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The assessment of risk caused by domino effect in quantitative area risk analysis

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Abstract

A systematic procedure for the quantitative assessment of the risk caused by domino effect was developed. Escalation vectors, defined as the physical effects responsible of possible accident propagation, were identified for the primary scenarios usually considered in the QRA procedure. Starting from the assessment of the escalation vectors, the methodology allows the identification of credible domino scenarios and the estimation of their expected severity. A simplified technique was introduced for consequence and vulnerability assessment of domino scenarios. The overall contribution of domino effect to individual risk, societal risk and to the potential life loss index was calculated by a specific procedure, taking into account all the credible combinations of secondary events that may be triggered by each primary scenario. The development of a software package allowed the application of the procedure to several case-studies. The results evidenced the relevant modifications of the risk indexes caused by domino effect and the importance of including the quantitative analysis of domino effect in QRA, in order to correctly assess and control the risk caused by escalation scenarios.

Keywords: Domino effect; Escalation; Accidental scenarios; Quantitative risk analysis; Major accident hazard

1. Introduction

The propagation of accidental scenarios to equipment not directly involved in the primary accident caused a high number of severe accidental events in chemical and process plants [1–4]. The propagation of accidental scenarios and the contemporary increase in the severity of the event are usually named as "domino" or "knock-on" accidents [5]. The severity of accidents where domino effects took place lead to important efforts for the prevention of these accidental scenarios. Technical standards and legislation concerned with the control of major accident hazard often include measures to assess, control and prevent domino effects. Several technical standards introduce preventive measures, as safety distances, thermal insulation or emergency water deluges, in order to control and reduce the probability of domino events. The European legislation requires the assessment of domino hazards since the first "Seveso" Directive (Directive 82/501/EEC), that was adopted in 1982 [6]. European Community "Seveso-II" Directive (Directive 96/82/EC) [7] requires to assess "domino" accident hazards inside and outside the industrial sites that fall under the obligations of the Directive. Moreover, the Italian implementation of the Directive (D.Lgs. 334/99) also requires the comprehensive quantitative risk analysis of areas where a high concentration of industrial sites is present, in order to assess the potential hazards

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due to the interaction of multiple risk sources in a narrow area.

In spite of the relevant attention dedicated in the legislation to the assessment and prevention of domino effects, a well assessed methodology for the quantitative estimation of the risk deriving from domino accidental events is still not available in the technical literature. Several pionieristic studies were mainly concerned with qualitative methodologies for domino assessment [8–11]. Important contributions were dedicated to some aspects of the problem (e.g. domino frequency estimation [8,9,12], deterministic estimation of domino effect due to radiation [13,14], models for accident propagation [8,15,16]). However, only few authors proposed comprehensive methodologies, suitable for the analysis of complex (and thus realistic) plant layouts, as those actually of concern in most applications [8,17]. Nevertheless, many of these methodologies were possibly forced to oversimplifications or to unjustified simplifying assumptions, mainly due to the limitations in the computational resources available at the time. As a result, the quantitative risk assessment of domino accidents is usually not performed in safety reports, and the assessment of domino hazard is limited to the detailed and deterministic analysis of a few representative cases.

Therefore, specific criteria for the estimation of the risk due to domino accidental events are still needed. Furthermore, a methodology to yield at least a simplified quantitative assessment of domino contribution to risk indexes calculated in quantitative risk analysis (QRA) of complex lay-outs or in quantitative area risk analysis (QARA) [18] is not yet available. In this framework, it is also worth to remark that the potential simplifications in complex lay-out analysis aimed to the identification of domino scenarios, deriving from the use of geographical information systems (GIS) have not been fully exploited up to date.

In a previous publication, a methodology for the identification of domino events and the assessment of expected domino frequencies in simplified lay-outs was carried out [19]. The present study was aimed to the development of a systematic procedure for the quantitative assessment of the contribution of domino effect to industrial risk. Fig. 1 summarizes the main steps of the methodology. The starting point of the procedure was the assumption that a full characterization of all primary risk sources present in the lay-out of concern is available, as usual when the assessment of domino effect in a QRA or QARA study is undertaken. A method was developed to calculate the propagation probability of primary scenarios and the expected frequencies of domino events. Several simplified approaches for the calculation of vulnerability in domino accidents were compared and assessed. The methodology was applied to the analysis of several representative case-studies derived from the lay-outs of existing plants. The contribution of domino events to individual and societal risk, as well as to the potential life loss was calculated for the defined case-studies.

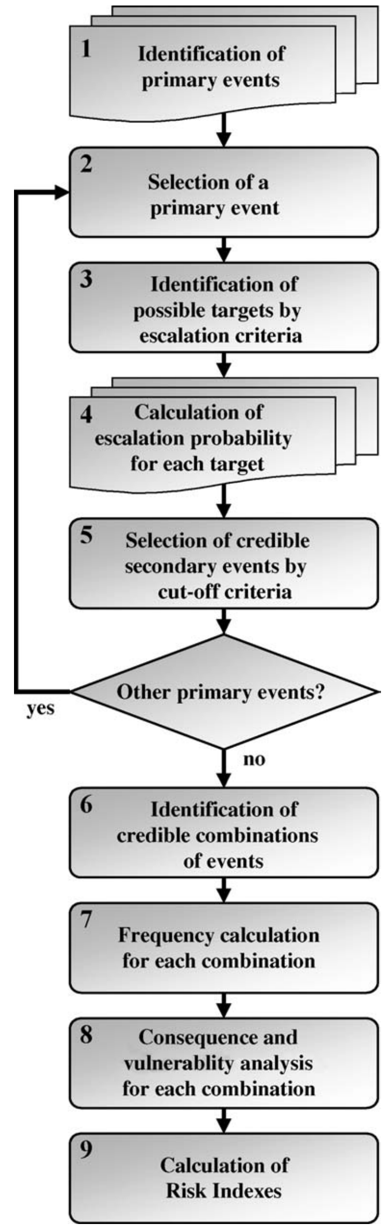


Fig. 1. Flow diagram of the procedure used for the quantitative assessment of risk caused by domino accidental scenarios.

2. Definition of domino effect

Several different and somehow contradictory definitions are reported in the literature to identify domino accidental scenarios [1,5]. The following definition of domino effect will be assumed: an accident in which a primary event propagates to nearby equipment, triggering one or more secondary events resulting in overall consequences more severe than those of the primary event.

Thus, three elements characterize a domino event:

(i) a primary accidental scenario, which triggers the domino effect;

(ii) a propagation effect following the primary event, due to the effect of escalation vectors caused by the primary event on secondary targets;
(iii) one or more than one secondary accidental scenarios, involving the same or different plant units.

However, in the literature and in accident databases, the accident is considered as a "domino event" only if its overall severity is higher or at least comparable to that of the primary accidental scenario. Thus, it is important to understand that the propagation sequence is relevant only if it results in an "escalation" of the primary event, triggered by an "escalation vector" originated by the primary scenario.

In the present approach, escalations due to the damage of secondary equipment caused by the primary event will only be considered. This limits the escalation vectors to radiation, overpressure and fragment projection. As a matter of fact, toxic releases were reported as a cause of domino accidents [8], but due to lacks in emergency management and not to the direct damage of secondary equipment.

Moreover, only "first level" domino effects were considered in the present approach (that is, the possible further escalation of secondary scenarios was not included in the analysis), although the methodology may be applied as well to the assessment of higher level domino events.

3. Identification of domino scenarios

3.1. Data required to apply the assessment procedure

The data required to apply the procedure defined in Fig. 1 are discussed in detail in the following. However, it is useful to summarize the main information that is necessary for the quantitative assessment of domino effect:

- a lay-out of the site examined;
- the position on the lay-out of the risk sources that may generate the primary events of concern;
- the full characterization of all the primary events of concern (expected frequencies and consequence analysis);
- the position of all the possible escalation targets of concern (equipment with relevant inventories of hazardous substances, etc.);
- the consequence analysis of the secondary event that is supposed to take place following the damage of the target equipment.

The list of top-events identified by HazOp analysis may also be required to identify low-severity initiating events.

It is quite evident that most of the data required are available from a conventional QRA, thus the assessment procedure does not require a relevant data additional work for data collection.

3.2. Steps required for the identification of credible domino scenarios

The identification of possible accidental scenarios due to domino effect (step 1 in Fig. 1) may be performed in three stages: (i) the identification of the primary events to be considered in the analysis of the possible accidental scenarios; (ii) the identification of escalation vectors; (iii) the preliminary selection of credible escalation events on the basis of simplified criteria. In this stage of the analysis, the aim is to identify all the possible scenarios that may arise from a primary event. The possible contemporary occurrence of more than one secondary scenario will be considered in the subsequent steps of the procedure (frequency and consequence assessment). It must be remarked that in the following, the secondary scenarios will be conservatively defined as "contemporary" even if they will actually always take place in sequence (few seconds to few minutes after the primary event, depending on the primary escalation vector and on the loss intensity at the secondary unit damaged by the primary event).

3.3. Identification of primary events

As stated above, the starting point of the present procedure is the assumption that a full characterization of all primary risk sources present in the lay-out of concern is available. Thus, the possibility of escalation should be evaluated for each of the primary scenarios considered. Even if conventional techniques as the event tree method may still be used, it seems useful to approach the problem introducing two different categories of "escalation" leading to domino events. The analysis of past accidents evidences that domino accidents may have two different causes:

(i) propagation of a low-severity initiating event (LSIE);
(ii) interaction of different "major accidental events" (MAE);

In the first type of events, the escalation is caused by the propagation of a minor accident that usually is not considered as a relevant accidental event in the safety analysis of the plant. In order to define the scenarios due to this type of escalation, it is necessary to identify all potential LSIEs. Assuming that the hazard and operability analysis (HazOp) of the plant is available, the identification of LSIEs may only require the critical revision of all the top-events identified in HazOp but considered of negligible importance and not further examined in consequence analysis. Minor jet fires (i.e. from small diameter pipes or valves) or pool fires (i.e. caused by leaks from seals) are the more likely events that may cause accident propagation. Due to the limited damage distances of the primary event, the secondary scenario caused by LSIEs is expected to take place in the same unit affected by the LSIE.

On the other hand, the interaction of MAEs is caused by the extended damage of a secondary unit due to a

Table 1
Physical effects responsible of escalation in 100 domino accidents

Primary scenario	Events	Escalation vector		
		Radiation	Overpressure	Fragments
VCE	17	0	16	1
Mechanical explosion	17	0	10	7
BLEVE	13	0	0	13
Fireball	1	1	0	0
Jet fire	8	8	0	0
Pool fire	44	44	0	0
Flash fire	0	0	0	0

primary major accident, usually considered in the safety report of the plant. Since a relevant domino effect requires an "escalation", this sequence is only relevant if the secondary scenario is as well a major accident. The identification of all the possible MAEs is usually available from the safety report of the plant. The higher damage distances of MAEs generally result in secondary events affecting nearby units.

It must be remarked that only the second category of escalation events is usually of concern if domino effect analysis is performed in order to identify the possible domino scenarios affecting nearby plants or installations.

3.4. Identification of escalation vectors

After the identification of the primary accidental events, the escalation vectors associated to each scenario should be defined (step 2 in Fig. 1). In the framework of domino effect assessment, this requires a procedure different from that used in the standard QRA studies.

In the consequence assessment, the event tree technique is usually applied to identify the possible accidental scenarios that are usually considered as alternative. In domino effect assessment all the possible escalation vectors identified by the event tree technique should be considered. Table 1 summarizes the results of the analysis of 100 domino accidents. As shown in the table, domino escalation from the same type of primary event was caused by different escalation vectors (e.g. escalation due to mechanical explosions was caused by fragment projection as well as by blast wave damage). Moreover, the physical effect due to the primary event that caused damage to the exposed individuals is often different from that responsible of the escalation.

Thus, it is important to recognize that each accidental scenario should be associated to a "vulnerability vector" (used to estimate the damage to the exposed individuals) and to one or more than one "escalation vectors". Table 2 summarizes the vulnerability and the credible escalation vectors associated to the accidental scenarios usually considered in a QRA. The credible escalation vectors were identified both on the basis of the analysis of past accidents, summarized in Table 1, and of a specific assessment [20].

Table 2
Vulnerability and escalation vectors for the primary scenarios usually considered in QRA

Primary scenario	Vulnerability vector	Escalation vectors
VCE	Overpressure	Overpressure
Mechanical explosion	Overpressure	Fragments, overpressure
BLEVE	Overpressure	Fragments, overpressure
Fireball	Radiation	Radiation
Jet fire	Radiation	Radiation
Pool fire	Radiation	Radiation
Flash fire	Radiation	Radiation

3.5. Preliminary selection of credible escalation events

In order to limit the complexity of the analysis, it is important to perform a preliminary screening of the possible escalation events in order to include in the analysis only the credible secondary scenarios (step 3 in Fig. 1). Usually this step is performed using threshold criteria for damage to equipment. If the physical effect due to the escalation vector is lower than a given threshold value, the possibility of escalation is considered not credible. A number of discordant threshold values are reported in the literature for domino effect and equipment damage (e.g. see [1,5,21]). The more frequently cited thresholds reported in the literature are of 37 kW/m^2 for radiation and of 70 kPa for overpressure. However, the reliability of these thresholds is questionable and different values are suggested by other sources [9]. Table 3 summarizes the threshold criteria derived from the revision of literature data and from the application of equipment damage models, performed in a recent study [20], and used in the case-studies analyzed in the followings.

Table 3
Threshold values for escalation considered in the present study

Escalation vector and primary scenario	Target equipment	Threshold
Radiation		
Flash-fire	All	Unlikely
Fireball	Atmospheric	Credible only in the case of engulfment
	Pressurized	unlikely
Pool fire and jet-fire	Atmospheric	15 kW/m^2 for more than 10 min
	Pressurized	50 kW/m^2 for more than 10 min
Overpressure		
All overpressure scenarios	Atmospheric	22 kPa
	Pressurized	17 kPa
	Elongated (toxic)	16 kPa
	Elongated (flammable)	31 kPa
	Auxiliary (toxic)	37 kPa
	Auxiliary (flammable)	Unlikely
Fragments		
All fragmentation scenarios	All	300 m

4. Frequency analysis

4.1. Overall frequency of a single escalation event

The expected frequency of a single escalation event (that is, a primary event triggering a secondary accidental scenario) may be calculated as

$$f_{de} = f_{pe} P_d \qquad (1)$$

where f_{de} is the expected frequency of the domino event (events/year), f_p the expected frequency (events/year) of the primary event (PE), and P_d is the probability of escalation (E) given the primary event:

$$P_d = P(E|PE) \qquad (2)$$

The expected frequency of the primary event may be available from the safety report or may be calculated by fault-tree techniques. The propagation probability should be evaluated using a specific damage propagation model, as discussed in the followings.

The above relations are only valid if the primary and the secondary event may take place at the same time only due to escalation. This means that the primary and the secondary event should be "mutually exclusive" from a probabilistic point of view, unless escalation effects take place. This assumption is justified if the expected frequencies of the primary event and of the secondary event not triggered by escalation have sufficiently low values.

4.2. Damage probability models

As shown by Eq. (1), the quantitative assessment of domino effect requires the estimation of the propagation probability (step 4 in Fig. 1). In the literature, three different approaches are proposed: (i) vulnerability threshold models (P_d equals 1 if the physical effect on the secondary target is higher than a threshold value for damage, otherwise P_d equals 0) [9,11,12]; (ii) propagation functions based on empirical decay relations for physical effects [8,22]; (iii) propagation functions based on specific probabilistic models [15,16,23–25]. Even if the latter approach seems the more promising, additional work is needed in this field. The current activity of the authors is aimed to the further development of simplified models for the assessment of damage and escalation probability. An extended discussion of the problem is reported elsewhere [16,22]. Table 4 summarizes the models used in the present study for the assessment of escalation probability. However, since the present study focuses on the development of a procedure for the quantitative assessment of domino effect that may be used with any model that allows the estimation of the escalation probability, this aspect will not be discussed further.

4.3. Frequency of domino scenarios

In a complex lay-out, usually a single primary event may be able to trigger more than one secondary event. In this framework, Eq. (1) is still valid, yielding the overall probability of a given secondary event to be initiated by the primary event considered. However, the frequencies of domino scenarios should be calculated taking into account the possibility of having more than one secondary scenario triggered by the same primary event (steps 6 and 7 in Fig. 1).

If the possible further escalation of secondary events is neglected, the escalation events may be reasonably considered as independent from a probabilistic point of view.

Therefore, if N secondary events are possible, the probability of a secondary scenario given by a generic combination m of k secondary events ($k \leq N$) is the following:

$$P_d^{(k,m)} = \prod_{i=1}^{N} [1 - P_{d,i} + \delta(i, J_m^k)(2P_{d,i} - 1)] \qquad (3)$$

where $P_{d,i}$ is the probability of escalation for the i-th secondary event defined by Eq. (2), $J_m^k = [\gamma_1, \ldots y_k]$ is a vector whose elements are the indexes of the m-th combination of k secondary events, and the function $\delta(i, J_m^k)$ is defined as

Table 4
Models for escalation probability used for the case-studies (Y: probit value for escalation given the primary scenario; ttf: time to failure (s); I: radiation intensity on the target equipment (kW/m^2); V: equipment volume (m^3); P_s: peak static overpressure on the target equipment (kPa))

Escalation vector and primary scenario	Target equipment	Model for escalation probability
Radiation		Probit model based on "time to failure" and simplified models for ttf vs. radiation [22]
All radiation scenarios	Atmospheric vertical cylindrical vessel	$Y = 12.54 - 1.847 \ln(\text{ttf}), \ln(\text{ttf}) = -1.128 \ln(I) - 2.667 \times 10^{-5} V + 9.877$
	Pressurized horizontal cylindrical vessels	$Y = 12.54 - 1.847 \ln(\text{ttf}), \ln(\text{ttf}) = -0.947 \ln(I) + 8.835 V^{0.032}$
Overpressure		Probit model based on peak static overpressure [16]
All overpressure scenarios	Atmospheric	$Y = -18.96 + 2.44 \ln(P_s)$
	Pressurized	$Y = -42.44 + 4.33 \ln(P_s)$
	Elongated	$Y = -28.07 + 3.16 \ln(P_s)$
	Auxiliary	$Y = -17.79 + 2.18 \ln(P_s)$
Fragments		Probabilistic model based on the analysis of fragment trajectories
All fragmentation scenarios	All	See Gubinelli et al. [25]

follows:

$$\delta(i, J_m^k) = \begin{cases} 1, & i \in J_m^k \\ 0, & i \notin J_m^k \end{cases} \quad (4)$$

The total number of domino scenarios in which the primary event triggers k contemporary secondary events is

$$\nu_k = \frac{N!}{(N-k)!k!} \quad (5)$$

Thus, the total number of different domino scenarios that may be generated by the primary event is

$$\nu = \sum_{k=1}^{N} \nu_k = 2^N - 1 \quad (6)$$

where ν is the total number of domino scenarios that needs to be assessed in the quantitative analysis of domino effect, unless cut-off criteria based on frequency values are applied.

The expected frequency of a generic combination m of k events is thus

$$f_{\mathrm{de}}^{(k,m)} = f_{\mathrm{pe}} P_{\mathrm{d}}^{(k,m)} \quad (7)$$

In the application of the procedure, the (k, m) combination may be neglected if the frequency value falls below a given threshold. This should be decided on the basis of the values of risk that are considered of interest in the analysis.

The total probability that an escalation will take place thus becomes

$$P_{\mathrm{e}} = \sum_{k=1}^{N} \sum_{m=1}^{\nu_k} P_{\mathrm{d}}^{(k,m)} \quad (8)$$

The expected frequency of the primary event in the absence of escalation thus results from the following:

$$f_{\mathrm{pe},n} = f_{\mathrm{pe}}(1 - P_{\mathrm{e}}) \quad (9)$$

If a quantitative assessment of domino effect is undertaken, the frequency value given by Eq. (9) should be used to estimate the frequency of the primary event in the absence of escalations.

5. Consequence assessment

5.1. Consequences of the secondary events

A detailed consequence analysis of domino accidents is a very complex task to afford. As pointed out above, very complex scenarios with multiple contemporary events may take place. A complete assessment of the consequences of so complicated scenarios is a difficult aim even using advanced tools as CFD codes. The conventional models used for consequence assessment in a QRA framework are not able to consider the effects of multiple scenarios (e.g. the overall radiation caused by more than one pool fire). Moreover, the contemporary presence of multiple events may cause synergetic effects that are not taken into account in the available models for consequence analysis. Thus, a detailed consequence assessment would require that each scenario should be analyzed with specific tools, taking into account the lay-out and introducing in the analysis a full geometrical characterization of the problem. However, in a QRA framework the necessity to limit the computational effort requires to introduce simplifying assumptions in order to carry out the consequence assessment. The assumptions that are necessary to identify the possible secondary scenarios and the primary event result in uncertainties that would not justify the use of an extremely detailed approach to consequence assessment.

A first assumption in the consequence analysis of domino scenarios may be to neglect the synergetic effects that may arise from accident interaction. Thus, accident consequences may be analyzed superimposing the physical effects (radiation, overpressure, toxic gas concentration) separately calculated for each of the primary and secondary events that may take place. This approach obviously results in an oversimplification of the problem, allowing only a rough estimate of the actual potential consequences of domino scenarios. However, the approximations introduced in the analysis by this assumption seem acceptable in a QRA framework.

As a matter of fact, with this assumption the consequence assessment of the possible domino scenarios only requires: (i) the assessment of the consequences of the primary scenario and of each of the secondary events by conventional models used for consequence assessment [5,26]; (ii) the calculation of a "damage map" for each of the scenarios of concern (a matrix yielding the physical effects due to the event as a function of the position with respect to the source of the event); (iii) the combination of the "damage maps" of the primary and secondary events involved to yield the overall consequences of the domino scenario of interest.

Moreover, it must be remarked that many of the damage maps required in the analysis may be already available, since both the primary and the secondary events involved in domino scenarios may be relevant top-events already included in the safety report of the site.

5.2. Consequences of domino scenarios

The last step of the consequence assessment of domino scenarios (step 8 in Fig. 1) requires a combination of the "damage maps" of the single interacting events to yield the overall consequences of the scenario. However, a correct approach to this point is not simple, since damage maps in general are not homogeneous (the different events may result in different physical effects, or in a different duration of the physical effect) and a significant combination is not easily obtained. In a conventional QRA, this problem is usually overcome introducing a risk recomposition procedure, aimed to the estimation of individual and societal risk indexes, in which the "vulnerability" (death probability of an exposed individual) is calculated from the physical effects and the estimated time of exposure using probit models for human vulnerability [27,28]. This route seems the more appropriate also in the framework of the simplified assessment of domino scenarios.

"Vulnerability maps" [29] (a matrix yielding the death probability due to the event as a function of the position with respect to the source of the event) may be obtained for each event from the "damage maps" of the single events by the application of probit models. The "probit analysis" is a well known method to evaluate the dose–effect relation for human responses to toxic substances, thermal radiation and overpressure, that derives from the cumulative expression for a normal Gaussian probability distribution function [30]:

$$V = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{Y-5} e^{-u^2/2}\, du \quad (10)$$

where V is the probability ($0 \leq V \leq 1$, in this case the "vulnerability" or death probability), and u is defined as follows:

$$u = \frac{D-\mu}{\sigma} \quad (11)$$

where D is the independent variable or the "dose", μ and σ the median and the variance of the Gaussian distribution. The variable Y in Eq. (10) is the probit unit:

$$Y = a + b\ln(D) \quad (12)$$

An extended review of probit models for human vulnerability is reported elsewhere [1,27]. Table 5 summarizes the probit models used in the case-studies discussed in the following, that were selected within those reported by Lees [1].

On the basis of the simplifying assumptions discussed above, the consequences of a domino scenario involving multiple contemporary events may be calculated by a combination of vulnerability maps. Considering an individual in a generic position with respect to a domino scenario involving a primary event and n secondary scenarios, the vulnerability due to the domino event has the following general expression:

$$V_{de} = \varphi(D_{pe}, D_{d,1}, \ldots, D_{d,n}) \quad (13)$$

where φ is a function that needs to be defined, D_{pe} the "dose" due to the physical effects caused by the primary event that triggers the domino scenario, and $D_{d,i}$ are the doses due to the secondary scenarios. A proper definition of function φ should take into account both the effects due to the combination of the physical effects of the contemporary scenarios, and the synergetic effects arising from the exposure to physical effects due to multiple scenarios.

The difficulties in the consequence assessment of multiple scenarios were already discussed above. In the present approach, the synergetic effects due to the contemporary exposition to different types of physical effects (e.g. radiation and toxic concentration, etc.) have been neglected and the overall vulnerability, V_{de}, was calculated as a combination of the vulnerabilities due to the single scenarios that take place in the domino event. Nevertheless, even this procedure is not straightforward. As a matter of fact, the combination of the vulnerabilities may be performed by different strategies, taking into account that vulnerabilities are actually probability values, thus requiring the application of probabilistic rules for their combination. Four methods were identified for the combination of vulnerabilities:

1. The overall vulnerability is assumed to be the sum of the death probabilities due to all the scenarios involved in the domino event, with an upper limit of 1:

$$V_{de} = \min\left[\left(V_{pe} + \sum_{i=1}^{N} V_{d,i}\right), 1\right] \quad (14)$$

2. The multiple scenarios are assumed to be independent events with respect to the vulnerability assessment, thus the overall vulnerability has the following expression:

$$V_{de} = 1 - (1 - V_{pe})\prod_{i=1}^{N}(1 - V_{d,i}) \quad (15)$$

3. An overall dose is calculated superimposing the physical effects of the primary and the secondary scenarios, taking into account the assumed time sequence of the domino event:

$$D_{de} = \sum_{i=1}^{n} E_i^{\alpha}\Delta t_i \quad (16)$$

where E_i is the overall physical effect during time interval, Δt_i, α the coefficient used in dose calculation ($\alpha \geq 1$, depending on the vulnerability model of concern) and the sum of time intervals Δt_i represents the overall duration of the domino event. The overall vulnerability is calculated from the overall dose, D_{de}, applying the correct vulnerability model. Obviously this method may only be applied to scenarios resulting in the same physical effects (radiation, overpressure, or toxic concentrations of the same substance).

4. An approximated overall dose is calculated superimposing the physical effects of the primary and the secondary scenarios, neglecting the time sequence of the domino event.

$$D_{de} = E_{pe}^{\alpha} t_{pe} + \sum_{i=1}^{N} E_{d,i}^{\alpha} t_{d,i} \quad (17)$$

Table 5
Models for human vulnerability [1,27] used in the case-studies (Y: probit value for fatality; I: radiation intensity (W/m^2); P_s: peak static overpressure (kPa); C: toxic concentration (ppm); t_e: exposure time (min))

Vulnerability vector	Probit equation	Dose
Radiation	$Y = -14.9 + 2.56\ln(D)$	$D = 6 \times 10^{-3} I^{1.33} t_e$
Overpressure	$Y = 5.13 + 1.37\ln(D)$	$D = P_s$
Toxic release: chlorine	$Y = -10.1 + 1.11\ln(D)$	$D = C^{1.65} t_e$
Toxic release: ammonia	$Y = -9.82 + 0.71\ln(D)$	$D = C^2 t_e$

where E is the value of the physical effect and t the assumed exposure time for the scenarios of concern. Again, the overall vulnerability is calculated from the overall dose by the application of the proper vulnerability model. Also the application of this method is limited to multiple scenarios resulting in the same physical effect.

Clearly enough, all these methods are approximated and allow only a rough estimation of the overall vulnerability in a domino accident. However, these approximations seem acceptable in the framework of a quantitative risk analysis, at least if the aim is a comparative quantitative assessment of the risk due to domino accidental events.

With respect to the different methods proposed, method 2 is the more correct from a probabilistic point of view. Actually, the possibilities of death due to each of the different scenarios may reasonably be considered as independent events. However, method 2 does not consider the non-linearity of the doses. Since the α coefficient in the calculation of the dose is usually higher than 1, if multiple scenarios resulting in the same physical effect are of concern, method 2 underestimates the overall vulnerability. Method 1 represents a simplification of method 2, that greatly reduces the computational effort required for the assessment and partially compensates the underestimation of vulnerability in scenarios having the same physical effects. Method 3 is the more correct to be used in the case of scenarios resulting in the same physical effects. However, the application of the method also requires to assume a precise time sequence for the scenarios involved in the domino effect, that is often rather uncertain. Method 4 is a useful simplification of method 3, introducing a further approximation that avoids the necessity of assuming an arbitrary time sequence for the evolution of the scenario. An important limitation of both methods 3 and 4 is that they may be used only for physical effects of the same type. Thus, methods 3 and 4 should always be used in combination with method 1 or 2 when physical effects of different type should be taken into account in the domino scenarios.

In the following, the differences due to the use of the different methods defined above in the risk calculation were evaluated defining different case-studies. When necessary, method 2 was used in combination with methods 3 and 4 in the assessment of the case-studies.

6. The domino version of the aripar-GIS software

It is quite evident from Eqs. (5) and (6) that the above procedure for the quantitative assessment of the contribution to individual and societal risk of domino accidents (step 9 in Fig. 1) results in the assessment of a very high number of scenarios even in rather simple lay-outs (e.g. if 10 secondary events may be triggered, more than 1000 different domino scenarios may be generated by a single primary scenario and need to be assessed). Therefore, the development of a software tool was a necessary step in order to apply and validate the methodology discussed above for the assessment of domino events.

A specific software package was added to the Aripar-GIS software. The Aripar-GIS software was developed in the framework of the ARIPAR project [18], one of the first applications of Quantitative Area Risk Analysis techniques to the evaluation of comprehensive hazards in an industrial area. The Aripar-GIS software allows the assessment of individual and societal risk due both to fixed risk sources and to risk sources due to transport systems. An extended description of the software is reported elsewhere [31,32].

The domino package was developed in order to apply the above procedure to the analysis of complex scenarios. The software allows the identification of all the possible secondary events for each primary scenario considered on the basis of a simplified lay-out that should be implemented in a GIS environment. The software procedure automatically generates all the possible domino scenarios and performs the quantitative evaluation of the risk in each cell of the area of interest by the above procedure.

7. Case-studies

7.1. Definition of case-studies

The above defined procedure was assessed by its application to the analysis of a number of case-studies. Several common assumptions, discussed in the following, were introduced to allow the assessment of the different case-studies. All the case-studies were based on plant lay-outs and process equipment derived from the actual lay-outs of existing chemical plants and oil refineries. Figs. 2 and 3 show the lay-outs used for the case-studies. Table 6 summarizes the relevant characteristics of the equipment considered in each plant lay-out. For the sake of simplicity, in general a single scenario was associated to each equipment item, and was considered as the only possible primary and/or secondary event. Only in the case of LPG sphere TK10 several alternative primary events were considered. The scenarios were defined on

Table 6
Equipment considered in the case-studies

Unit	Reference lay-out (figure)	Type	Substance	Content (t)
TK1-8	2(a), 2(c), 3(a), 3(b)	Atmospheric tank	Ethanol	2000
TK9	2(a)	Pressurized tank	LPG	150
TK10	2(a), 2(b), 3(b)	Pressurized tank	LPG	1400
TK11	2(b)	Pressurized tank	Chlorine	390
TK12	2(b)	Pressurized tank	Chlorine	390
TK13	2(c)	Pressurized tank	Ammonia	100
TK14	2(c)	Pressurized tank	Ammonia	100

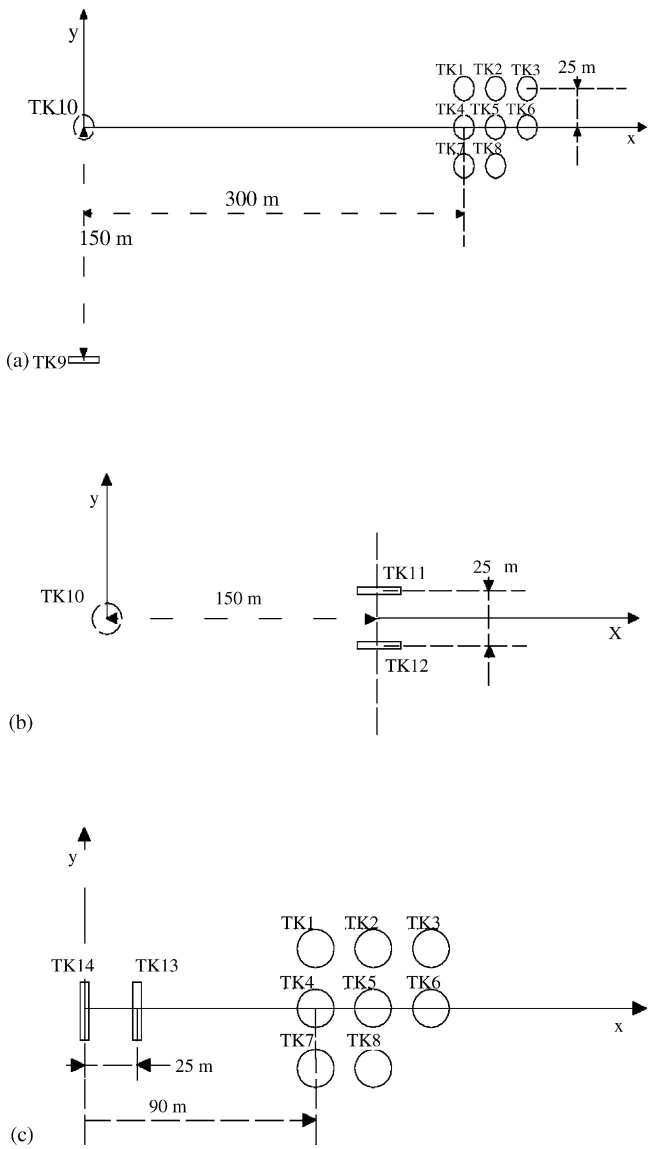


Fig. 2. Lay-outs used for case-studies (1–16) and (c).

the basis of credible accidental events involving the equipment items described in Table 6. Table 7 reports the details of the events considered for each equipment item. The study was mainly aimed to domino effect assessment, thus only

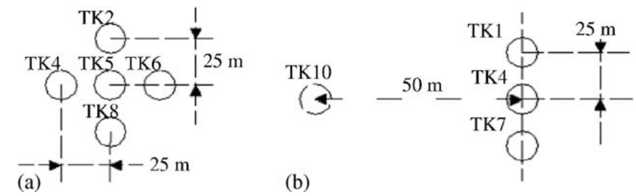


Fig. 3. Lay-outs used for case-studies (a), (b), (d), and (e).

severe scenarios were considered: VCEs, BLEVEs and toxic dispersions from instantaneous release or 10 min release of vessel content, or pool fires involving the entire catch basin and the complete tank inventory. Literature models as those described in the TNO "yellow" book were used for consequence assessment [26]. The results of the consequence assessment models were used to generate the vulnerability maps for the primary and secondary events, using the probit models listed in Table 5. The results of consequence assessment of each primary event were used to identify and calculate the escalation vectors generated. The escalation probability was thus calculated using the models listed in Table 4.

In the framework of the comparative assessment of the case-studies, in each case the individual risk, the societal risk and the potential life loss were calculated for the primary event considered and for the domino scenarios. In order to allow the calculation of the societal risk and of the potential life loss index, the presence of an unprotected population was assumed, having a unitary probability of presence 24 h/day. The overall number of expected fatalities, N, for the different scenarios assessed was calculated as the integral of vulnerability multiplied by the population density extended to the entire area of interest. In each case-study, the area of concern was chosen as sufficiently wide to have vulnerability values lower than 10^{-4} at the borders.

Three different sets of case-studies were defined in order to understand different aspects in the quantitative assessment of domino effect. A first set of 16 simplified case-studies (1–16) was defined. In each of these case-studies, a single primary event and a single combination of secondary events were considered. Up to four contemporary secondary events were considered in the case-studies. Thus, each of the case-studies represents one of the possible domino scenarios that

Table 7
Primary and secondary scenarios considered for each equipment item in Table 6

Unit	Type of release	Quantity released	Primary scenario	Secondary scenario	Escalation vector
TK1-8	Instantaneous	All inventory	Pool fire, 25 m diameter	Pool fire, 25 m diameter	Radiation
TK9	Instantaneous	All	Fireball	Fireball	Fragments
TK10	(i) Instantaneous	(i) All inventory	Fireball	Fireball (from inst. release)	(i) Fragments
	(ii) Total 10 min	(ii) All inventory	VCE		(ii) Overpressure
TK11	Instantaneous	All inventory	BLEVE and toxic release	Toxic release	Fragments
TK12	Instantaneous	All inventory	BLEVE and toxic release	Toxic release	Fragments
TK13	Instantaneous	All inventory	BLEVE and toxic release	Toxic release	Fragments
TK14	Instantaneous	All inventory	BLEVE and toxic release	Toxic release	Fragments

Table 8
Case-studies (1–16): single domino scenarios

ID	LO	Primary unit	Primary. scenario	Escalation vector	Secondary units	No of secondary events	Type of secondary events
1	a	TK10	VCE	Overpressure	TK4	1	PF
2	a	TK10	VCE	Overpressure	TK9	1	FB
3	a	TK10	VCE	Overpressure	TK9	1	FB
4	a	TK10	CFB	Missiles	TK4	1	PF
5	a	TK10	CFB	Missiles	TK9	1	FB
6	a	TK5	PF	Radiation	TK4	1	PF
7	b	TK10	VCE	Overpressure	TK11	1	TR
8	c	TK10	CFB	Missiles	TK11	1	TR
9	c	TK13	CTR	Missiles	TK4	1	PF
10	c	TK13	CTR	Missiles	TK14	1	TR
11	a	TK10	VCE	Overpressure	TK1, TK4	2	PF, PF
12	a	TK5	PF	Radiation	TK2, TK4	2	PF, PF
13	b	TK10	VCE	Overpressure	TK11, TK12	2	TR, TR
14	a	TK10	VCE	Overpressure	TK1, TK4, TK7	3	PF, PF, PF
15	a	TK5	PF	Radiation	TK2, TK4, TK6	3	PF, PF, PF
16	a	TK5	PF	Radiation	TK2, TK4, TK6, TK8	4	PF, PF, PF, PF

LO: reference lay-out in Fig. 2. Scenarios: VCE: vapour cloud explosion; FB: fireball; PF: pool fire; TR: toxic release; CFB: catastrophic failure followed by fireball; CTR: catastrophic failure followed by toxic release.

must be considered in the complete quantitative assessment of the lay-out considered. The case-studies were based on the three lay-outs reported in Fig. 2, and the data on the primary and secondary scenarios considered are summarized in Table 8.

A second set of three case-studies was defined (a–c). In this set, a single primary event was considered and all the possible combinations of secondary scenarios were assessed. Table 9 summarizes the main details of these case-studies, that were based on the lay-outs reported in Figs. 2 and 3.

A third set of two case-studies (d–e) was also introduced, were all the possible primary scenarios and all the resulting secondary scenarios were assessed. These were based on the lay-outs reported in Fig. 3. The primary and secondary events considered are listed in Table 9.

7.2. Escalation factor in single domino scenarios: results of the first set of case-studies

The first set of case-studies was defined in order to assess the increase in the expected number of fatalities due to escalation effects. For each case-study, a uniform population density of 0.04 persons/m^2 was assumed and the expected number of fatalities was calculated for both the primary scenario and the domino scenario. The results of these calculations are reported in Table 10. The table also reports an escalation factor, defined as the ratio between the expected number of fatalities in the domino scenario and that in the primary event. As shown in the table, the escalation factor calculated only on the basis of the expected number of fatalities may have relevant values, as high as 300, in particular if toxic releases are present among the secondary events initiated by the escalation. This confirms that domino effect may trigger severe accidents, that result in a relevant amplification of the consequences of the primary event.

In order to calculate the PLL, it was necessary to estimate the frequencies of the primary events and of the escalation. The results are reported in Table 11. The frequencies of the primary events were assumed on the basis of the suggestions given in the TNO purple book [27]. The frequencies of the domino scenarios were calculated adopting the appropriate model for the escalation of propagation probability (see Table 4). As expected, the frequencies calculated for the

Table 9
Case-studies (a–e)

ID	LO (figure)	Primary unit	Primary scenario	Escalation vector	Secondary units	Type of secondary events
a	3(a)	TK5	PF	Radiation	TK2, TK4, TK6, TK8	PF (TK2, TK4, TK6, TK8)
b	3(b)	TK10	VCE[a]	Overpressure	TK1, TK4, TK7	PF (TK1, TK4, TK7)
c	2(c)	TK10	VCE	Overpressure	TK1-8, TK9	PF (TK1–8), FB (TK9)
d	3(a)	All	PF (TK2, TK4–TK6, TK8)	See Table 7	All	PF (TK2, TK4–TK6, TK8)
e	3(b)	All	VCE (TK10), PF (TK1, TK4, TK7)	See Table 7	All	FB (TK10), PF (TK1, TK4, TK7)

LO: lay-out. Expected frequencies of primary scenarios: pool fire (PF) 1×10^{-5} events/year; vapor cloud explosion (VCE) 1×10^{-6} events/year; fireball (FB) 1×10^{-6} events/year.

[a] Fireball was also considered as primary event, but excluding escalation possibility.

Table 10
Expected number of fatalities in the primary scenario (N) and in domino scenarios (N_i) calculated by the i-th method

ID	N primary scenario	N_1	Escalation factor	N_2/N_1	N_3/N_1	N_4/N_1
1	467	716	1.53	1.000	n.a.	n.a.
2	467	4650	9.96	0.964	n.a.	n.a.
3	43	4290	99.77	0.995	n.a.	n.a.
4	27369	27372	1.00	1.000	1.001	1.000
5	27369	27498	1.00	0.996	1.072	1.040
6	250	345	1.38	0.989	1.158	1.156
7	480	111200	231.67	1.000	n.a.	n.a.
8	57000	145400	2.55	0.995	n.a.	n.a.
9	1270	1300	1.02	0.984	n.a.	n.a.
10	1270	1630	1.28	0.951	1.035	0.936
11	467	812	1.74	0.995	1.120	1.066
12	250	421	1.68	0.988	1.313	1.231
13	480	152400	317.50	0.922	1.254	1.028
14	467	905	1.94	0.993	1.203	1.107
15	250	496	1.98	0.988	1.418	1.268
16	250	555	2.22	0.990	1.507	1.265

The ratio between the fatalities calculated by methods 2–4 to those calculated by method 1 is also reported.

domino scenarios are always lower than those of the primary events. In particular, the frequencies of the domino events involving more than one secondary scenario are usually very low. The assessment of domino frequencies allowed the calculation of the F–N curves and of the potential life loss (PLL) for this first set of case-studies. The F–N curves for this simplified case-studies always show a first step corresponding to the primary event, while the domino scenario is responsible of a second step, having a lower frequency but a higher expected number of fatalities. Table 11 reports the PLL values calculated using method 1 for the primary events and for the overall domino scenarios in all the case-studies. As shown in the table, the escalation factor calculated for the PLL (defined as the ratio of the PLL of the domino scenario with respect to the PLL of the primary event) is always lower than 2 even for scenarios that evidenced an escalation factor higher than 300 with respect to the expected number of fatalities (e.g., see case-studies 7 and 13). This is clearly caused by the lower frequencies of the domino scenarios, that compensate the higher number of expected fatalities associated to these scenarios in the PLL calculation. These results confirm that the high severity of some domino scenarios may be often associated to rather low expected frequencies. These findings are confirmed by the other sets of case-studies, where all the possible secondary scenarios triggered by a single primary event were taken into account in the calculation of the risk indexes.

A comparison between the expected number of fatalities calculated by the different methods discussed in Section 5 is reported in Table 10. Method 3 resulted the more conserva-

Table 11
PLL (fatalities/10^6 years), expected frequencies of primary events (events/year) and of domino scenarios (events/year) for the case-studies considered. PLL_i: overall PLL including domino effect with vulnerability calculated by the i-th method

ID	Frequency of primary scenario	Domino prob	Domino frequency	PLL primary scenario	Domino PLL_1	Escalation factor	PLL_2/PLL_1	PLL_3/PLL_1	PLL_4/PLL_1
1	5.4×10^{-8}	1.01×10^{-1}	5.43×10^{-9}	25	27	1.08	1.00	1.00	1.00
2	5.4×10^{-8}	1.41×10^{-5}	7.61×10^{-13}	25	25	1.00	1.00	1.00	1.00
3	5.4×10^{-8}	2.40×10^{-6}	1.30×10^{-13}	2	2	1.00	1.00	1.00	1.00
4	3.5×10^{-8}	3.14×10^{-3}	1.10×10^{-10}	958	958	1.00	1.00	1.00	1.00
5	3.5×10^{-8}	1.03×10^{-2}	3.61×10^{-10}	958	958	1.00	1.00	1.00	1.00
6	3.25×10^{-8}	9.57×10^{-1}	3.11×10^{-8}	8	11	1.38	0.99	1.15	1.15
7	5.4×10^{-8}	1.41×10^{-5}	7.61×10^{-13}	26	26	1.00	1.00	1.00	1.00
8	3.5×10^{-8}	1.01×10^{-2}	3.54×10^{-10}	1993	2025	1.02	1.00	1.00	1.00
9	5.0×10^{-7}	5.65×10^{-2}	2.83×10^{-8}	635	636	1.00	1.00	1.00	1.00
10	5.0×10^{-7}	1.09×10^{-1}	5.43×10^{-8}	635	655	1.03	0.99	1.01	0.99
11	5.4×10^{-8}	1.01×10^{-3}	5.47×10^{-11}	25	25	1.00	1.00	1.00	1.00
12	3.25×10^{-8}	9.16×10^{-1}	2.98×10^{-8}	8	13	1.63	0.99	1.30	1.22
13	5.4×10^{-8}	1.99×10^{-10}	1.07×10^{-17}	26	26	1.00	1.00	1.00	1.00
14	5.4×10^{-8}	1.02×10^{-4}	5.50×10^{-12}	25	25	1.00	1.00	1.00	1.00
15	3.25×10^{-8}	8.76×10^{-1}	2.85×10^{-8}	8	15	1.88	0.99	1.39	1.25
16	3.25×10^{-8}	8.39×10^{-1}	2.73×10^{-8}	8	16	2.00	0.99	1.47	1.24

tive, always yielding the higher values of *N*. This is caused by the influence of the non-linear response of the doses to the intensities of physical effects. Method 4, that is a simplification of method 3, yields results that are slightly less conservative. On the other hand, method 2 always yields the lower values of *N*. Method 1 results more conservative than method 2. However, the differences in the expected number of fatalities are lower than a factor 1.5. This difference becomes even less important if the PLL index is considered, thus taking into account the effect of domino frequencies. Table 11 shows that the differences in the PLL due to the use of the different methods for the calculation of vulnerability in domino scenarios are lower than a factor 1.4. In the framework of a QRA, the relevance of these differences is limited due to the wide uncertainties affecting this type of analysis. Thus, these results seem to suggest that no significant difference is introduced by the use of the different simplified methods for the calculation of vulnerability. This leads to select method 1 as the more suitable for the calculation of vulnerability in domino scenarios, since it is more simple and more conservative than method 2, while the possible use of methods 3 and 4 is limited by the presence of scenarios resulting in

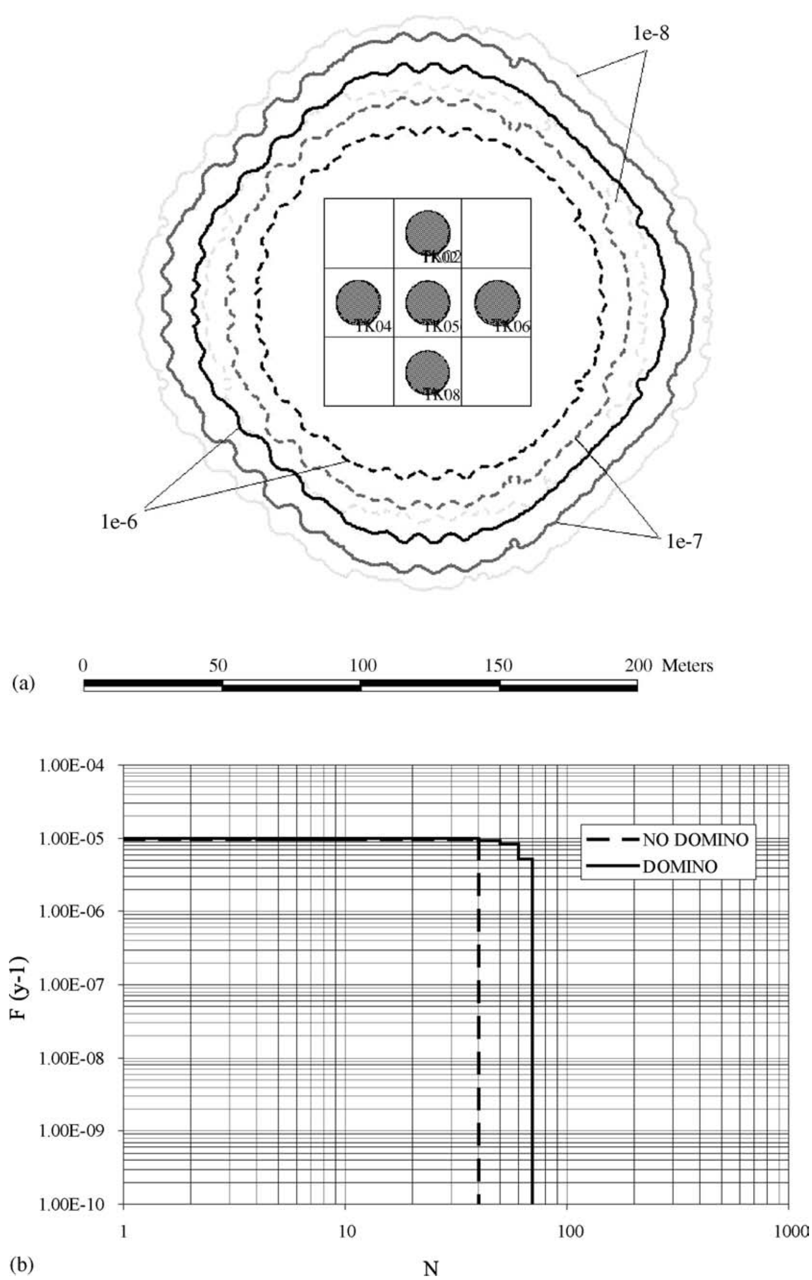


Fig. 4. (a) Map of individual risk (events/year) and (b) *F*–*N* societal risk curves obtained from the analysis of case-study (a). Dashed lines: results from the assessment of the primary scenario; solid lines: results including domino scenarios.

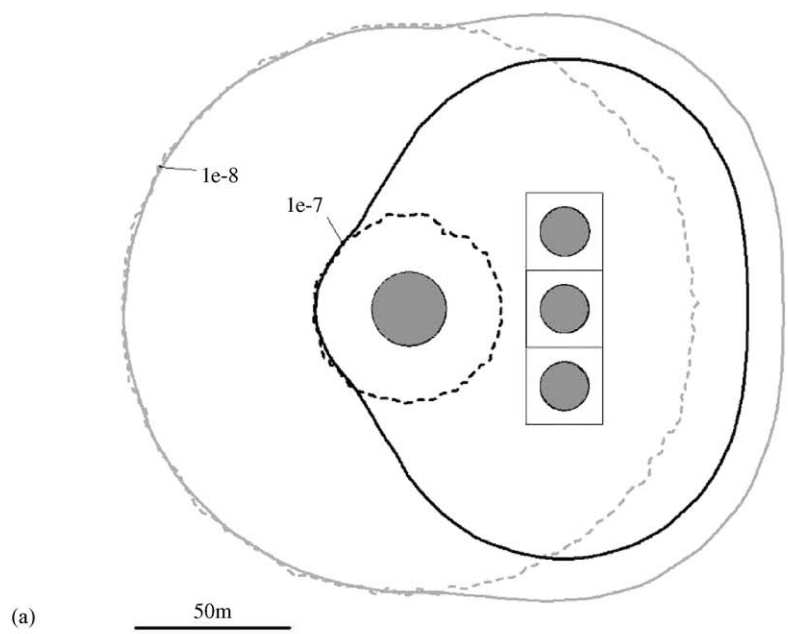
different physical effects. Thus, in the followings, method 1 will be used for the calculation of vulnerability in domino scenarios.

7.3. Assessment of the possible combinations of domino scenarios following a primary event: results of the second set of case-studies

In the second set of case-studies, the effect on individual risk of all the possible domino scenarios that may be triggered by a single primary event is assessed. Figs. 4–6 report the individual risk maps and the *F–N* societal risk curves obtained from the Aripar-GIS software for case-studies (a)–(c).

As shown in the figures, the domino scenarios result in important modifications of the individual risk. In particular, the individual risk results significantly higher in correspondence of the secondary units affected by the possible escalation effects. It must be recalled, however, that in these case-studies the individual risk coming from primary events in these units was not considered.

With respect to the *F–N* curves calculated for the case-studies, additional steps having lower expected frequencies but a higher number of expected fatalities are present



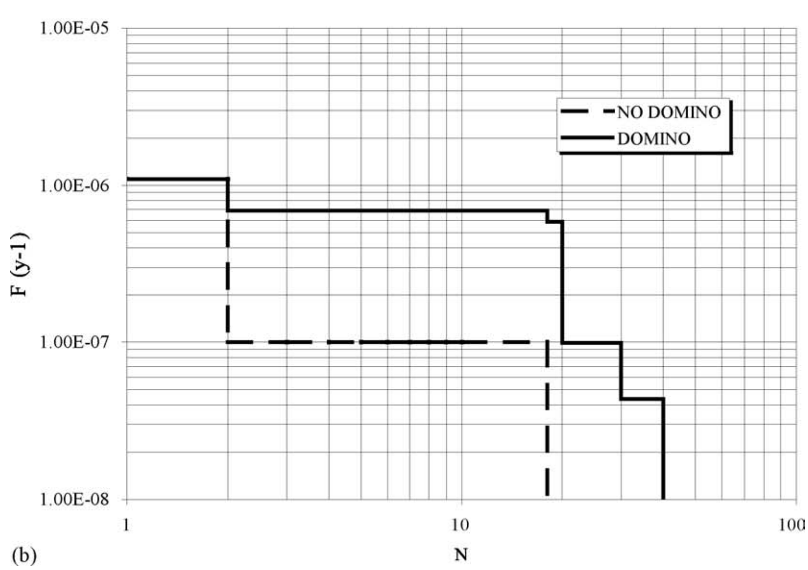


Fig. 5. (a) Map of individual risk (events/year) and (b) *F–N* societal risk curves obtained from the analysis of case-study (b). Dashed lines: results from the assessment of the primary scenario; solid lines: results including domino scenarios.

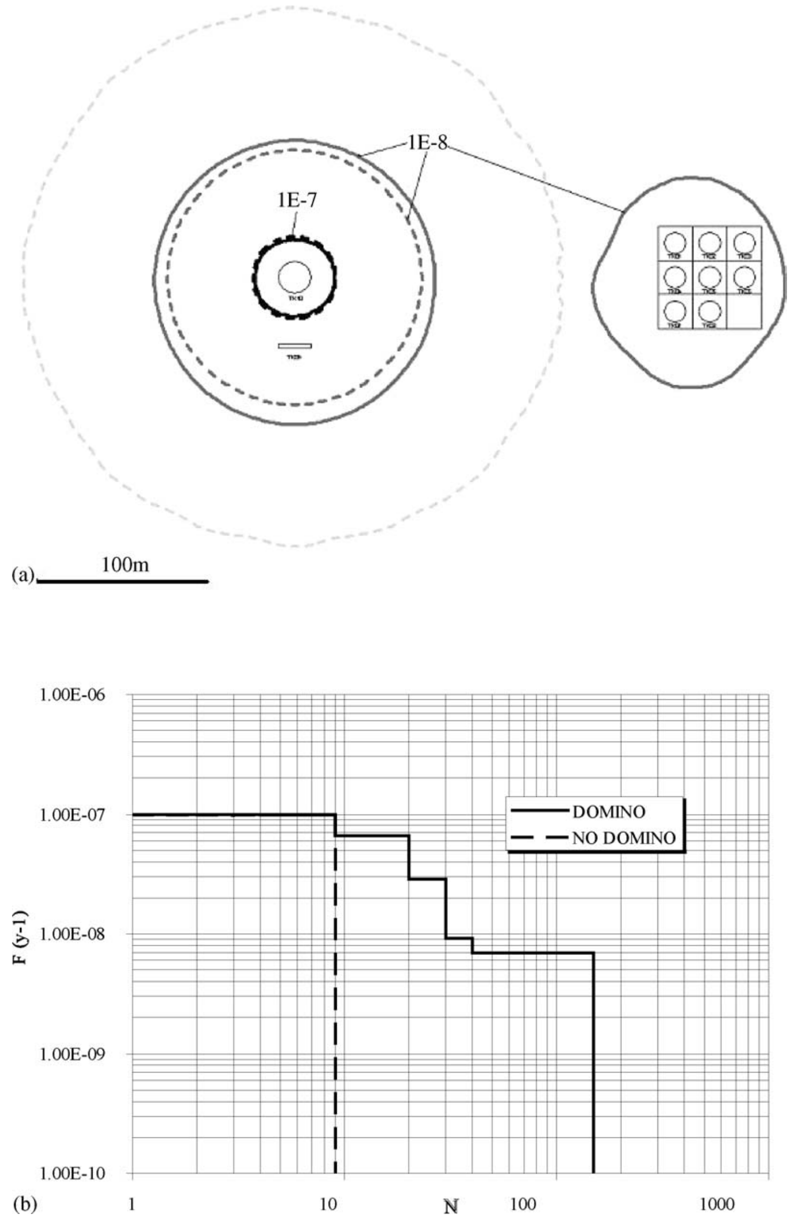


Fig. 6. (a) Map of individual risk (events/year) and (b) *F–N* societal risk curves obtained from the analysis of case-study (c). Dashed lines: results from the assessment of the primary scenario; solid lines: results including domino scenarios.

when considering the domino scenarios. Table 12 reports the PLL calculated in each case-study for the primary event and considering all domino scenarios. The table evidences that in these case-studies, the PLL escalation factor due to domino effect is comprised between 1.57 and 4.16. The higher values of the PLL escalation ratio were obtained for severe primary scenarios originated from pressurized vessels, causing relevant escalation probabilities at high distances. It must be recalled, however, that the effect of the possible primary accidents involving the secondary vessels were not taken into account in these case-studies.

Table 12
PLL of primary scenarios, PLL including domino effect and PLL escalation factor in case-studies (a)–(e)

ID	PLL not considering escalation	PLL including escalation	PLL escalation factor
a	4.00×10^{-4}	6.27×10^{-4}	1.57
b	3.80×10^{-6}	1.58×10^{-5}	4.16
c	9.04×10^{-7}	2.78×10^{-6}	3.08
d	2.00×10^{-3}	2.58×10^{-3}	1.29
e	3.04×10^{-4}	5.28×10^{-4}	1.74

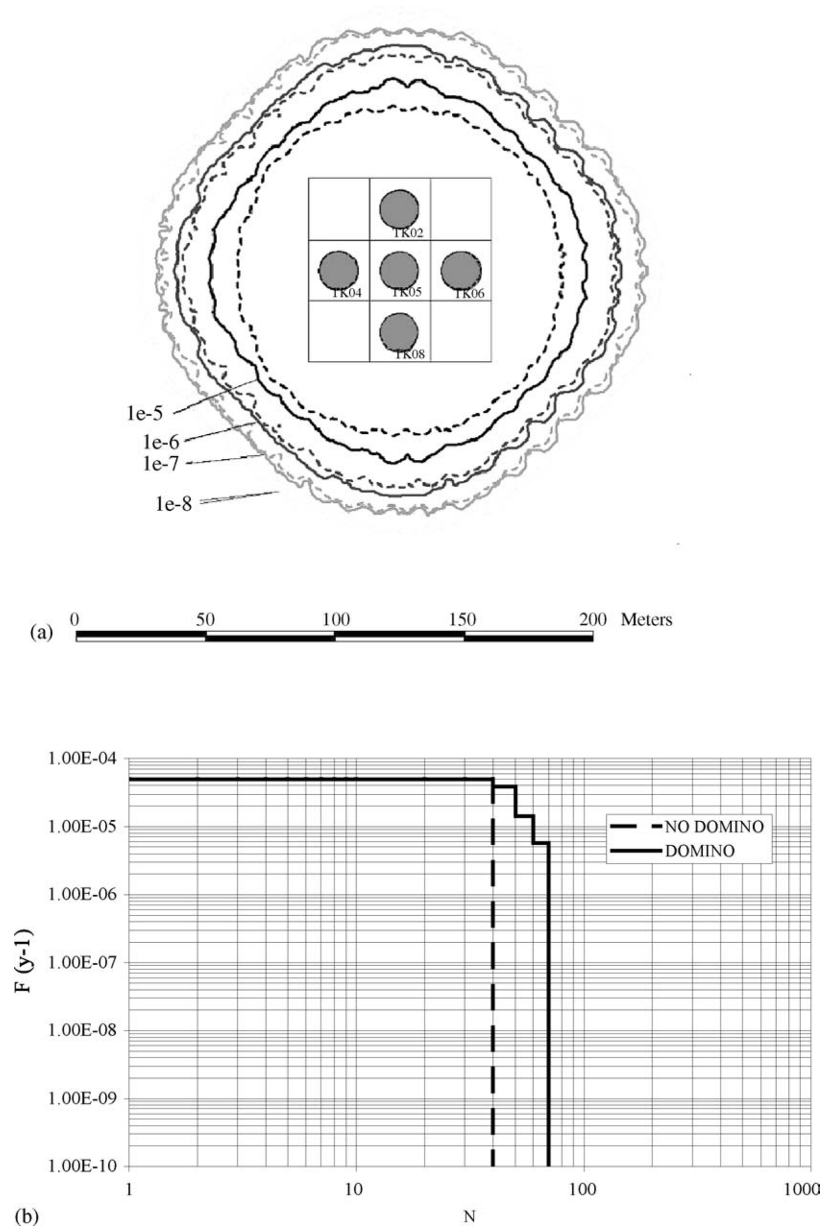


Fig. 7. (a) Map of individual risk (events/year) and (b) *F–N* societal risk curves obtained from the analysis of case-study (d). Dashed lines: results from the assessment of the primary scenarios; solid lines: results including domino effect.

7.4. Quantitative assessment of domino effect: results of the third set of case-studies

Fig. 7 shows the results obtained for individual and societal risk in case-study (d). The results obtained for case-study (e) are reported in Fig. 8. PLL escalation factors are shown in Table 12. As shown in Table 9, in these case-studies a primary event was associated to each unit present on the layout, and all the possible combinations of secondary events were considered for each possible primary scenario.

The quantitative assessment shows that the individual risk is incremented, although the changes in individual risk maps are less significant than in case-studies (a)–(c). This is evident if Figs. 7(a) and 8(a) are compared with Figs. 4(a) and 5(a), respectively.

If societal risk is considered, also in these case-studies domino scenarios result in additional steps of the *F–N* curves, having higher number of expected fatalities and lower frequencies. Table 12 evidences that the PLL escalation is of 1.29 and 1.74 for case-studies (d) and (e), respectively. Significantly lower PLL escalation factors are present in these case-studies with respect to those evaluated for case-studies (a) and (b), due to the inclusion of the primary scenarios of the target units in risk calculation. Thus, correctly taking into

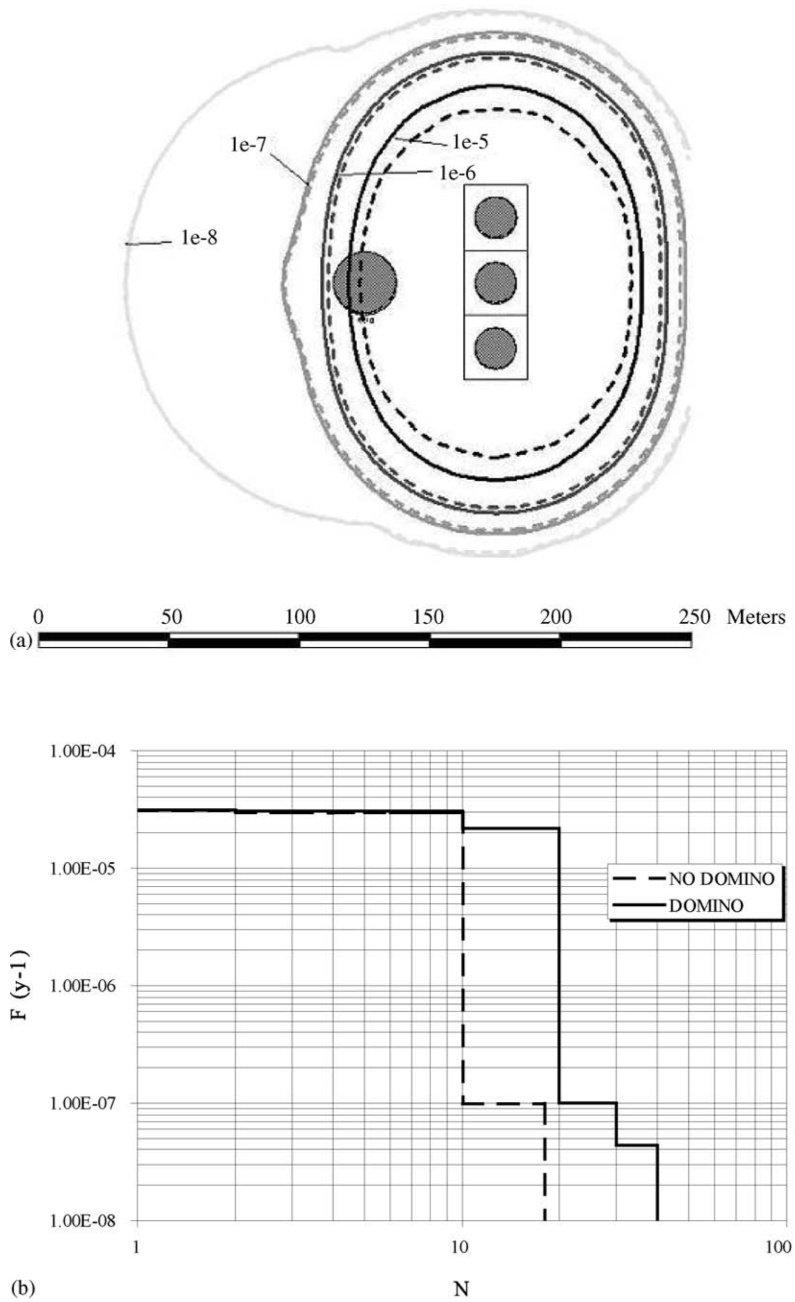


Fig. 8. (a) Map of individual risk (events/year) and (b) *F–N* societal risk curves obtained from the analysis of case-study (e). Dashed lines: results from the assessment of the primary scenarios; solid lines: results including domino effect.

account the escalation probabilities and the domino scenarios is an important element to obtain credible values for the increase of risk indexes caused by domino effect.

8. Conclusions

A methodology for the quantitative analysis of domino effect was developed. The procedure, based on a simplified approach to consequence assessment, allowed the estimation of the contribution of domino scenarios to individual and societal risk, and to the PLL index. The methodology was implemented in a software tool to allow the calculation of risk indexes, and was applied to the analysis of several case-studies.

An important increase in the number of expected fatalities was always evidenced in domino scenarios. This is in agreement with the experienced severity of escalation events. Nevertheless, the extremely high severity of some domino scenarios is in several cases associated to expected frequencies that may be of some orders of magnitude lower than those of the primary events triggering the escalation sequence.

The results obtained for the risk indexes evidence that relevant modifications are often experienced in the individual risk maps and in the *F–N* societal risk curves. However, the PLL escalation factor (defined as the ratio between the PLL index taking into account domino scenarios and the PLL index obtained considering only primary events) always resulted below 5 and in many cases was below 2.

Therefore, these results point out the importance of a domino effect quantitative analysis in a QRA framework, in order to correctly identify the credible and relevant escalation events to be addressed in the control of risk, as well as in emergency response and in land-use planning with respect to possible domino scenarios.

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