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Abstract: Domino effects or cascade events in the chemical and process industries are since three decades recognized as possible accident scenarios. They represent a growing concern since they hold the potential to cause devastating consequences. The 'domino effect' as a phenomenon, is also a controversial topic when its assessment is required. A number of different approaches exist in technical standards and in literature. The present contribution aims at providing an orientation and a number of up-to-date sources for the assessment of escalation leading to domino scenarios, and to the assessment of safety distances to prevent escalation. An overview of current regulations in the European framework is also provided in this paper.

Thresholds for Domino Effects and Safety Distances in the Process Industry: a Review of Approaches and Regulations

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Highlights

- Definition and approach to domino effect assessment in EU member states (MS) were analyzed
- A survey on criteria to identify domino hazard in eight EU MS was carried out
- Threshold criteria for the assessment of domino scenarios were critically compared
- Important differences in requirements concerning domino effect are present in EU MS
- Agreement on escalation thresholds may improve protection from domino scenarios

Keywords

Domino effect; major accident hazard; escalation; damage; threshold values.

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Abstract

Domino effects or cascade events in the chemical and process industries are since three decades recognized as possible accident scenarios. They represent a growing concern since they hold the potential to cause devastating consequences. The ‘domino effect’ as a phenomenon, is also a controversial topic when its assessment is required. A number of different approaches exist in technical standards and in literature. The present contribution aims at providing an orientation and a number of up-to-date sources for the assessment of escalation leading to domino scenarios, and to the assessment of safety distances to prevent escalation. An overview of current regulations in the European framework is also provided in this paper.

1. Introduction

The Mexico City disaster that took place in November 1984 [1], calling for 542 fatalities and huge destruction, is possibly one of the best known domino accidents that ever affected an industrial site. Since that event, a specific concern on domino accidents was raised in the chemical and process industries. Also as a consequence of requirements from the legislation (EU Directives), technical standards and preventive measures, such as safety distances, fireproofing and emergency water deluges were introduced specifically to control and reduce the probability of domino events [2]. However, the complexity of domino scenarios caused a rather jeopardized approach to the issue, which turned out in the existence of different approaches, methods and thresholds.

Different tools and even different values for safety distances concerning the same phenomenon are adopted in different countries [3]. This was the consequence of the technical and managerial complexities going hand in hand with domino effect- or escalation events. Moreover, even the adoption of a single definition of such events in the literature, in technical documents and in the regulations was hampered and has never been realized [4].

As pointed out by Larsen et al. [3], inspection services from European Member States mention that, amongst other problems, one of the more important challenges, when it comes to the follow-up of the current legislation concerning domino effect between adjacent industrial sites, is the lack of criteria for the identification of establishments being obliged to exchange information due to their proximity and possibility of domino effects. Another problem arising due to insufficient harmonization between the different European countries in the field of domino effect is that sites may be classified as ‘domino establishment’ in one country, while if situated in another country they might obtain the status of ‘non-domino establishment’ due to the different thresholds being used in the EU Member States, and due to the different domino distance calculations across Europe.

The present contribution, starting from an up-to-date definition of domino effect, a review is provided of escalation thresholds and safety distances for domino effects in the process industry, with the aim of defining a process that may lead to the selection of appropriate values, based on a physically-sound analysis of escalation mechanisms.

2. Definition of Domino Effect

This section discusses which parameters should be looked at in order to understand the escalation possibility, and what actually constitutes a domino effect. Actually, no universally-accepted definition of a domino effect exists in the technical and scientific literature, due to the complexity of such events and due to the different perspectives that may be adopted in their analysis. Nevertheless, defining what should be considered as a domino accident is not a mere academic exercise, since several technical standards as well as the European legislation specifically demand the assessment of “domino effects”. For example, article 9 of the European Directive 2012/18/EU (the so-called “Seveso-III” Directive) [5]

requires to identify establishments that may be affected by domino scenarios and to include such scenarios in safety reports and in major accident prevention policies (MAPPs).

Due to the inexistence of a non-polysemous formalization to describe the domino effect phenomenon, most of the EU Member States' competent authorities refer to the definition given by Article 8 of Council Directive 96/82/EC (the so-called "Seveso-II" Directive, reported in Table 1) [6]. However, the latter only considers accidents that propagate from one establishment to another establishment (also called 'external domino effect') and omits the so-called internal domino effects [4]. This limited definition is unchanged in Article 9 of Directive Seveso-III, which will enter into force on 1 June 2015 [5]. If the definition provided by EU legislation is adopted, safety managers may meet regulatory requirements (safety report, major accident prevention policies, licensing...) without assessing part of the risk resulting from escalation possibility, and specifically that of escalation from one to another plant unit inside the same Seveso site. Another obvious limit of the definition reported in the Seveso Directives is the fact that it concerns only Seveso installations. An accident in one Seveso plant can affect a nearby installation not falling under the obligations of Seveso Directives, or vice-versa. For these reasons, some EU Member States (see Table 1) proposed their own definition. The Member State competent authorities in these countries adopted their own specific definition, either formally or informally. In France the Ministry of Ecology and Sustainable Development adopts the definition given by Vallee et al. [7]. In Belgium, Wallonian practices use the definition proposed by Delvosalle [8], whereas the Flemish Ministry of Environment, Nature and Energy adopts the definition given by Gorrens et al. [9]. In Italy no specific official definition is yet available, although several guidance documents and draft decrees recognize domino effects being possible, not only across different Seveso establishments, but also from one unit to another within the same establishment. In the United Kingdom, in order to implement the Seveso II Directive, the following definition of a domino effect is reported in the Control of Major Accident Hazard (COMAH) Regulations: *"In some circumstances a major accident at one COMAH establishment might be triggered by an incident at another COMAH establishment (the so-called domino effect). The initiating event needs not necessarily to be a major accident itself but must be at a COMAH establishment, either top-tier or lower-tier, and involve a defined dangerous substance"* [10].

Table 1 summarizes some definitions proposed within the EU in order to specify the notion of 'domino effect', especially with reference to the chemical and process industries. As evident from the table, no agreement is present. This also emerged from the rather different interpretations given to the concept of domino effect in an expert workshop recently organized ([Expert Workshop on Domino Effect, University of Bologna, 2014](#)) [11].

In order to avoid jumbling this perception and adding confusion, it may be interesting to go back to studies that have pointed out the sequential nature of events leading to an accident, so as to remove ambiguity. This was underlined for the first time by Heinrich [12] with respect to accident modelling, introducing what has become known as the 'domino theory', where the author described the accident as a chain of independent events that occur in particular order, causing harm [13]. However, the domino theory is not to be confused with the "domino effect" phenomenon, the latter constituting the focus of this paper. Indeed, Heinrich's domino theory does not join the meaning of domino effect as it was defined in Table 1, since it does not consider the propagation of a major accident that occurs in one unit to other nearby units. Heinrich's theory only discusses and explains the sequence of events that has led to an occupational accident.

In order to unambiguously identify the character of the domino event under consideration, Reniers [14] proposed a classification, which categorizes domino events according to the various features that

domino scenarios may have. Four categories are suggested, each having two subcategories: category.1 (internal or external), category.2 (direct or indirect), category.3 (temporal or spatial), and category.4 (in serial or parallel).

Table 1: Domino effect definitions

Author (s)	Domino effect definition
Council Directive 96/82/EC [6]	Domino effects, where establishments are sited in such a way or so close together as to increase the probability and possibility of major accidents, or aggravate their consequences.
Cozzani et al. [15] Italy	Accidental sequences having at least three common features: 1) a primary accidental scenario, which initiates the domino accidental sequence. 2) the propagation of the primary event, due to “an escalation factor” generated by the physical effects of the primary scenario, that results in the damage of at least one secondary equipment item. 3) one or more secondary events (i.e. fire, explosion and toxic dispersion), involving the damaged equipment items (the number of secondary events is usually the same of the damaged plant items).
Delvosalle [8] Wallonia (Belgium)	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
Health and Safety Executive (HSE) [10] The United Kingdom	In some circumstances a major accident at one COMAH establishment might be triggered by an incident at another COMAH establishment (the so-called domino effect). The initiating event needs not necessarily to be a major accident itself but must be at a COMAH establishment, either top-tier or lower-tier, and involve a defined dangerous substance.
Gorrens et al. [9] Flanders (Belgium).	A major accident in a so-called secondary installation which is caused by failure of a so-called external hazards source.
Vallee et al. [7] France	An accidental phenomenon affecting one or more installations in an establishment that can cause an accidental phenomenon in an adjacent establishment, leading to a general increase in consequences.

With the purpose of standardizing the domino effect definition intended to progress towards a non-polysemous formalization to describe the phenomenon and converge to a broad consensus, at least within the scientific community, Reniers and Cozzani [4] have proposed the following definition: “*An accident in which a primary unwanted event propagates within an equipment (‘temporally’), or/and to nearby equipment (‘spatially’), sequentially or simultaneously, triggering one or more secondary unwanted events, that may in turn trigger further (higher order) unwanted events, resulting in overall consequences more severe than those of the primary event*”.

The above definition encompasses all specific aspects found in most domino event definitions, including the four categories cited above [14] as well as the concept of local domino effect, proposed by Abdolhamidzadeh et al. [16]. Thus, on the basis of the definition suggested by Reniers and Cozzani [4], the key elements of a domino accident are *propagation* (“a primary unwanted event propagates...”) and *escalation* (“resulting in more severe consequences”). Therefore, when assessing a domino accident, three elements should be clearly assessed:

- (i) The primary event (that is, the accident scenario of concern and its final outcome expressed in terms of physical effects - thermal radiation, overpressure, etc.)

- (ii) The possible significant secondary scenarios that may be triggered by propagation of the primary event (that are, the secondary scenarios started by the damage of equipment items causing the release of hazardous substances resulting in final outcomes able to “escalate” the primary scenario)
- (iii) The relevant secondary targets (equipment items that may be damaged by the primary event and that, if damaged, have the potential to cause final outcomes escalating the primary event)

It is clear from the above that on the one hand damage distances are crucial to assess the actual potential of a primary scenario in triggering a domino effect. On the other hand, damage alone is not an element that characterizes a domino event: in order to produce an escalation, the final outcome of the secondary scenario should have the potential to cause further damage or fatalities with respect to that already caused by the primary scenario. In the preliminary assessment of domino effect, it is thus crucial to understand which primary scenarios have the potentiality to trigger escalation and what are the safety distances to prevent these events.

3. Damage and Escalation Thresholds

Damage and escalation thresholds are a valuable approach to identify secondary scenarios possibly resulting from a domino effect. The results of consequence analysis models applied to the simulation of primary scenarios may easily be compared to threshold values, identifying a maximum credible escalation radius [17]. Such procedure is simple and transparent, although it oversimplifies somehow the problem, reducing escalation assessment to a mono-dimensional problem. However, due to its simplicity, the approach is useful at least as a screening tool [4].

Nonetheless, as already mentioned, the issue is quite controversial since a relevant uncertainty exists in threshold values for escalation. Actually, proposed threshold values span over orders of magnitude [15,18]. This is due to the number of factors that influence the possible propagation of the primary accident: e.g. the duration of the scenario that may influence the possibility of escalation due to radiation, the design features of the possible target equipment, etc. Moreover, the damage of a secondary equipment is not sufficient to trigger a domino accident by itself: in order to obtain a relevant domino accident, escalation should be present: the overall consequences of the domino scenario should be higher than those of the primary event. Thus, a minor pool fire triggered as a consequence of a devastating explosion may not be considered a relevant escalation, since the consequences of the primary explosion may be by far more relevant. If this is not kept in mind, almost all severe industrial accidents should be considered as domino events.

Table 2 shows the primary scenarios that are more likely to trigger escalation effects [4]. Definition, modelling details and physics of the scenarios listed in Table 2 are widely described in literature [19-21]. As shown in the table, three main escalation vectors were identified: heat radiation or flame impingement, overpressure and fragment projection. Toxic release was excluded from the present analysis because this physical effect does not result directly in a loss of containment (LOC) or in the damage of secondary equipment [22].

Thresholds values can be effectively used to describe the minimum intensity of primary scenarios able to trigger escalation. Actually, some scenarios may not be able to critically damage secondary equipment, either because not sufficiently intense (e.g. low energy explosions) or because of their quick time evolution (e.g. flash-fires). For other scenarios, vulnerability may depend on the characteristics of the target unit. For example, different thresholds for escalation can be defined for scenarios involving

Table 2: Direct escalation: escalation vectors generated by different categories of primary scenarios.

Primary scenario	Escalation vector
pool fire	radiation, fire impingement
jet fire	radiation, fire impingement
fireball	radiation, fire impingement
flash fire	fire impingement
mechanical explosion	fragment projection, overpressure
confined explosion	fragment projection, overpressure
BLEVE	fragment projection, overpressure
VCE	overpressure, fire impingement
toxic release	---

BLEVE: Boiling Liquid Expanding Vapour Explosion; VCE: Vapour Cloud Explosion.

blast wave as escalation vector, depending on the type of target equipment and on the material contained in the target vessels that may be damaged. This is the combined result of (i) the different toughness of the equipment to the escalation vector, and (ii) the different damage states required to initiate a severe secondary scenario depending on the physical properties of the substances involved in the loss of containment.

Several authors have reported different and apparently contradictory threshold values for equipment “damage” caused by overpressure or radiation (Fig. 1 and 2; Table 3). The wide uncertainty in threshold values derives from the complexity of the escalation phenomenon. Among the factors which may have caused these apparent inconsistencies in literature data, with reference to overpressure effects, two seem the more important: (i) the complete lack of indications on the specific characteristics of target equipment; and (ii) the ambiguities in the definition of “damage” and/or “loss”. As regards radiation effects, other factors in addition to the ones mentioned, may greatly influence the possibility of escalation, and thus may be at the origin of these inconsistencies, as they are seldom taken into account: (iii) the damage mechanism of the primary scenario (fire impingement or distant radiation); and (iv) the duration of the fire scenario (exposure time).

Fig.1: Thermal radiation thresholds for domino effect proposed by different authors.

Thresholds suggested by the international Oil and Gas Producers association, (OGP, Table 3) [23,24] are recommended as a starting point (conservative) for evaluation of damage due to explosions and fires.

OGP emphasizes the fact that the proposed values are only indicative and that the vulnerability of a plant (structure) should be determined based on an assessment of the criticality of the structure followed by a proportionate modelling approach (i.e. one based on the criticality and complexity).

Fig.2: Overpressure thresholds for domino effect proposed by different authors.

Table 3: Damage estimates based on overpressure/thermal radiation effect proposed by OGP.

Escalation vector	Threshold	Target equipment	Effect/damage
Radiation (kW/m ²)	12.5	Not specified	Thin steel with insulation on the side away from the fire may reach thermal stress level high enough to cause structural failure.
	25	Not specified	Unprotected steel will reach thermal stress temperatures that can cause failure.
	35	Not specified	Cellulosic material will pilot ignite within one minute's exposure.
Overpressure (mbar)	207	Cone / Floating roof tank	Unit uplifts "half tilted"
	207	Oil storage tanks	Rupture
	241-483	Cracking reactor	Unit moves and pipes break
	276	Chemical reactor	Unit moves and pipes break
	379	Fractionation column	Frame cracks
	414	Horizontal pressure vessel	Frame deforms & unit moves and pipes break
	448	Extraction column	Unit moves and pipes break
	517	Heat exchanger	Unit moves and pipes break
	552 -965	Spherical tank	Unit moves and pipes break
	827	Vertical pressure vessel	Unit moves and pipes break

A conceptual framework based on the description of secondary target damage by a discrete number of structural damage states (DS) and of loss intensities (LI) was proposed to approach the problem [25]. The analysis carried out evidenced that while severe damage states always lead to large loss intensities and, consequently to severe secondary scenarios, also minor structural damages can trigger severe secondary consequences if specific operative conditions and material hazards are present. An example is the case of volatile toxic substances contained in pressurized equipment, which may form relevant toxic dispersions also in case of relatively moderate leak diameters (e.g. failure of connection nozzles). Therefore, specific escalation thresholds, rather than thresholds for structural damage, should be used in the analysis of escalation hazard. Table 4 reports threshold values for damage and escalation obtained for several accident scenarios. The thresholds in the table were obtained from the analysis of literature data and from simplified structural models, validated on the basis of a wide number of representative case-studies. A sensitivity analysis of all factors affecting the escalation possibility was also performed, in order to assess critical values for the different parameters [15].

Table 4: Damage and escalation thresholds (adapted from [15]).

Scenario	Escalation vector	Modality	Target category	Damage threshold	Escalation threshold	Safety distance
Flash fire	Heat radiation	Fire impingement	Floating roof tanks	Damage unlikely	Flame envelope	Max. flame distance
			All other units	Damage unlikely	Escalation unlikely	–
Fireball	Heat radiation	Flame engulfment	Atmospheric	$I > 100 \text{ kW/m}^2$	$I > 100 \text{ kW/m}^2$	Maximum flame distance
			Pressurized	Damage unlikely	Escalation unlikely	–
		Distant radiation	Atmospheric	$I > 100 \text{ kW/m}^2$	$I > 100 \text{ kW/m}^2$	Maximum flame distance
			Pressurized	Damage unlikely	Escalation unlikely	–
Jet fire	Heat radiation	Fire impingement	All	Flame envelope	Flame envelope	–
		Stationary radiation	Atmospheric	$I > 15 \text{ kW/m}^2$	$I > 15 \text{ kW/m}^2$	50 m from flame envelope
			Pressurized	$I > 45 \text{ kW/m}^2$	$I > 45 \text{ kW/m}^2$	25 m from flame envelope
Pool fire	Heat radiation	Flame engulfment	All	Flame envelope	Flame envelope	–
		Stationary radiation	Atmospheric	$I > 15 \text{ kW/m}^2$	$I > 15 \text{ kW/m}^2$	50m from pool border
			Pressurized	$I > 45 \text{ kW/m}^2$	$I > 45 \text{ kW/m}^2$	20m from pool border
VCE	Overpressure	Blast wave interaction	Atmospheric	$P > 7 \text{ kPa}$	$P > 22 \text{ kPa}$	R = 1.75 (ME); 1.50 (BS)
			Pressurized	$P > 20 \text{ kPa}$	$P > 20 \text{ kPa}$	R = 2.10 (ME); 1.80 (BS)
			Elongated (toxic)	$P > 14 \text{ kPa}$	$P > 20 \text{ kPa}$	R = 2.10 (ME); 1.80 (BS)
			Elongated (flammable)	$P > 14 \text{ kPa}$	$P > 31 \text{ kPa}$	R = 1.35 (ME); 0.85 (BS)
	Heat radiation	Fire impingement	See flash fire	See flash fire	See flash fire	See flash fire
Confined explosion	Overpressure	Blast wave interaction	Atmospheric	$P > 7 \text{ kPa}$	$P > 22 \text{ kPa}$	20 m from vent
			Pressurized	$P > 20 \text{ kPa}$	$P > 20 \text{ kPa}$	20 m from vent
			Elongated (toxic)	$P > 14 \text{ kPa}$	$P > 20 \text{ kPa}$	20 m from vent
			Elongated (flammable)	$P > 14 \text{ kPa}$	$P > 31 \text{ kPa}$	20 m from vent
Mechanical explosion	Overpressure	Blast wave interaction	Atmospheric	$P > 7 \text{ kPa}$	$P > 22 \text{ kPa}$	R = 1.80
			Pressurized	$P > 20 \text{ kPa}$	$P > 20 \text{ kPa}$	R = 2.00
			Elongated (toxic)	$P > 14 \text{ kPa}$	$P > 20 \text{ kPa}$	R = 2.00
			Elongated (flammable)	$P > 14 \text{ kPa}$	$P > 31 \text{ kPa}$	R = 1.20
	Missile projection		All	Fragment impact	Fragment impact	300 m (prob. $< 5 \times 10^{-2}$)
BLEVE	Overpressure	Blast wave interaction	Atmospheric	$P > 7 \text{ kPa}$	$P > 22 \text{ kPa}$	R = 1.80
			Pressurized	$P > 20 \text{ kPa}$	$P > 20 \text{ kPa}$	R = 2.00
			Elongated (toxic)	$P > 14 \text{ kPa}$	$P > 20 \text{ kPa}$	R = 2.00
			Elongated (flammable)	$P > 14 \text{ kPa}$	$P > 31 \text{ kPa}$	R = 1.20
	Missile projection		All	Fragment impact	Fragment impact	300 m (prob. $< 5 \times 10^{-2}$)
Point-source explosion		Blast wave interaction	Atmospheric	$P > 7 \text{ kPa}$	$P > 22 \text{ kPa}$	–
			Pressurized	$P > 20 \text{ kPa}$	$P > 20 \text{ kPa}$	–
			Elongated (toxic)	$P > 14 \text{ kPa}$	$P > 20 \text{ kPa}$	–
			Elongated (flammable)	$P > 14 \text{ kPa}$	$P > 31 \text{ kPa}$	–

I, heat radiation intensity; P, maximum peak static overpressure; R, Energy scaled distance: ME, Multi Energy method [26]; BS, Baker-Sthrelow method [27,28].

4. Escalation safety distances

The intensity of each escalation vector depends on the total amount of energy (or substance) which is possibly released from the primary system of containment (reactor, storage tank, etc.). The maximum distance at which escalation effects may be considered credible is called “safety distance”. The safety distance is the minimum separation distance between units required to avoid an escalation event. If threshold values for escalation are available, the safety distance may be easily calculated by the application of standard literature models for consequence assessment [29-31]. Based on these considerations, Cozzani et al. proposed simplified normograms for the swift assessment of safety distances [4, 17, 32]. The safety distances not only closely reflect the nature of the escalation vector, but also depend on the primary accident scenario and the characteristics of the target unit.

In case of flash-fire scenarios, the extension of the flame envelope is the safety distance for potential sources of flammable vapours (e.g. floating roof tanks), while other kind of equipment is usually unaffected by such scenario.

For fireballs, a safety distance related to the radius of the fireball should be assumed only for atmospheric vessels. In fact, recent results confirmed that the possibility of escalation may be reasonably excluded for pressurized vessels, even in the absence of passive protections [15].

In the case of jet fires, the safety distance depends on the maximum flame length and direction. A study by Cozzani et al. [15] suggests that the time to failure for atmospheric vessels is always higher than 15 min for targets within 50 m from the flame envelope. The value of 15 min was assumed as a reference time for activation of mitigation actions having a high probability of success (e.g. activation of water deluges at the arrival of the fire brigade). Since in general no passive fire protection is used on atmospheric tanks, this value may be assumed as the safety distance in the case of jet fires. With respect to pressurized vessels, the minimum value calculated by Cozzani et al. [15] for the time to failure is of about 13 min. These values are comparable to the time assumed as necessary for an effective mitigation. Thus, an escalation as a consequence of stationary radiation, without flame impingement, may not be excluded for an unprotected pressurized vessel. However, pressurized vessels have usually passive fire protections (thermal insulation), as well as active protections (water deluges), that may raise the actual value of the time to failure up to safe values. Therefore, the escalation involving pressurized vessels is scarcely credible in the case of distant source radiation from jet fires. Furthermore, even in the case of unprotected vessels, the escalation is definitely not credible for distances higher than 25 m from the flame envelope in the jet direction.

The same analysis applied to pool fires evidenced that escalation may be considered possible for atmospheric vessels at distances lower than 50 m from pool border with a reference time of 15 min [15]. In the case of pressurized vessels, a conservative safety distance of 20 m may be assumed, although this value may be further reduced taking into account the effect of thermal insulation. For scenarios involving overpressure as escalation vector, the safety distance depends primarily on the amount of energy released in the scenario, as well as on the type of scenario. The safety distance is related to the distance at which the peak overpressure of the blast wave equals the threshold values for damage by overpressure. In the case of VCEs, this may be calculated by the standard approach used in QRA [29,31] estimating the explosion energy and evaluating the “strength” of explosion on the basis of plant lay-out and fuel reactivity, i.e. the “strength factor F” for the Multi-Energy method [26] or the flame Mach number (M_f) in the Baker-Strehlow methodology [28]. The explosion of industrial equipment due to the internal combustion of gases, vapours or dust, is in general destructive even for high strength enclosures. Hence, venting devices are often introduced for mitigation purposes. When the vent section opens, the rapid depressurization through the vent section may produce a blast wave. External explosions due to the combustion of un-burnt gases released after the vent opening were also observed [33,34]. The analysis

of safety distances by Cozzani et al. [15] evidenced as failures due to overpressure effects are not possible for targets located more than 20 m from the vent outlet.

Missiles are an escalation vector generated in the case of mechanical explosions and BLEVEs. The escalation is caused by the missile impact on a target vessel, causing a loss of containment. This requires two conditions to be verified: the distance of the target vessel must be lower than the maximum credible projection distance and the impact must be followed by a loss of containment at the target vessel. The latter requirement is usually assumed to be verified in the conservative approach used in the assessment of missile damage [35,36]. The distance of projection is mainly dependent on the initial missile velocity, direction and on the drag factor [29]. For most mechanical explosions, the maximum projection distance of fragments is usually higher than 1000 m and projection distances up to 900 m were observed in past accidents [35,37,38]. Since these distances are well beyond typical inter-unit distances of a plant, defining an escalation threshold based solely on possible projection distances is therefore impractical. However, the probability of impact quickly decreases with the projection distance. A study by Gubinelli et al. [15,35] shows that the impact probability of a fragment from a mechanical explosion is about 3×10^{-1} at 100 m and of 5×10^{-2} at 300 m. In the case of BLEVE, conservative values of impact probability are of 2.5×10^{-1} at 100 m and of 2.5×10^{-2} at 300 m. Once defined a tolerability criteria for impact probability, these findings can be used to evaluate likely affected areas. It should be clear that such distances do not take into account the role of safety barriers.

5. Approach to domino effect assessment in EU member states

As discussed above, current regulations and technical standards are influenced by the jeopardized approach to domino effects that took place since the issue became of concern. Nevertheless, the more frequent approach in regulations and standards is based on threshold values.

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. 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 [3]. The report evidenced that not all countries¹ have identified the “domino establishments” (only 14 countries did report to have completed such activity). Furthermore, the vast majority of EU MS have no specific tools (guidelines, checklists, models, software) dedicated to the assessment of domino effects. Evaluation of possible domino effects is either carried out as a part of the safety report assessment, or as a separate activity where the inspection authorities are not involved at all. Furthermore, in the vast majority of the countries, non-Seveso establishments are not in any way included in the inspections of neighbouring Seveso establishments as potential targets of escalation leading to domino scenarios.

Therefore, no harmonized EU guidelines or recommendations for the assessment of domino effect distances exist. In order to gather updated information on the topic, a survey was carried out within ten EU member states (MS). The survey was focused on threshold values used for the assessment of safety distances for escalation leading to domino scenarios and on the definition of domino effect adopted in the Member States, and was addressed to safety experts or to members of competent authorities for Seveso Directive implementation. The survey carried out within the present study evidenced that each Member State has its own approach to deal with domino effects, even if most are based on predefined

¹ The study was conducted on Seveso countries which are considered to include the 27 EU Member States, Norway and Iceland as countries of the European economic area, and Croatia, an EU Candidate Country.

threshold values or safety distances. Table 4 reports the threshold values collected for the eight EU Member States included in the survey that apply threshold values in domino assessment: Belgium, France, Greece, Italy, Poland, Spain, The Netherlands, and the United Kingdom. Reference to legislation related to threshold values, assessment methods/software tools used, and other details reported by the respondents, are provided in annex 1. As evident from Fig. 3, the proposed values span over an order of magnitude.

a

b

Fig. 3: (a) Overpressure thresholds for domino effects in different EU Member States without specification of targets. (b) Thermal radiation thresholds for domino effects in different EU Member States.

Table 4: Summary of domino threshold values in eight EU Member States.

Country	Threshold values		
	Overpressure effects	Radiation effects	Mechanical effects
Member State region Flanders, Belgium	Threshold 1: 100 mbar (total collapse of warehouses) Threshold 2: 160 mbar (damage of pressurized installations) Threshold 3: 450 mbar (total collapse of pressurized installations)	Threshold 1: 8 kW/m ² (unprotected installation item) Threshold 2: 32 kW/m ² (protected installation item) Threshold 3: 44 kW/m ² (protected pressure storage)	Threshold 1: rupture of wing of wind turbine Threshold 2: height of external hazard installation such as wind turbine, power lines Optional: missile effects with threshold 3: 80% of the fragments
Member State region Wallonia, Belgium	Threshold 1: 160 mbar	Threshold 1: 8 kW/m ² (unprotected installation item) Threshold 2: 32 kW/m ² (protected atmospheric storage) Threshold 3: 44 kW/m ² (protected pressure storage)	Threshold 1: no reference value
France	Threshold 1: 200 mbar	Threshold 1: 8 kW/m ²	(Only for neighbouring equipment inside the establishment. No threshold exists: case by case)
Greece	Threshold 1: 700 mbar (for UVCE)	Threshold 1: 37.5 kW/m ² (for pool fire), fireball radius (for BLEVE), length of the flame (for jet fire)	No reference value
Italy	Threshold 1: 300 mbar	Threshold 1: 12.5 kW/m ² (for stationary radiation) Threshold 2: 200-800m (fireball)	Threshold 1: 200-800m
Poland	Threshold 1: 1140 mbar (partially collapse of structure) Threshold 2: 1300 mbar (serious damages)	Threshold 1: 37.5 kW/m ²	No threshold exists: case by case, based on specific calculation
Member State region Catalonia, Spain	Threshold 1: 160 mbar	Threshold 1: 8 kW/m ²	Threshold 1: maximum reach of missiles
The Netherlands	Threshold 1: 100 mbar (storage buildings) Threshold 2: 200 mbar (atmospheric storage vessel) Threshold 3: 300 mbar (atmospheric double or full containment storage vessel, total collapse of dwellings) Threshold 5: 450 mbar (pressure storage vessel)	Threshold 1: 8 kW/m ² (unprotected installation item) Threshold 2: 10 kW/m ² (buildings and other vulnerable storage vessels) Threshold 3: 35 - 37.5 kW/m ² (protected installation item)	Threshold 1: the chance to hit by a missile is 0.5%
United Kingdom, Great Britain (England, Scotland, Wales) ^a	Threshold 1: 70 mbar	For pool fire, fireball, jet fire, threshold 1: 500 thermal dose units (kW) ^{4/3} .s For flash fire, threshold 1: ½ LFL Threshold 2: individual risk of 0.3×10 ⁻⁶ chances of being within the flash fire envelope defined by LFL	Threshold 1: furthest extent of missile travel from actual incidents (often not applied)

^a In contrast to the other MS, in the UK the reported thresholds are set for human (used for the identification of domino groups based on human vulnerability, details are given in section 5)

In Germany no specific definition of domino effects exists. The evaluation is based on the “Störfall Verordnung”, that is a national legislation that implements Directive 96/82/EC and following amendments. A distinction is made between domino effects inside the establishment and those involving several establishments. To prevent these scenarios, the German competent authorities apply two safety distances (no threshold values for physical effects are applied). As a rule of thumb, lower-tier establishments have to show that possible escalation effects of fires and explosions are coped with up to 200 m from the border of the site, and upper-tier establishments are obliged to deal with fire and explosion effects up to 500 m.

In the Netherlands, Directive 96/82/EC is implemented by the “Brzo 1999” legislation [39]. The Dutch competent authorities make a distinction between internal and external domino effects. In order to identify Seveso establishments liable to give rise to external domino effects, an easy-to-handle guidebook named ‘Instrument Domino Effects’ (IDE) is used [40]. The determination of a domino effect distance in the IDE assumes that only the immediate energy transfer mechanisms such as fragment impact, peak overpressure, long lasting heat radiation, and long lasting flame contact may lead to a domino effect. The primary accident scenarios possibly starting escalation leading to a domino effect can be identified as: explosion and fire for explosives and fireworks; and bursting of pressurized vessels, boiling liquid evaporating vapor explosion (BLEVE), vapour cloud explosions (VCE), pool fire, and building fire for all other hazardous materials. Hence, the IDE does not consider e.g. dust explosions, and all other non-flammable materials that may start primary scenarios leading to domino effects. The domino effect distance is calculated using data concerning installations and systems containing substances classified as explosive, flammable, highly flammable or extremely flammable according to WM categories (WM: Wet Milieubeheer, Dutch law on environment management). The IDE considers a fixed list of primary accident scenarios and a fixed list of physical effects leading to equipment failure, as well as fixed amounts of substances. Thus, the basic information required to determine safety distances for escalation are available. The IDE tables report the actual values of the safety distances for domino effect for all primary scenarios. In order to obtain the correct safety distance for a domino effect using the IDE, the installation type (storage tank, process equipment, loading and unloading, gas cylinders, storage building or storage of explosives) and the substance conditions (pressurized, atmospheric, cryogenic, or explosive class 1-4) need to be determined. Thus the IDE is a tool that is rather simple to use and that makes available numerical values for safety and escalation distances, although providing very conservative figures. Among the limitations of the tool, the possible protective effect of buildings or walls between two installations is not taken into account.

In the United Kingdom, the competent authority (HSE) identifies domino groups using a contour established for land-use planning purposes called the Consultation Distance. This contour, where it overlaps with the site boundary of other establishments, is used as the basis to group establishments. The main purpose of designating domino groups is to ensure that operators can fully consider the implications of all such events affecting them and their neighbours as part of their Major Accident Prevention Policy (MAPP) and safety report assessments. Such assessments provide operators with the opportunity for a deeper analysis to identify potential sources or targets of escalation leading to domino scenarios. Table 5 summarizes the procedure applied for the definition of domino groups and their interaction. The limitation of this method is that Consultation Distances have been developed to protect the population, not to prevent escalation, and thus are not specific to account for escalation effects.

Table 5: Procedure applied for the identification of domino groups in the UK

Steps	Description
1	A consultation distance is set for each establishment.
2	Where a consultation distance is waiting to be assigned, a distance of 500 m for establishments with flammable/explosives risks, and 1000 m for sites with toxic risks, is used. Distances are measured from the establishment boundary.
3	Each establishment that has another establishment partly or fully within its consultation distance is identified, and for each of these establishments it is identified which establishments come within the consultation distance. The competent authority writes to the operators of the establishments.
4	When received by the competent authority from the land-use-planning authority, information about amended maximum allowable quantities of hazardous substances is taken into account which might result in a change to the consultation distance.
5	Any changes to consultation distances are reviewed to check for any impact on the domino groupings.
6	Where the groupings are affected, step 3 is repeated.

In Greece, Catalonia (Spain), France and Italy a different approach is applied, derived from land-use planning practices. The approaches all start from the definition of zones based on specific threshold values for damage to population and/or to assets. A zoning is established separating the impacted zone in different areas on the basis of threshold values corresponding to different types of expected damage. However, as stated above, no harmonisation exists, so each member state has its own zoning rules and thresholds.

In France, for structural targets (equipment items, vessels, etc.) the domino effect zone is delimited using the following threshold values:

- 200 mbar overpressure for blast waves, although a modulation is possible depending on the materials and structures involved;
- 8 kW/m² radiation for thermal effects.

No threshold exists for fragment projection that is assessed on a case-by-case approach and usually only considered for damage to neighbouring equipment inside the establishment. Conceptually similar approaches, with different values assumed for damage thresholds, are applied in Italy, Catalonia and Greece and are not discussed in detail for the sake of brevity. Threshold values are reported in Table 4. It is important to highlight that even if specific requirements regarding the assessment of domino effects exist in the legislation, plant managers and safety analysts usually are not required to apply specific tools to analyse in detail such potential scenarios. Thus, safety studies usually consist in reporting the possibility of an escalation in an impact area identified using the threshold values for physical effects provided by the competent authority on the basis of the above approach, without any further assessment of the actual domino scenarios.

In Belgium, external domino effects are investigated within the safety reports of high-tier Seveso establishments. In such reports, companies need to identify whether there are any external domino effects possible: what are the domino effects from the company to surrounding Seveso establishments, and what are the domino effects that the company is subject to, outgoing from surrounding Seveso companies. This procedure entails that the establishments have the necessary information to identify and to take into account domino scenarios in their risk management process. A new approach to deal with the problem of domino effects within chemical industrial areas is being considered, and will be

implemented in 2015, when the Seveso-III Directive will be implemented in Belgian law. However, this new approach is still being finalized to date and details are not yet fully known.

Finally, in Poland no specific regulations exist concerning domino scenarios, but in the current practice two thresholds are used for overpressure effects and one for thermal effects, to estimate potential damages to structures leading to escalation and cascade effects.

All Member States have provided threshold values, referred to the physical effects only (Table 4), except Belgium and the Netherlands, where a distinction is made between target equipment, and where also the protection devices are taken into account for radiation effects (Fig. 3b).

In order to make industrial parks safer and more secure as regards domino effects, clear definitions of what constitutes an industrial park, and of the phenomenon ‘domino effect’, are needed. Furthermore, tools to evaluate and to control industrial parks as a whole (checklists, guidelines), as well as more precise legislation and clear legal requirements, should be drafted and agreed upon within Europe.

6. Conclusions

Although domino effects and domino scenarios are well known since decades, the definition of domino effect, the approach to the quantitative assessment of domino scenarios and even the technical criteria to identify the possibility of escalation are still discordant in the scientific literature and in technical standards. The revision of current practices in some EU Member States, where a specific legislation requiring to assess domino scenarios is in force since about 20 years, evidenced that harmonized criteria to cope with such scenarios are missing. Even if a significant progress was made in the scientific literature concerning the assessment of domino effects, industry is still missing a clear and unambiguous guidance on the requirements concerning the assessment of domino scenarios. Furthermore, the requirements of competent authorities are often limited to the identification of potential impact areas for escalation. In this framework, the progress toward the implementation of a shared definition of domino effect and of updated and widely agreed-upon threshold criteria, able to take into account differences among equipment categories, may represent a substantial improvement in the assessment and protection from severe cascading scenarios.

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Appendix

Annex.1: Assessment of domino effect distances by different EU Member States

Country	Framework for the assessment	Assessment methods and software tools	Assessment of threshold distances	
			Specific model required	Legislation related to threshold values
Member State region Flanders, Belgium	Safety reports required by Seveso II Directive. Regional legislation: environmental safety reports (OVR) required by decree of 05/04/1995 (DABM).	Quantitative Risk Analysis by using different methods and programs by the certified safety experts: Commercial programs: EFFECTS/RISKCURVES; PHAST RISK; SAVE II. Non-commercial programs developed by certified safety experts.	Overpressure: VCE: TNO-multi-energy. BLEVE, Pressure vessel explosion: Baker Strehlow models. Radiation: Fireball: TNO, HSE, the SFPE and the model of Martinsen and Marx. Pool fire: POLF (Phast), POOLFIRE6, the TNO model, the model of SAVE II and the model of Mudan and Croce. Jet fire: Chamberlain model, Cook model, the model of Johnson. Missile: Not included in calculation domino-effects.	Threshold values for domino effects not in legislation, but described in guidelines for safety reports (guidelines from AMINAL).
Member State region Wallonia, Belgium	Safety reports required by Seveso II Directive. Regional legislation: safety studies (ES) and reports for hazard identification (NID) required by Walloon Government Decree of 04/07/2012.	PHAST; EFFECTS; DOMINOXL; Purple book; ARAMIS.	Overpressure: No specific model required. Radiation: No specific model required. Missile: No specific model required.	Regional guidelines (Vade-Mecum - spécifications techniques relatives au contenu et à la présentation des études de sûreté, des notices d'identification des dangers et des rapports de sécurité (partie région wallonne) Janvier 2005.
Member State region Catalonia, Spain	Safety reports required by Seveso II Directive.	EFFECTS; ALOHA; RISKCURVES; Purple book; Reference Manual Bevi Risk Assessments (Bevi 3.2).	Overpressure: TNT equivalent, Multi-energy Yellow book, Purple book. Radiation: Green book, Yellow book, Bevi 3.2. Missile: no specific required model.	Decret 174/2001 de la Generalitat de Catalunya correspondent a l'aplicació a Catalunya del Real Decreto 1254/1999 de 16 de juliol de 1999 (B. O. E. de 20 de juliol de 1999). Directriz Básica de protección civil para el control y planificación ante el riesgo de accidentes graves en los que intervienen sustancias peligrosas aprobada por el Real Decreto 1196/2003 de 19 de Setiembre de 2003 (B. O. E. de 9 de Octubre de 2003). Llei 12/2008 de 31 de juliol de Seguretat Industrial (DOGC nº 5191 de 8 d'agost de 2008). Instrucció 11/2010 SIE (Generalitat de Catalunya, 29 d'octubre de 2010).

Annex.1: Assessment of domino effect distances by different EU Member States- cont'd

Country	Framework for the assessment	Assessment methods and software tools	Assessment of threshold distances	
			Specific model required	Legislation related to threshold values
France	Safety reports required by Seveso II Directive.	Guidance and recommendation given in Circulaire du 10 Mai 2010. No specific assessment method required.	Overpressure: VCE: Multi Energy (Yellow Book), CAM ^a , or Baker Strehlow models. BLEVE: model of Shield (TRC ^b) (for filling degree between 30% and 85 % otherwise no specific model required). Radiation: Fireball: model of Shield (TRC) (for filling degree between 30% and 85 % otherwise no specific model required). Missile: No specific model required.	French legislation (Ministerial decree of 29 September 2005 concerning the evaluation and consideration of the probability of occurrence, the kinetics, the intensity of the effects, and the severity of the consequences of potential accidents in hazard studies).
Greece	Safety reports required by Seveso-II Directive.	EFFECTS; ALOHA; PHAST; SOCRATES.	Overpressure: TNT equivalent, Multi-energy, Yellow book, Purple book. Radiation: Green book, Yellow book. Missile: no specific model required.	None (not defined in legislation). The values given in Table 4 are used in Greek practice.
Italy	Safety reports required by the Italian implementation of Seveso-II Directive (D.Lgs.334/99).	General criteria given in DPCM 31/3/1989. No specific assessment method required.	Overpressure: No specific model required. Radiation: No specific model required. Missile: No specific model required.	D.M. 09/05/2001 (Requisitiminimi di sicurezza in materia di pianificazione urbanistica e territoriale per le zone interessate dastabilimenti a rischio di incidente rilevante).
Poland	Safety reports required by Seveso II Directive.	No specific assessment method required.	Overpressure: No specific model required. Radiation: No specific model required. Missile: No specific model required.	None (not defined in legislation). The values given in Table 4 are used in Polish practice.
The Netherlands	Safety reports required by Seveso II Directive. Quantitative Risk Analysis reports required by decree of Bevi (Besluit externe veiligheid inrichtingen).	Reference Manual Bevi Risk Assessments; Instrument Domino Effects; Publication series of hazardous substances (Publicatiereeks Gevaarlijke Stoffen, PGS). SAFETI-NL; PHAST; Risk-NL.	Overpressure: TNT equivalent or multi energy model (TNO) Yellow Book, AASTP-1. Radiation: Green Book, Yellow Book, AASTP-1. Missile: Green Book; AASTP-1.	Dutch legislation (Ministry of Housing, Physical Planning and Environment: BRZO 1999 and BEVI 27-04-2004).

^a CAM: Congestion Assessment Method, Shell. ^b Thornton Research Centre (SHELL research center).

Annex.1: Assessment of domino effect distances by different EU Member States- cont'd

Country	Framework for the assessment	Assessment methods and software tools	Assessment of threshold distances	
			Specific model required	Legislation related to threshold values
United Kingdom, Great Britain (England, Scotland, Wales)	COMAH (Seveso) notifications. Land use planning - hazardous substances consent. Notification by the competent Authority of domino groupings.	Land use planning risk assessments. Either: 1) Quantified risk assessments (risk of receiving a specified dangerous dose) 2) Protection concept assessments (range to a specified level of harm, usually threshold of fatality for a vulnerable population) Or: Some combination of the above for a particular establishment.	Overpressure: TNO multi energy method for VCE and TNT equivalence for solid phase explosives. Thermal radiation: HSE in-house models for pool fire, fireball and jet fire. Flash fire: dispersion using DRIFT dispersion model. Toxic gas: dense or passive gas dispersion using DRIFT. Warehouse fire using HSE in-house model for pesticide warehouse fires. Oxygen enrichment: dispersion using DRIFT. Missiles: based on analysis of past incidents.	None (not defined in legislation). Set as assessment policy by HSE for the purposes of providing land use planning advice.