranking of the different types of risk taking into account possible cascade effects.

The growing need to develop multi-risk approaches has led to the development of different projects in Europe and in different countries with the aim to provide tools and procedures for a successful planning and management of territory, and to homogenize existing methodologies within a unique approach.

The multi-risk concept refers to a complex variety of combinations of risk, and, for this reason, it requires a review of existing concepts of risk, hazard, exposure and vulnerability within a multi-risk perspective.

A multi-risk approach entails a multi-hazard and a multi-vulnerability perspective.

The multi-hazard concept [12] may refer to the fact that

- Different sources of a hazard might threaten the same exposed elements (with or without temporal coincidence), or
- One hazardous event can trigger other hazardous events (cascade effects) that is the main issue of this deliverable.

On the other hand, the multi-vulnerability perspective may refer to

- A variety of exposed sensitive targets (e.g. population, infrastructure, cultural heritage, etc.) with possible different vulnerability degree against the various hazards, or
- Time-dependent vulnerabilities, in which the vulnerability of a specific class of exposed elements may change with time as consequence of different factors (as, for example, wearing, the occurrence of other hazardous events, etc.).

Most activities regarding multi-risk assessment have developed methodological approaches that consider the multi-risk problem in a partial way, since their analysis basically concentrate on risk assessments for different hazards threatening the same exposed elements. Within this framework, the main emphasis has been towards the definition of procedures for the homogenization of spatial and temporal resolution for the assessment of different hazards related to cascade effects.

For vulnerability being a wider concept exist a stronger divergence regarding definition and assessment methods. In case of physical vulnerability issues, a more or less generalized agreement on the use of vulnerability functions (fragility curves) has been reached which facilitate the application of such a kind of multi-risk analysis.

However, for other kinds of vulnerability assessment (e.g. social, environmental, etc.) it is less clear how to integrate them within a multi-risk framework.

Following the definitions provided in [11], the concept of multi-hazard assessment may be understood as the process to determine the probability of occurrence of different hazards either occurring at the same time or shortly following each other, because they are dependent from one another or because they are caused by the same triggering event or hazard, or merely threatening the same elements at risk without chronological coincidence.

On the other hand, the definition provided in [11] for multi-risk assessment is: to determine the whole risk from several hazards, taking into account possible hazards and vulnerability interactions.

It is important to point out that the concept of multi-hazard risk assessment, following the definition provided in [22], refers to the risk raised from multiple hazards and is in contrast to the term multi-risk because the latter would relate also to multiple vulnerabilities and risks such as economic, ecological, social, etc.

Thus, a multi-risk approach entails a multi-hazard and multi-vulnerability perspective. This includes the following possible events:

- Events occurring at the same time or shortly following each other, because they are dependent on one another or because they are caused by the same triggering event or hazard; this is mainly the case of "cascade events"; or,
- Events threatening the same elements at risk (vulnerable/exposed elements) without chronological coincidence.

A multi-hazard and multi-risk analysis consists of a number of steps and poses a variety of challenges. A multitude of methodologies and approaches is emerging to cope with these challenges, each with certain inherent advantages and disadvantages. Whatever approach is chosen, it has to be adjusted according to the objectives (e.g., which results are required?) and to the inherent issues (e.g., stakeholder interests), respectively [22].

Thus, the adjustment of the whole framework toward the aspired result, considering the inherent issues, is a fundamental necessity. Hence, right from the beginning, several principal choices have to be made:

- The first major choice is the definition of the kind of analysis, namely, multi-hazard risk or multi-risk. This does not only depend on the research objective, but is also a question of data availability;

- Additionally, the terms of the expected outcome have to be decided, i.e., whether a qualitative, semi-quantitative, or quantitative outcome is needed.

To account for the multi-hazard nature in the simplest way, two hazards ("H1" and "H2") and their combination ("H1+H2") are introduced to the framework [27]. Though not explicitly mentioned in the framework, more hazards can be added to the analysis, which would increase its complexity. Looking at two hazards simultaneously allows for a separate analysis to account for the interacting effects between the two hazards. It also means going beyond a simple aggregation (addition) of hazard 1 and hazard 2 (see *Figure 1*).

Additionally, the interaction effects between different hazards (e.g. cascade effects) are also important to analyze.

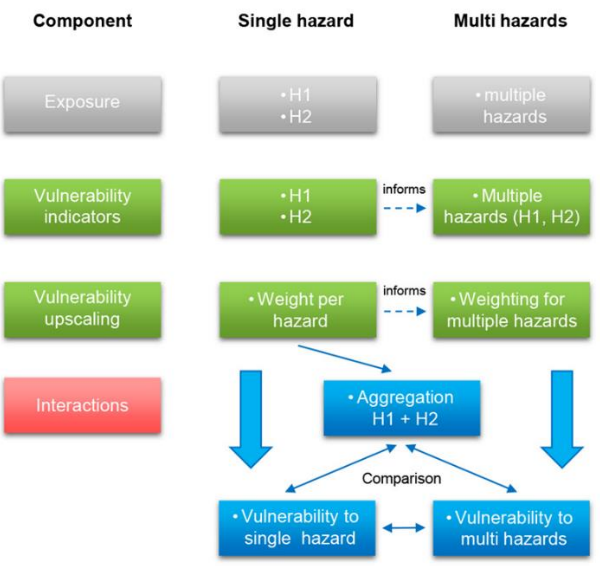

Figure 1. Single hazard and multi hazards risk assessment

According to the contribution to natural hazards, the geophysical environmental factors in the hazard forming environment were categorized into two types, stable factors and trigger factors. Based on these geophysical environmental factors for notable major hazards, the stable factors were used to identify which types of natural hazards influence a given area, and trigger factors are used to classify the relationships between these hazards into four types: independent, mutex, parallel and series relationships [35].

Figure 2 lists a basic framework of multi-hazard risk assessment consisting of five main components.

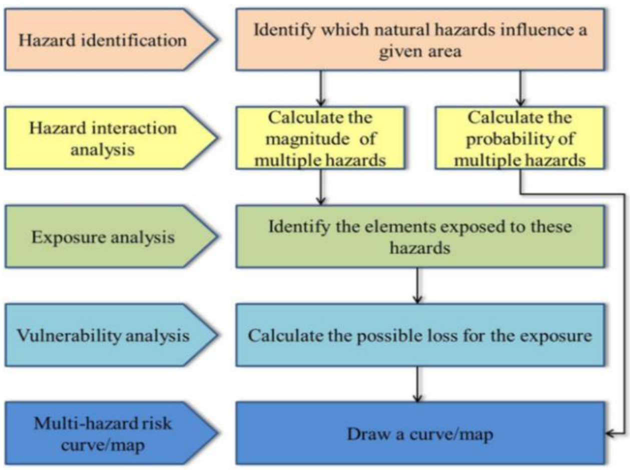

Figure 2. Basic framework of multi-hazard risk assessment

This classification is useful as it helps to ensure all possible relationships among different hazards are considered. It can effectively fill a gap in current for multi-hazard risk assessment methods which to date only consider domino effects. In addition, based on this classification, the frequency and magnitude of multiple interacting hazards occurring together can be calculated with the change in trigger factors.

Therefore, in multi-hazard risk assessment, these multiple interacting hazards can be treated as a multiple hazards group, with the change of degree in the relevant trigger factors representing the magnitude, and the probability of changes in them representing the probability of this group. In this way, the results obtained are more reliable.

Hence, the developed hazard interaction classification based on hazard-forming environment provides a useful tool to facilitate improved multi-hazard risk assessment.

3. 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 [15].

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) [21], [28]:

- 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) [37]:

- 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) [15]:

- Fire: pool fire, flash fire, fireball and jet fire;
- Explosion: confined vapour cloud explosions (CVCE), boiling liquid expanding vapour explosion (BLEVE), vented explosion, vapour 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).

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 provided information whose evolution conditions are guided by features such as:

- physical (atmospheric, geological, hydrological),
- material (buildings, sites, facilities, roads, etc.),
- ecological (vegetation, animals),
- informational (detections and observations, information systems),
- human (individual behaviour, organization and logistics, local demography).

More details about the propagation of danger from potential source to a potential target and the concepts of "source" and "target" can be found in [39].

4. Methodologies

To address the problem posed by the assessment and/or analysis of domino effects in industrial sites, several methods have been developed. The main existing methods for analysis and modelling of domino effects are presented below.

An industrial site contains different installations under pressure, including tanks that store flammable liquids. The risk of explosion and fire is 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 [16], [19], and [20]:

- 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, one can find in literature several models trying to deal with this phenomenon.

In that context one can find models that are used to assess:

- Domino effect generated by heat load and overpressure, and
- Domino effect caused by projection of fragments.

The evolution of domino accidents, in particular in chemical plants, triggered, e.g., by heat radiation, overpressure effects, or missile projection, depends on the presence and the performance of safety barriers. Safety barriers may have the potential to prevent escalation, for example, in case of heat radiation, delaying or avoiding the heat-up of secondary targets. Thus, safety barriers play crucial role in domino effect prevention and mitigation within existing industrial settings. More specifically, add-on safety barriers can indeed:

- restrict the propagation of domino effects;
- mitigate the consequences of domino effect; and
- be extremely important in terms of increasing the time to failure of chemical installations.

Based on the features of an industrial area that may be affected by domino accidents, and knowing the characteristics of the safety barriers that can be installed between installations, a decision model can help practitioners in their decision-making. Such a model based on metaheuristics is described in [14].

Cascading effects and cascading disasters are emerging fields of scientific research. The widespread diffusion of functional networks increases the complexity of interdependent systems and their vulnerability to large-scale disruptions. Although in recent years studies of interconnections and chain effects have improved significantly, cascading phenomena are often associated with the ‘‘toppling domino metaphor’’, or with high-impact, low-probability events.

Another approach aimed to support a paradigm shift in the state of the art by proposing a new theoretical approach to cascading events in terms of their root causes and lack of predictability [41].

By means of interdisciplinary theory building it is demonstrated how cascades reflect the ways in which panarchies collapse and suggested that the vulnerability of critical infrastructure may orientate the progress of events in relation to society’s feedback loops, rather than merely being an effect of natural triggers. The conclusions point to a paradigm shift in the preparedness phase that could include escalation points and social nodes, but that also reveals a brand new field of research.

It is assumed in this approach [41] that cascading disasters have similar dynamics to the spread of crisis in panarchies: an environmental hazard or other threat can be a trigger of dynamic processes that weaken the system. Society and its components (e.g. policies, organizations and economics) occupy the intermediate levels between localized infrastructure and international interdependencies. Nodes in critical infrastructure amplify the structural weaknesses by transmitting them across scales. Cascades may result from a lack of sustainability in the system, for example where they are associated with long-range supply processes, management cultures or to consumer behaviour.

On the one hand, this is in line with the idea that cascading ecological crises, such as those related to climate change, are nonlinear consequences of complex causal chains in which environmental dynamics react to human stressors. On the other hand, cascading effects accompany a transition from a stable to an unstable state of the system and are amplified by latent vulnerabilities, such as the increasing interdependency of functional sectors in modern global society.

4.1. Domino effect caused by fire and over-pressure

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].

In [4] an approach for the estimation of domino accident frequencies is described. This approach 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 centre of the explosion [5]:

$$F_d = 1 - \frac{r}{r_{th}^2} \tag{1}$$

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

A quantitative study, however, of the domino effect has been provided in [33] describing 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 [44] providing a methodology for predicting domino effects from pressure equipment fragmentation.

A simplified model proposed by [10] assesses the damage probability of process equipment, caused by a blast overpressure. The "probit function” relates the equipment damage to the peak static overpressure:

$$Y = a + b \times In \ (P^0) \tag{2}$$

where Y is the probit function for equipment damage, P^0 is the peak static overpressure (Pa), a and b are the probit coefficients (a = –23.8 and b = 2.92).

A further proposal is to use a probit function similar to the model in equation (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 equipment, without taking into account the categories of equipment and other characteristics. Also, the same probit coefficients (a and b) are kept 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 [15].

4.2. Advanced models and associated tools

Existing models have been analysed and reviewed to develop a probabilistic model for damage to specific categories of industrial equipment [17].

The damage probability model proposed in [15] takes into account four categories of industrial equipment (atmospheric vessels, pressurized vessels, elongated vessels, and small equipment).
The probit coefficients for overpressure damage probabilities for four equipment categories are presented in the *Table 1*.
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 equipment.
To estimate the time to failure *ttf* of industrial equipments exposed to fire. A simplified model proposed by [18], [31] is based on the probit approach.

Table 1. Probit coefficients for different equipment categories

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

The applied damage probability model takes into account the categories of industrial equipment. *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 $T \geq 10$ min	$Y = 12.54 - 1.847 \times \ln(ttf)$ $\ln(ttf) = -1.128 \times \ln(I) - 2.667 \times 10^{-5} - 5V + 9.887$
Pressurized vessels	50 kW/m^2 $T \geq 10$ 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. Moreover, it is difficult to classify all industrial equipment to specific categories based on their resistance to physical effects.
Studies of past accidents indicated that also other events can trigger a chain of cascade events (human error, malicious acts, and natural risk).
However, overpressure is one important cause of domino effect in accidents of chemical process equipment.
One model to consider propagation probability and threshold values of the domino effect caused by overpressure is the probit model [45]. In order to prove the rationality and validity of the models reported in the reference, two boundary values of three damage degrees reported were considered as random variables respectively in the interval < 0, 100% >.
Based on the overpressure data for damage to the equipment and the damage state, and the probit method, the mean square errors of overpressure were calculated with random boundary values, and then a relationship of mean square error vs. the two boundary values was obtained, the minimum of mean square error was obtained, compared with the result of the present work, mean square error decreases by about 3% [45].
Therefore, the error was in the acceptable range of engineering applications, the probit model can be considered reasonable and valid.
A methodology for domino effects caused by projectiles is described in [15].

4.3. DEA methodologies

The Domino Effect Analysis is developed in [24] and some applications of this approach are described in [25]. This methodology includes two levels: 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 equipment (target) are used (an overpressure of 0.7 atm, a heat load of 37 kW/m2, 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 so-called Maximum Credible Accident Scenarios methodology is proposed. This method starts with the development of all plausible accident scenarios in the unit, and it allows to evaluate the damage radii for each accidental scenario.
In the case that 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 [26].

The Domino Effect Analysis procedure is illustrated in *Figure 3*.

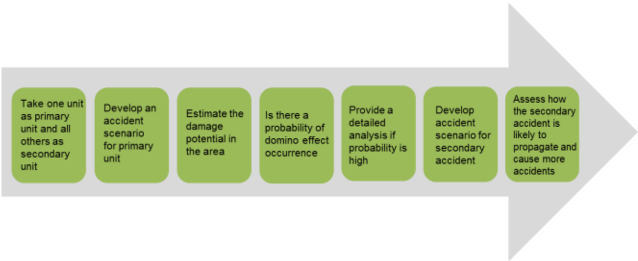

Figure 3. Domino Effect Analysis (DEA) procedure

4.4. Procedure for a quantitative domino effect analysis

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 and further research is needed to determine what the cause is and how the domino effect can be prevented and/or mitigated.
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 cascade 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.
Therefore, these phenomena can be modelled 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, one can use models that take into account deterministic and probabilistic aspects, or the coupling of both probabilistic-deterministic methods.
A systematic procedure for the quantitative assessment of the risk caused by domino effect to industrial plants has been developed [7]. 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 is a very simplified technique which is limited to only assess the primary events without taking into account the probability of escalation of secondary events.
It is difficult to introduce the domino effect in risk analysis and there are no clear criteria for identifying it. However, relative probability event trees and the frequency of the initiating event can establish the frequency that corresponds to each sequence and offer a systematic means of introducing the domino effect in quantitative risk analysis [8].
An analytic methodology for the quantitative assessment of industrial risk due to accidents triggered by seismic events has been developed [3]. 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,
- Assess the expected consequences of the possible scenarios.

A further approach in the form of a flowchart has been proposed [43]. This method allows the assessment of accidental scenarios caused by lightning. Occurrence of lightning may cause damage to industrial equipment/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.

A most recent method for assessing domino effects based on Monte Carlo simulation has been developed by [1]. This so-called FREEDOM algorithm (FREquency Estimation of DOMino accidents) is based on conducting several hypothetical experiments to simulate the actual behaviour 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.

The 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.

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, see, e.g., [15] for more details.

5. Examples of the combination of hazards and events

The interdependent nature of many systems significantly increases the potential for cascade effects that could spread from one kind of infrastructure to another. In [34] two examples are described.

On the one hand, electricity is conveyed by generators and substations, which are susceptible to cascade failures when power fluctuations exceed the margin of tolerance, and this affects many other activities.

On the other hand, the damage to the road system can be related to simultaneous failures in water and gas supplies that lie underground, while because of the lack of water supply and pressure, any fires generated by the damage could not be fought effectively. Vulnerability in infrastructure can be caused by physical elements and can be passed directly on to human activity, as for example when loss of electricity supply causes meetings to be cancelled and results in a variety of modifications to normal activities.

Social and political decisions can determine not only the vulnerability of infrastructure but also that of society itself: the relationship between vulnerability, politics, policies and crisis management capacities determines how escalating events are managed.

For example, the adoption land use planning against floods, the will to respect the regulations, and the instruments to limit contraventions are integral parts of flooding risk reduction.

When a major accident occurs in a process plant or a storage area such as a liquefied petroleum gas (LPG) storage, its physical effects (overpressure, thermal flux, impact of missiles, etc.) often damage surrounding equipment. In some cases the affected equipment fails, which can lead to loss of containment and an additional accident scenario: for example, the flames of a jet fire impinge on a vessel causing it to explode, or a fragment ejected by an explosion impacts on a pipe causing loss of containment of a flammable liquid and subsequent ignition. Therefore, a relatively minor accident can initiate a sequence of events that cause damage over a much larger area and lead to far more severe consequences.

A domino effect can occur in a variety of ways, although an essential aspect is whether it involves a single plant or progresses from one plant, where the accident took place, to others. According to this criterion [42], domino effects are classified into two categories: internal domino and external domino. In internal (single-company) domino effects, the escalation of an accident occurs inside the boundaries of a chemical plant; in external domino effects also to facilities of other companies, one or more secondary accidents occur outside the boundaries of the plant where the primary event occurs.

The population affected by industrial accidents can be classified into three categories according to the severity of the consequences:

- Number of fatalities,
- Number of injured persons,
- Number of evacuees.

The accident that caused the highest number of fatalities occurred in San Juan Ixhuatepec (Mexico) in 1984 where a series of explosions and fires destroyed a large number of cylindrical and spherical vessels in an LPG storage area [8]. This accident has killed 503 people.

The accident with the highest number of injured was also the San Juan Ixhuatepec accident which caused injury to approximately 3,800 people.

The worst cases led to the evacuation of 200,000 people (San Juan Ixhuatepec) and 100,000 people in Visakhapatnam (India) where a leaking pipe caught fire during the unloading of an LPG vessel, causing a series of large fires in storage tanks.

Further well known external hazards with dramatic consequences occurred in Japan and the United States a few years ago.

The Tōhoku earthquake of 11th March 2011 is considered to be an outstanding example of a cascade disaster. It affected three prefectures in northeast Honshu, the main island of Japan. Although only about 100 people died as a direct result of the earthquake, about 18,000 were killed by the ensuing tsunami. The most enduring consequence of this may be radioactive contamination resulting from tsunami damage to the Fukushima Dai'ichi nuclear power plants which, in the short term, caused the evacuation of 200,000 people from the surrounding area.

The consequences of this earthquake and the resulting tsunami persuaded the global community to consider more realistically the problem of combination of hazards with cascade effects.

Interdependencies, vulnerability, amplification, secondary disasters and critical infrastructure are important factors that need to be addressed in risk reduction practices in order to limit cascade effects during accidents.

Hurricane Sandy developed as a tropical depression in the Southwest Caribbean Sea on 22nd October 2012 and increased in strength during the next days. On 29th October the hurricane made landfall in the United States. Direct damage to residential and industrial buildings was high, while there were many power outages that lasted between several days and two weeks. Fires of electrical origin broke out and could not be controlled [29]. Moreover, the hurricane caused 72 fatalities in the USA, 41 of which were linked to the storm surge. At least 650,000 houses were damaged or destroyed and about 8.5 million customers lost power supply. Damages were estimates at more than 50 billion dollars.

Hurricane Sandy originated many subsidiary disasters that amplified the emergency as time progressed. The storm surge, and associated flood damage, can be considered as a secondary disaster generated by the hurricane, after the direct effects of wind damage. The joint physical effects of storm surges and winds interacted with the vulnerability of critical infrastructures and generated subsidiary events. A major leak involved an oil and refining storage facility in the small village Sewaren where a large tank ruptured under pressure from the storm which resulted in a leak of 12,700 hectoliters into the waterway. Many wastewater treatment plants were affected, with the worst event at a wastewater treatment plant in Newark where 37 million hectoliters of untreated sewage flooded the bay [40].

6. Concluding Remarks

Cascade effects are the dynamics present in accidents in which the impact of a hazard or the development of an initial technological or human failure generates a sequence of events. Thus, an initial impact can trigger other phenomena that lead to consequences with significant magnitudes. Cascade effects are complex and multi-dimensional and evolve constantly over time and are associated with a high magnitude of vulnerability.

The domino effect occurs in many major accidents, increasing significantly both their complexity and their final effects and consequences. Although in recent years the interest on this aspect has increased, the research achievement is still less compared to other aspects of industrial accidents. This is the reason that its main features are still insufficiently known.

Typically site specific occurring hazards cause or induce other hazards to occur. In particular, natural hazards rarely happen alone. Thus, it is very important to note that almost any event combination of hazards is possible and that it is necessary to identify these interactions and find ways to mitigate the effects of hazard combinations.

In [38], the state of the art of available approaches to the modelling, assessment, prevention and management of domino effects and natural hazards triggering industrial accidents is described. On the other hand, the relevant work carried out during past studies still needs to be consolidated and completed, in order to be applicable in a real industrial framework.

Therefore, improved tools and methods have to be developed to assist the progress toward a consolidated and universal methodology for the assessment and prevention of cascade events, contributing to enhance safety and sustainability of the chemical and process industry.

Since the accident in Mexico in 1984 a specific concern on domino accidents was raised in the chemical and process industry. Also to comply with the requirements of the legislation (EU Directives), technical standards and preventive measures, such as safety distances, fireproofing and emergency water deluges were introduced to control and reduce the probability of domino events.

Although the application of the Seveso Directives in the EU Member States should be based on methods and tools for the identification of sites liable to trigger domino effects, no generally accepted procedure to accomplish such task is available. This is somehow the result of the lack of a harmonized approach to the assessment of major accident hazard in the European countries, where either qualitative, quantitative or semi-quantitative approaches are used, depending on the Member State [2]. In 2012, the EC Joint Research Centre and the Norwegian Directorate for Civil Protection released a report concerning the approach to domino effect in Europe [32]. The report evidenced that not all countries have identified the “domino establishments”, only 14 countries did report to have completed such activity.

Therefore, combinations of events have already been investigated in the process/chemical industry for many years because several major accidents occurred, often damaging equipment enclosures. Typically the domino effect is investigated by different methods [8]. The significance of domino effects in chemical accidents is described in [13]. A domino effect can occur in various types of scenarios. However an essential aspect is whether it is confined to a single plant or area or progresses to others.

A recent study [23] has assessed the main features of domino effect accidents in process/storage plants and in the transportation of hazardous (flammable) materials through an analysis of 225 accidents. One of the goals of this study was to analyse the domino effect sequences applying probability event trees. The most frequent sequences were explosions inducing fires (27.6 %), fires inducing explosions (27.5 %) and fires inducing secondary fires (17.8 %) for this specific type of installations.

Furthermore, nuclear operating experience from recent years underlines the necessity to take into account event combinations in the safety assessment of nuclear power plants. Large projects are started on international level by the OECD/NEA and the International Atomic Energy Agency addressing combination of different hazards and multi-unit sites.

Operating experience from different types of industrial installations has shown that event combinations of fires and other events occur during the entire lifetime of the installations.

The international database OECD FIRE on fire incidents in nuclear power plants has been recently investigated regarding the operating experience in the participating member countries with respect to event combinations of fires and other events. Causally related events, either fires and consequential events or initiating events and consequential fires, have been observed as well as combinations of fires and other events having occurred independently of each other at the same time. The investigation has shown that more than 10 % of the entire 448 event records investigated are event combinations [6].

Moreover, it should be underlined that hazard analysis including multiple natural hazards is part of investigations not only in the technical field because a social-ecological system (SES) or social group within a SES can be affected by multiple natural hazards. One example is provided in [27] dealing with West Africa as one of the most vulnerable regions globally to the effects of climate change where draughts, dry spells and floods are the key influencing factors of food production in the region with often long-term impacts on the social-ecological system.

References

[1] Abdolhamidzadeh, B., Abbasi, T. & Rashtchian, D., et. al. (2010). A new method for assessing domino effect in chemical process industry. *Journal of Hazardous Materials* 182, 1-3, 416-426.

[2] Alileche, N., Cozzani, V., Reniers G., et. al. (2015). Thresholds for domino effects and safety distances in the process industry: A review of approaches and regulations. *Reliability Engineering and System Safety* 143, 74-84.

[3] Antonioni, G., Spadoni, G. & Cozzani, V. (2007). A methodology for the quantitative risk assessment of major accidents triggered by seismic events. *Journal of Hazardous Materials* 147, 1-2, 48-59.

[4] Bagster, D. F. & Pitblado, R. M. (1991). The Estimation of Domino Incident Frequencies-An Approach. *Trans IChemE*. 69, 195-199.

[5] Bagster, D. F. & Pitblado, R. M. (1991). *Process Safety Environ. Protect* 69.

[6] Berg, H. P., Röwekamp, M. & Fritze, N. et. al. (2016). Consideration of event combinations of fires and other events in Fire PRA - Insights from the OECD FIRE Database, *PSAM13*. Seoul.

[7] Cozzani V. et al. (2005). The assessment of risk caused by domino effect in quantitative area risk analysis. *Journal of Hazardous Materials*. 127, 14-30.

[8] Darbra, R. M., Palacios, A. & Casal, J. (2010). Domino effect in chemical accidents: main features and accident sequences. *Journal of Hazardous Materials* 183, 1-3, 565-573.

[9] Delvossalle, C. (1996). Domino Effects Phenomena: Definition, Overview and Classification. *First European Seminar on Domino Effects*. Leuven, Belgium, Federal Ministry of Employment, Safety Administration, Direction Chemical Risks, Brussels, Belgium, 5-15.

[10] Eisenberg, N. A., Lynch, C. J. & Breeding, R. J. (1975). *Vulnerability Model: A Simulation System for Assessing Damage Resulting from Marine Spills*. Report CG-D-136-75, Enviro Control Inc., Rockville, MD.

[11] European Commission. (2010). *Risk assessment and mapping guidelines for disaster management*. Brussels.

[12] Garcia-Aristizabal, G. et al. (2013). *Dynamic scenario concept models*. CRISMA project of EU.

[13] Hemmatian, B., Abdolhamidzadeh, B. & Darbra, R. M. et al. (2014). The significance of domino effect in chemical accidents. *Journal of Loss Prevention in the Process Industries* 29, 30–38.

[14] Janssens, J., Talarico, L. & Reniers, G. et al. (2015). A decision model to allocate protective safety barriers and mitigate domino effects. *Reliability Engineering and System Safety* 143, 44-52.

[15] Kadri, F. & Chatelet, E. (2013). Domino Effect Analysis and Assessment of Industrial Sites: A Review of Methodologies and Software Tools. *International Journal of Computers and*

Distributed Systems. HAL-ID: hal-01026495, 1-10

[16] Kadri, F., Chatelet, E. & Chen, G. et al. (2011). Method for Quantitative Assessment of Domino Effect Caused by Heat Radiation in Industrial Sites. *International Conference on Risk Analysis (ICRA4)*. Limassol, Cyprus, 1-8.

[17] Kadri, F., Châtelet, E. & Chen, G. (2012). Quantitative Risk Assessment of Domino Effect Caused by Heat Load. *Int. J. Syst. Control* 3, 42-48.

[18] Kadri, F., Lallement, P. & Chatelet, E. (2012). The Quantitative Risk Assessment of domino effect on Industrial Plants Using Colored Stochastic Petri Nets. *PSAM11 & ESREL Conference*. Helsinki, Finland.

[19] Kadri, F., Chatelet, E. & Lallement, P. (2013). The Assessment of Risk Caused by Fire and Explosion in Chemical Process Industry: A Domino Effect-Based Study. *J. Risk Anal. Crisis Response* 3, 66-76.

[20] Kadri, F., Châtelet, E. & Chen, G. (2013). Method for quantitative assessment of the domino effect in industrial sites. *Process Saf. Environ. Prot* 91, 452-462.

[21] Kadri, F., Birregah, B. & Châtelet, E. (2014). Natural Disaster Impacts on Critical Infrastructures: A domino effect-based study. *Journal of Homeland Security and Emergency Management* 11, 2, 217-241.

[22] Kappes, M., Keiler, M. & Elverfeldt, K. et al. (2012). Challenges of analyzing multi-hazard risk: a review. *Nat. Hazards* 64, 2, 1925-1958.

[23] Khakzad, N., Khan, F. & Amyotte, P. et al. (2013). Domino effect analysis using Bayesian networks. *Risk Analysis*. 233, 2, 292-306.

[24] Khan F.I. & Abbasi S.A. (1998). Models for domino effect analysis in chemical process industries. *Process Safety Progress-AIChE* 17, 2, 107-113.

[25] Khan, F. I. & Abbasi, S. A. (2001). An assessment of the likelihood of occurrence, and the damage potential of domino effect (chain of accidents) in a typical cluster of industries. *Journal of Loss Prevention in the Process Industries* 14, 4, 283-306.

[26] Khan, F. I. & Abbasi, S. A. (2002). Criterion for developing credible accident scenarios for risk assessment. *Journal of Loss Prevention in the Process Industries* 15, 6, 467-475.

[27] Kloos, J., Asare-Kyei, D. & Pardoe, J. et al. (2015). *Towards the Deveopment of an Adapted Multi-hazard Risk Assessment Framework for the West Sudanian Savanna Zone*. UNU-EHS Publication Series 11, 1-37.

[28] Krausmann, E. & Mushtaq F. (2008). A qualitative Natech damage scale for the impact of floods on selected industrial facilities. *Natural Hazards* 46, 2, 179-197.

[29] Kunz, M. et al. (2013). Investigation of Superstorm Sandy 2012 in a multi-disciplinary approach. *Natural Hazards and Earth System Sciences* 13, 2579-2598.

[30] Labath, N. A. & Amendola, A. (1989). Analysis of domino effect incident scenarios by the DYLAM approach. *6th International Symposium on Loss Prevention and Safety Promotion in the Process Industries*. Oslo, Norway. 12-22.

[31] Landucci, G., Gubinelli, G. & Antonioni, G. et al. (2009). The assessment of the damage probability of storage tanks in domino events triggered by fire. *Accident Analysis and Prevention* 41, 6, 1206-1215.

[32] Larsen, R.G., Wood, M. & Olsen, A.L. et al. (2012). Seveso inspection series. *Chemical hazards risk management in industrial parks and domino effect establishments*. Luxembourg Publications Office of the European Union. 5.

[33] Latha, P., Gautam, G. & Raghavan, K. V. (1992). Strategies for Quantification of Thermally Initiated Cascade Effects. *Journal of Loss Prevention Process Industries* 5, 1, 15-21.

[34] Little, R.G. (2002). Controlling cascade failure: understanding the vulnerabilities of interconnected infrastructures. *Journal of Urban Technology* 9, 1, 109-123.

[35] Liu, B., Siu, Y.L. & Mitchell, G. (2016). Hazard interaction analysis for multi-hazard risk assessment: a systematic classification based on hazard-forming environment. *Nat. Hazards Earth Syst. Sci* 16, 629-642.

[36] Marzocchi, W., Mastellone, M.L. & Ruocco A.Di. et al. (2009). *Principles of multi-risk assessment. Interaction amongst natural and man-induced risks. Project Report*. FP6 SSA Project: Contract. 511264.

[37] Mohaghegh, Z. & Mosleh, A. (2009). Incorporating organizational factors into probabilistic risk assessment of complex socio-technical systems: Principles and theoretical foundations. *Safety Science* 47, 139-1158.

[38] Necci, A. (2015). *Cascading events triggering industrial accidents: quantitative assessment of NaTech and domino scenarios*. PhD thesis, Alma Mater Studiorum Università di Bologna.

[39] Perilhon, P. (2000). MOSAR, Traité sécurité et gestion des risques, *Techniques de l'ingénieur SE 4 060*, 1-16.

[40] Pescaroli, G. & Alexander, D. (2015). A definition of cascading disasters and cascading effects. Going beyond the "toppling dominos"

metaphor. *Planet@Risk*. *Davos: Global Risk Forum GRF Davos* 2, 3, 58-67.

[41] Pescaroli, G & Alexander, D. (2016). Critical infrastructure, panarchies and the vulnerability paths of cascading disasters. *Natural Hazards* 82, 1, 175-192.

[42] Reniers, G. (2010). An external domino effects investment approach to improve cross-plant safety within chemical clusters. *J. Hazard. Mater* 177, 167.

[43] Renni, E., Antonioni, G. & Bonvicini, S. et. al. (2009). A novel framework for the quantitative assessment of risk due to major accidents triggered by lightning. *Chemical Engeneering Transactions* 17, 311-316.

[44] Scilly, N. F. & Crowther, J. H. (1992). Methodologies for Predicting Domino Effects from Pressure Vessel Fragmentation. *International Conference on Hazard Identification and Risk Analysis, Human Factors and Human Reliability in Process Safety*. Florida, CCPS, AIChE, 15-17.

[45] Sun, D., Huang, G. & Jiang, J. et al. (2013). Study on the Rationality and Validity of Probit Models of Domino Effect to Chemical Process Equipment caused by Overpressure. *Journal of Physics*. IOP Publishing, 423, 012002.