The domino effect — i.e., the occurrence of a cascading chain of events when the fire, explosion, missile projection, etc., generated by an accident in one process unit causes secondary accidents in other units — is a likely scenario in many major industrial plants and has the potential for catastrophic consequences \cite{Ref. 1, 2}. However, while in the literature there is plenty of information about accidents in single process units, the chain-of-accidents phenomenon has received much less attention. Although sophisticated models have been developed to assess the interactions among specific process units in case of accidents, few approaches have attempted to model the overall domino scenario in industrial plants. Nevertheless, the cited models are mainly suited for a detailed risk assessment of chains of accidents. In fact, they are quite sophisticated and require a great deal of input data and effort to carry out the analysis. However, a unified framework for preliminary risk assessment of domino effects is still missing.

In a previous paper \cite{Ref. 3}, a simplified quantitative method for domino-effect risk assessment was proposed. The method is suitable for a preliminary investigation aimed at assessing whether a domino
accident scenario is likely to occur in an industrial plant, in order to determine the necessity of a more in-depth analysis. The model also enables us to quickly identify the most critical units, acting as a potential source or a target of a chain of accidents, so that proper mitigation measures can be identified early. While the method is by no means intended as a substitute for a more detailed quantitative risk assessment, it may help plant managers to carry out a rapid screening of domino-effect hazards. This paper presents an improved model, which is the outcome of an ongoing research effort. In fact, the original manual procedure has been revised and extended to include a more comprehensive set of primary accidents (vapor cloud explosion and boiling liquid expanding vapor explosion were added), improved and more detailed effects computation, and the introduction of revised rating indices and a ranking scale. This paper details all major modifications to the earlier model, and also describes a software tool implementing the proposed risk analysis procedure.

Assessing the Probability of Domino Effect Occurrence

A domino effect occurs when a "primary" accident propagates to other process units, producing "secondary" accidents (Figure 1). The likelihood of a chain of accidental events to be triggered is therefore a function of the probability $P_{ij}$ that a target unit $j$ has of being involved by the physical effects of an accident occurring in a source unit $i$ (Figure 2). This sustains damage, resulting in a hazardous release of material and energy.

Let us consider a generic process unit $i$, and a set $A$ of possible accidental events, including explosion, fragment projection, pool fire, jet fire, vapor cloud explosion and boiling liquid expanding vapor explosion which, in the following, will be denoted by subscripts EX, FP, PF, JF, VCE and BLEVE, respectively.

The overall probability $P_{ij}$ of an interaction between unit $i$ and $j$ triggering a secondary event in unit $j$, provided that the initiating accident in unit $i$ has occurred, may be expressed as:

$$P_{ij} = \min\left(1, \sum_{A} \left[ \delta_{ij,A} P_{ij,A} \right]\right)$$

where

$$\begin{cases} 
\delta_{ij} = 0 & \text{unit } j \text{ is outside damage area of unit } i \\
\delta_{ij} = 0 & \text{unit } j \text{ is within damage area of unit } i
\end{cases}$$

(1)

and can be computed after determining, for each accident scenario, the damage area and the actual probability $P_{ij,A}$ of damage to the target unit according to the specific initiating event $A$.

In the following, the criteria adopted for computing the damage radius extension and the value of $P_{ij,A}$ will be given separately for the various initiating events considered.
Probability of domino effect triggered by overpressure:

* a) Determination of damage area radius
In the case of an explosion, either from condensed phase material or a vapor cloud at the unit location, the well-known TNT-equivalent method [Ref. 10-12] is adopted. This is used to compute the radius $r_A$ at which the conservative threshold limit value of peak overpressure $p^r = 7$ kPa suggested by Gledhill and Lines [Ref. 13] is obtained, which determines the boundary of the area where a major damage occurs,

$$r_A = Z_A \# W_{TNT}^{1/3} \tag{2}$$

where $W_{TNT}$ is the TNT mass equivalent to the amount $W_C$ of actual exploding substance,

$$W_{TNT} = \eta W_c \left( \frac{H_c}{H_{TNT}} \right) \tag{3}$$
\( \eta \) is the equivalency factor (ranging from 0.03 to 0.1, according to the geometry of the explosion scenario), while \( H_C \) and \( H_{TNT} \) are the heat values of the exploding substance and TNT, respectively (\( H_{TNT} = 4643 \text{ kJ/kg} \)). \( z_A \) is the scaled distance obtained from Equation 4 [Ref. 11] by setting the specified overpressure threshold and assuming \( z_A = z_{eff} \). In Equation 4, \( P_A \) is the atmospheric pressure (Pa).

\[
P^2 = P_A * \left[ 1616 \left( 1 + \frac{z_{eff}^2}{4.5} \right) \right] \left[ 1 + \frac{z_{eff}^2}{0.048} \right] \left[ 1 + \frac{z_{eff}^2}{0.32} \right] \left[ 1 + \frac{z_{eff}^2}{1.35} \right]
\]

(4)

\( b) \) Determination of damage probability \( P_{ij, \text{EXP}} \)

The actual peak overpressure experienced by unit \( j \), located at distance \( D_{eff} < r_A \) from unit \( i \), is obtained by entering Equation 4 with the scaled distance \( z_{eff} = D_{eff}/W_{TNT}^{1/3} \).

The probability \( P_{ij, \text{EXP}} \) of actual damage to unit \( j \) is then computed adopting a probit model. In this work, reference is made to the probability plots obtained from experimental data by Cozzani and Salzano [Ref. 14, 15], with reference to atmospheric vessels, pressurized vessels, elongated vessels or small equipment as follows:

Atmospheric vessels \( Y = -18.96 + 2.44 \ln (p^\circ) \) (5)

Pressurized vessels \( Y = -42.44 + 4.33 \ln (p^\circ) \) (6)

Elongated equipment \( Y = -28.07 + 3.16 \ln (p^\circ) \) (7)

Small equipment \( Y = -17.79 + 2.18 \ln (p^\circ) \) (8)

1 Notable examples are References 4-9, and a more detailed literature review can be found in Reference 3.
A Software Tool for Domino Effect Risk Assessment in Industrial Plants

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Probability of domino effect triggered by fragment projection:

a) Determination of damage area radius

The previous model adopted the Clancey correlation [Ref. 16] linking the equivalent mass of explosive W_{TNT} to the maximum distance (D_{max}) reached by projectiles resulting from unit i explosion, which is assumed to be the boundary of the damage area (r{A} = D_{max}). In this revised model, the more precise model of Baker [Refs. 10, 17] is adopted. That model utilizes empirical correlations to compute a scaled initial fragment velocity from the scaled internal pressure of the vessel, and then a scaled fragment range from the scaled initial velocity. For the sake of simplicity in this work, the following parameter values were assumed: lift-to-drag ratio of fragments set at zero which represents a null lift coefficient of fragment as typical of large vessel fragments, a fragment mass of 480 kg, a diameter of 1.6 m and a drag coefficient C_{D} = 0.47.

b) Determination of damage probability P_{j,FP}

The probability P_{j,FP} of actual damage to unit j is computed by Equation 9:

\[ P_{j,FP} = P_{pr} \cdot P_{imp} \cdot DF \]  

where P_{pr} is the probability that fragments are actually projected following an explosion of a process vessel (P_{pr} = 0.8 for pressurized vessels and 0.4 for atmospheric vessels), P_{imp} is the fragment impact probability computed from Equation 10, and DF is the Damage Factor.

\[ P_{imp} = F_{D} \cdot F_{n} \cdot P_{imp_{frag}} \cdot n \]  

In Equation 10, F_{D} is a directional factor considering the relative position of the target vessel, with respect to the projectile’s trajectory and the position of the source vessel, as it is more likely that fragments will be projected from the two ends of the vessel, rather than the sides. If the target vessel is located within an area covered by arcs 30° to either side of the vessel's front and rear axial directions F_{D} = 1.5, while if it is not located in those two 60° sectors, F_{D} = 0.67 [Refs. 5, 18].

The number of fragments is instead denoted by n. As suggested by Holden and Reeves [Ref. 19], n = 4 for cylindrical vessels, n=8 for spherical vessels with volume lower than 1200 m³ and n=16 for greater volume.

The probability of fragment impact is computed as P_{imp_{frag}} = Δθ/2π(0.5 - PI), according to the method of Gubinelli et al. [Ref. 20], where Δθ is the angular width of the target as seen from the source vessel and PI is a trajectory-dependent probability factor, which may be evaluated from Equation 11:
being $D_{\text{min}}$ is the minimum distance of the target from the source and $D_{\text{max}}$ is the previously determined maximum distance reached by the projectile. To compute $P_I$, the assumption of a conservative value of the initial fragment velocity of 200 m/s is made which, with the above described fragment characteristics, according to the Gubinelli et al. procedure, yields $z_1 = 0.125$, $z_2 = 0.21$, $z_3 = 0.24$.

Finally, the Damage Factor $DF$ is computed using Equation 12:

$$DF = F_M \cdot p \cdot F_S$$

$F_M$ is a fragment mass factor function of the thickness of the primary unit walls, as a higher fragment’s mass can give rise to a higher damage to the target. It is assumed that $F_M = 1$ for thick walls (thickness > 20 mm) and 0.7 for thin walls. $F_S$ is a damage susceptibility factor ($F_S = 0.7$ for thick walls and 1 for thin walls), meaning that the probability that the target unit is actually damaged by the impact of a fragment of given kinetic velocity is an inverse function of the thickness of its walls. Finally, $p$ is a factor representing the kinetic energy of the fragments and is computed as the probability that fragments will travel a distance further than the source-target distance $D$. On the assumption that the distance traveled by fragments has a Gaussian probability distribution with maximum value $D_{\text{max}}$ and minimum value 0, $p$ can be computed by referring to the standard normal distribution and the corresponding standardized variable $Z = (D - \mu) / \sigma$ (i.e., the distribution has $\mu = D_{\text{max}}/2$ and $\sigma = D_{\text{max}}/6$).

Probability of domino effect triggered by pool fire:

a) Determination of damage area radius

The damage area is limited by the radius at which the threshold value of thermal radiation flow $I_S = 12.5$ kW/m$^2$ is obtained. This can be computed, assuming a point source model, by Equation 13, which relates the radiation intensity to the distance and pool fire characteristics [Refs. 21, 22]:

$$I = \frac{\tau F \cdot L \cdot m_s \cdot H}{16 \cdot r^3}$$

where $r$ is the radius, $F_S$ is the percent irradiated energy (usually ranging between 0.13 and 0.4), $m_s$ is the combustion velocity per unit surface area of the pool, $\tau = 2.02 (p_w r)^{0.08}$ is the atmospheric transmissivity coefficient, with $p_w$ being the water saturation pressure at ambient temperature, $H_c$ being the heat value of the burning substance and $D$ being the pool diameter.

b) Determination of damage probability $P_{S,PF}$

The damage probability is computed as

$$P_{S,PF} = F_{V,S} \cdot DF \cdot F_{FRP} \cdot F_{RF}$$

In Equation 14, $F_{V,S} = 1 - \frac{\theta_{\text{occ}}}{\theta}$ is the view factor, with $\theta$ being the angular width of the target as seen from the source vessel and $\theta_{\text{occ}}$ being the angular width, within $\theta$, of any obstacle shielding the target from the thermal radiation. $F_{FRP}$ is a factor accounting for the possibility of cooling the target vessel walls, ranging from 0.75 to 1. This depends on the availability of a vessel cooling system and a rapid deployment firefighting squad. $F_{RF}$ is instead a wall thermal resistance coefficient ranging from 0.55 to 1 and accounting for the thickness of vessel walls and the presence of an insulating layer. Finally, $DF$ is the damage factor given by Equation 15 as a function of the absorbed dose of thermal radiation $DTR$ [Ref. 22].
The dose of thermal radiation is computed as \( DTR = (I - I_x) s^{0.2} \), where \( I \) is the actual thermal radiation computed from Equation 13, \( I_x \) is the threshold value of thermal radiation and \( s \) is the exposure time (i.e., the pool burning time).

The exposure time is computed as \( t = \frac{V}{A} \), where \( V \) is the pool volume, \( A \) is the pool surface area and \( v \) is the burning velocity

\[
v = v_\infty (1 - \exp(-k_1 t))
\]

where \( k_1 \) is a constant depending on the flammable liquid \( \text{Ref. 21} \), and \( v_\infty \) is the combustion velocity of a pool with infinite diameter.

\[
v_\infty = \frac{H_x}{\Delta H_v}
\]

with \( k_2 = 0.0076 \text{ cm/min} \), and \( \Delta H_v \) being the latent heat of vaporization.
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**Probability of domino effect triggered by jet fire:**

a) **Determination of damage area radius**

In case of jet fire, given the complexity of the phenomenon, an average exposure condition is hypothesized, intermediate between the two limit conditions of a horizontal jet pointed at the target unit and a vertical jet. In both cases, it is assumed that the jet flame is stationary (i.e., burning rate equal to emission rate), with fixed shape and size dictated by a mass flow rate of $m' = 30 \text{ kg/s}$.

In the case of a horizontal jet, the damage area radius is assumed to be equal to the flame length which, according to Cook et al. [Ref. 23], is

$$L = 0.00326 \times (m' + \Delta L)^{4.75}$$  \hspace{1cm} (18)

In the case of a vertical flame, the same procedure utilized for pool fires is adopted. Setting $I_S = 12.5 \text{ kW/m}^2$ as the threshold value of thermal radiation flow, the resulting damage area radius (m) from Equation 13 is

$$y = \left( \frac{2.02 \times 30 \times \Delta H}{F_W \times 0.12 \times 4 \times 12500} \right)^{0.25}$$  \hspace{1cm} (19)

With the actual numerical values of the involved parameters, it is always $L > r$. Therefore, it is conservatively assumed that the radius of the damage area is $L$.

b) **Determination of damage probability $P_{ij,\text{JF}}$**

The damage probability is computed as

$$P_{ij,\text{JF}} = P_{ij} \times D_F \times P_{\text{DF}}$$  \hspace{1cm} (20)

where $F_V$ accounts for the shielding effect of obstacles interposed between source and target unit, and is computed as shown in the case of a pool fire. Also, $F_{\text{RP}}$ and $F_{\text{RT}}$ are computed as in the case of a pool fire.

The damage factor $DF$ is computed in a similar manner as for a pool fire on the basis of the DTR value, but assumes that the actual radiation intensity $I$ is computed as the average of the radiation level, considering horizontal flame impinging on the target ($I_1 = 280\text{kW/m}^2 \text{s}$) and vertical flame ($I_2$ computed from Equation 13).


\[ I = I_1 F_0 + I_2 (1 - F_0) \quad (21) \]

where \( F_0 = \frac{\Theta_{imp}}{360^\circ} \) is the orientation factor, \( \Theta_{imp} \) being the impingement angle (i.e., the angle of view of the target unit from the source unit), which represents the probability that the jet actually points toward the considered target unit.

To compute DTR, the burning time \( t_B \) is the ratio of the overall fuel mass to the emission rate (in this case, assumed to be 30 kg/s).

Probability of domino effect triggered by vapor cloud explosion:

\( a) \) Determination of damage area radius

In this case, there is no predefined damage area because the vapor cloud can be transported by wind anywhere over the plant area.

\( b) \) Determination of damage probability \( P_{ij,VCE} \)

This probability is computed as

\[ P_{ij,VCE} = P_W F_T P_K \quad (22) \]

where \( P_W \) is the probability that wind blows from the source unit toward the quadrant where the target unit lies with respect to the source unit. \( P_W \) is assumed, based on the prevailing atmospheric conditions of the site. \( P_I \) is the cloud ignition probability and depends on the cloud mass \( M_C \). If \( M_C \leq 1 \) t, then \( P_I = 10^{-3} \). If \( M_C > 10 \) t, then \( P_I = 10^{-1} \), while in the intermediate cases, \( P_I = 10^{-2} \). \( P_K \), instead, is the damage probability to the target unit, provided that the vapor cloud actually explodes in the surroundings of the unit (this occurs with probability \( P_D \times P_I \)). \( P_K \) is computed from the previously adopted probit models (Equations 5-8) according to the vessel type, but assuming a mean peak overpressure \( p_0^{avg} \), which is representative of the average value of the overpressure experienced at the target location when the cloud explodes at different possible locations along the path linking the source to the target. The generic distances of the exploding cloud to the target unit is computed as \( D_{ij} = |D - PL_i| \), where \( D \) is the source-target distance and \( PL_i = W T_i \) is the length of the path traveled by the cloud along the source-target direction before it explodes after the time delay \( T_i \), with \( W \) being the average wind speed. For the sake of simplicity, four values of ignition delay times and the corresponding probability values \( p_{T_i} \) were assumed, namely \( T_1 = 0.5 \) min, \( p_{T_1} = 0.25; T_2 = 2.5 \) min, \( p_{T_2} = 0.35; T_3 = 7.5 \) min, \( p_{T_3} = 0.25; T_4 = 15 \) min, \( p_{T_4} = 0.15 \). Corresponding to each \( D_{ij} \) distance, the scaled cloud-target distance \( z_{eff,i} \) is computed. The peak overpressure at target location \( p_0^{ij} \) is computed from Equation 4. Then the average peak overpressure is computed as

\[ p_0^{avg} = \frac{1}{2} \sum_{i=1}^{4} P_i p_0 \quad (23) \]

where the ½ factor accounts for the fact that the explosion occurs in open air off the ground level, instead of at the ground level.

Probability of domino effect triggered by BLEVE:

\( a) \) Determination of damage area radius

The BLEVE phenomenon is considered only for those process units containing a pressurized superheated liquid. Effects of a BLEVE are overpressure, fragment projection and a fireball. Due to the typically short duration of a fireball, it is often assumed that it cannot damage process equipment. Therefore, the fireball effects are neglected here. The damage radius of a BLEVE occurring at unit \( i \) is the maximum of the damage radii computed for the fragment projection and explosion effects separately: i.e., \( R_{i,BLEVE} = \max (R_{i,EXP}, R_{i,FP}) \).

\( b) \) Determination of damage probability \( P_{ij,BLEVE} \)

Damage probability of a target unit \( j \) from a BLEVE occurring at unit \( i \) is \( P_{ij,BLEVE} = \min (1, P_{ij,EXP} + P_{ij,FP}) \).

Domino Effect Rating Indices
According to the described model, each process unit may be either an initiator and/or a target of a chain of accidents. A domino effect may occur if an accident in unit \( i \) may affect unit \( j \) and trigger in this secondary unit a release of materials and energy with a high damage potential in the surrounding environment. Therefore, for each combination of units \((i,j)\), two domino interaction potentials may be assessed as follows: either a Domino Source Potential \( DSP_{i,j} \) when unit \( i \) is the source of the primary accident and unit \( j \) is the target unit generating the secondary accident, and a Domino Target Potential \( DTP_{j,i} \) when unit \( j \) is the target and unit \( i \) is the primary accident source. However, according to this definition, \( DSP_{i,j} = DTP_{j,i} \) but it should also be noted that in general, \( P_{ij} \neq P_{ji} \).

It follows that for each \( i-th \) major equipment or process unit that can be an initiator of the domino effect, a Domino Source Index \( DSI_i = f(DSP_{i,j}, j) \) is defined. This expresses the risk that the considered unit can trigger a domino effect in any other \( j \) process units located within its damage range. Conversely, for each \( i-th \) process unit, there is a defined Domino Target Index, \( DTI_i = f(DTP_{i,j}, j) \). This rates both the probability that the unit \( i \) can be involved in an accident initiated by the \( j \)-th unit and the amount of damage resulting from the release of materials and energy from the secondary unit. For the entire plant, a Domino Effect Potential (DEP) Index is then defined as a combination of the previous indices, computed for all units in the plant. The higher the DEP index, the higher the risk of a domino scenario occurring, while the single equipment indices \( DSI_i \) and \( DTI_i \) indicate which process unit is more critical as either a source or a target, in order to properly focus preventive and protective actions.

The Domino Source Potential of unit \( i \) with reference to unit \( j \) (or Domino Target Potential of unit \( j \) with respect to unit \( i \)) has been defined as

\[
DSP_{ij} = (P_{ij} + S_{ij}) M_j C_{M,j} \tag{24}
\]

where \( P_{ij} \) has been computed as shown before and is the overall probability that unit \( j \) may be damaged by unit \( i \), thus generating a secondary accident, \( S_{ij} \) is an effects amplification factor described below, \( M_j \) is the damage magnitude coefficient, and \( C_{M,j} \) is an effect mitigation factor.
In greater detail, $S_{ij}$ represents the likelihood that the target unit $j$ can sustain the chain of accidents by involving a generic further unit $k$ in its secondary accident. The value of $S_{ij}$ may range between 0 and 1. When $S_{ij} = 0$, the chain of accidents gets blocked at unit $j$ because a secondary accident occurring in that unit cannot extend its effects beyond those already generated by the primary accident. The interaction between units $i$ and $j$ remains thus confined within the damage to those units, and the domino effect does not propagate any further. When $S_{ij} > 0$, the secondary event may instead continue the chain of accidents by affecting further process units. To determine the value of $S_{ij}$, two cases should be analyzed.

**Case 1:** The damage area of unit $j$ is entirely within the damage area of unit $i$. In this case, shown in Figure 3a), $S_{ij} = 0$ when there is no other unit $k$ within the damage area of unit $j$ or when the probability of direct damage to unit $k$ from the primary accident in unit $i$ is greater than the probability of damaging unit $k$ as a result of the secondary accident in unit $j$, i.e., when $p_{ik} > p_{ij} p_{jk}$. If instead $p_{ik} < p_{ij} p_{jk}$, then $S_{ij} = 1$.

**Case 2:** The damage area of unit $j$ is partly outside the damage area of unit $i$. In this case, $S_{ij} = 1$ if there is some other unit $k$ outside the damage area of unit $i$, but within the damage area of unit $j$, as shown in Figure 3 b). $S_{ij} = 0$ if there is no other unit $k$ outside the damage area of unit $i$ but within the damage area of unit $j$, as shown in Figure 3c). When the damage area of unit $j$ extends outside the damage area of unit $i$, but additional units $k$ are within the damage area of both units then Case 1 applies.

In general, $S_{ij}$ is a weighted average of the values it may assume when considering the different accidental events.
The damage magnitude coefficient for unit \( j \) relates to the magnitude of effects of the secondary accident. The higher this magnitude, the higher the likelihood that the secondary accident triggers a tertiary accident, and so on. The magnitude of a secondary accident is intuitively correlated to the kind and amount of hazardous substance contained in unit \( j \) and its process conditions (temperature, pressure, etc.). Therefore, for the sake of simplicity we will assume \( M_j \) equal to the DOW Fire and Explosion Index [Ref. 24] computed for unit \( j \). In the present method, it is not necessary to explicitly consider the whole chain of events triggered from unit \( i \). The effects of a tertiary event caused by the secondary event in unit \( j \) are covered by the case when unit \( j \) is assumed to be the source unit instead of a target unit, and so on. The mitigation factor accounts for any protective measure that has been applied to unit \( j \) to reduce the consequences of the secondary event. It may be computed as

\[
C_{M,j} = \prod_{k=1}^{N} C_k \tag{26}
\]

the \( C_k \) coefficients adopted by the DOW Fire and Explosion Index procedure can be utilized here.

The overall Domino Source Index \( DSI_i \) for the generic source unit \( i \) is then

\[
DSI_i = \sum_j DSP_g = \sum_j \left[ \left( P_g + P_{S_g} \right) M_j C_{M,j} \right] \tag{27}
\]

Instead, the Domino Target Index \( DTI_j \) is

\[
DTI_j = \sum_i DTI_{ij} = \left[ \left( P_{S_g} + P_{S_{ij}} \right) M_j C_{M,j} \right] \tag{28}
\]

The indices \( DSI_i \) and \( DTI_j \) enable one to assess the criticality of a process unit with respect to its dangerousness or vulnerability so that specific preventive or protective mitigation measures may be taken.

Finally, the overall Domino Effect Potential (DEP) Index for the entire plant is computed as

\[
DEP = \frac{\sum_j DTI_j}{N_S} \tag{29}
\]

where \( N_S \) is the number of source units having \( DSI \neq 0 \).

It should also be pointed out that while the chain of accidents is an intrinsically dynamic phenomenon, the proposed analysis approach, which does not attempt to model the time-dependent sequence of accidents along each singular potential chain, nor the absolute probability of a chain of accidents to occur, gives instead a static assessment of the overall plant-related or process unit-related domino risk.

In order to define a meaningful, although empirical, ranking scale, the minimum and maximum score values were selected to span from a low domino risk condition to a high one. A low-risk situation was considered as the best case, where only two units are involved by the primary accident, having \( P_{ij} = 0.1 \), a low value of the damage magnitude coefficient (\( M = 90 \)) and only one target unit sustaining the chain of accidents. A high risk was considered as the worst case where up to six target units are involved with \( P_{ij} = 1 \), \( M = 140 \) and three units sustaining the chain of accidents. The resulting ranking scale is shown in Table 1.

Table 1 — Process Unit Risk Ranking Scale.
<table>
<thead>
<tr>
<th>DSII, DTIJ, DEP Score</th>
<th>Risk Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-70</td>
<td>Low</td>
</tr>
<tr>
<td>71-225</td>
<td>Moderate</td>
</tr>
<tr>
<td>226-392</td>
<td>Medium</td>
</tr>
<tr>
<td>393-630</td>
<td>High</td>
</tr>
<tr>
<td>&gt; 630</td>
<td>Severe</td>
</tr>
</tbody>
</table>
A Software Tool for Domino Effect Risk Assessment in Industrial Plants

by Antonio C. Caputo, Ph.D., L’Aquila, Italy

Domino Effect Evaluation Software Tool

A software tool was developed, implementing the above described risk assessment procedure. The tool is intended to provide a rapid criticality ranking of process units and can act as a decision support system for plant safety managers. The tool was developed in MS Visual Basic language, and is supported by a relational database developed in an MS SQL Server environment. The model has a graphical user interface (GUI) where process units are shown superimposed on a plant area map. The GUI is also used to input equipment data in an interactive manner (See figure 4) and can show the damage areas of selected units (Figure 5). The sequences of all possible domino chains of accidents starting from a selected source unit can also be shown on the map.

Figure 4 — Data Input Window.
In a separate window, the program shows the computation results (Figure 6). In particular, the program shows, for each unit, the absolute values of the DSI and DTI indices. A relative value with respect to the highest-ranking process unit within the plant is also shown. Results are color coded according to the risk level for a rapid guess of the most critical units. Finally, the DEP value is also shown.

For example, Figure 6 shows a case where four units have a DSI value of medium criticality (yellow), while as far as the DTI index is concerned, only two of them have the same criticality range, with only one unit having a high criticality (orange). The overall DEP value is 142. Figure 7 shows a risk simulation after some mitigation measures (including vessel cooling, inert gas supply, remote control valves, drainage system, leak detectors and sprinkler system) were applied to the most critical units. The effectiveness of the adopted measures is demonstrated by the DEP value being reduced to 84, and no unit having a DSI or DTI value above the moderate risk level.
Figure 6 — Ranking Results Window Before Mitigation.
Conclusion

In this paper, an improved method for the rapid rating of the domino effect potential in industrial plants has been presented. The method is based on three kinds of rating indices. One index describes the potential of each process unit of being the initiator of a chain. Another index expresses the potential of each process unit to be involved in an accident initiated by other units, thus generating a secondary accident and triggering the domino effect. An overall index expresses the likelihood that a domino effect will occur in the examined plant. A software tool implementing the proposed model was also developed and briefly described.

This domino effect rating assessment method adopts a simplified analytical procedure for ease of use and enables a "rough cut" assessment of the domino scenario to assess whether a more detailed analysis is required and to perform a preliminary screening of process units criticality. Furthermore, the method may help plant managers to correctly select risk mitigation measures for the most critical process units. However, the method is by no means intended as a substitute for a more detailed traditional quantitative risk assessment.

Finally, it should be noted that this new method does not aim to assess the actual probability of a domino effect, but rather to rate the susceptibility of a plant or specific pieces of equipment to a chain of accidents, provided that a primary accident has occurred.

About the Author

Antonio C. Caputo, Ph.D., received his Master's degree in mechanical engineering from the University of Roma, La Sapienza, in 1991. In 1995, he earned a Ph.D. in mechanical engineering and joined the engineering faculty at the University of L'Aquila, Italy, where he is currently a full professor in industrial and plant engineering. In 1991-92, he served as a volunteer in the Italian National Corps of Firefighters. His primary research interests include industrial safety, design of manufacturing systems, and production planning and control.

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