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Research Article

Studying Probability of Domino Effect in Chemical Storage Tanks Using Hazard Index

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The accidents caused by the domino effect in industries are highly harmful. This study aims to analyze the occurrence probability of the domino effect with respect to possible explosion and fire scenarios in chemical tanks. Using the results obtained by previous studies, reviewing past accidents, and according to the equipment damage models, threshold values were used for extraction process equipment and inherent safety distances as a criterion to prevent domino accidents. According to primary scenarios and experimental equations, the escalation vector was determined for different tanks. According to the assumption that fire radius is equivalent to inherent safety distance, the fireball radius for tank 1 was calculated 535.7 m. According to the results, the DCP index of tank 3 can be considered the most critical unit. This research studies the probability of the domino effect and means to prevent them according to criteria and hazard index parameters.

1. Introduction

Different accidents might happen in chemical industries depending upon the toxicity, flammability, and exploitability of chemical substances [1, 2]. If an explosion happens, a fire could also harm the surrounding equipment. Besides, accidents around flammable materials could lead to accidents that are more intense than the main accident, called the domino effect [3–6]. The consequent accidents caused by the domino effect are considered the most catastrophic events in industries. The consequence of these accidents has different levels. It subsequently affects not only industrial sites but also individuals, the environment, and the economy [7, 8]. In addition, over the past few years, the probability of a domino effect has increased thanks to the development of industrial units, their closeness, increased content and inventory, and transportation of hazardous materials [9–11].

Studies indicate that most accidents that happened between 1969 and 1998, including 207 chemical accidents, took place in the US and Europe, and 55% of them led to the domino effect. In this regard, 80 accidents caused secondary accidents, and 34 accidents led to the third accident. Statistically speaking, more than 50% of explosions do not end by the first incident, and it leads to other subsequent accidents [12]. According to the reports in domino accidents, explosions with an occurrence probability of 57% and fire with 43% are the most common reasons behind the domino effect. In terms of the occurrence site of domino effects and according to examinations into 225 accidents, 35% of these incidents occur in chemical storage sites, 28% in process industries, and 19% in the transportation of hazardous materials [7].

Usually, four major consequences or escalation vectors resulting from the domino effect (escalation vectors are defined as physical effects of primary accidents) include overpressure, radiation, projectile, and distribution of toxic substances [13, 14]. These effects are presented in Figure 1.

The passive safety approach includes the appropriate design of physical barriers and protection systems without any external intervention, such as fireproofing of industrial process equipment [15, 16]. This approach is widely used to reduce the consequences of accidents. It should be noted that this approach relies on the relevant costs to implement passive protection systems. On the other hand, active strategies are less reliable in preventing accidental propagation. Still, they are adequate for some primary scenarios, such as jet fire, for example, water

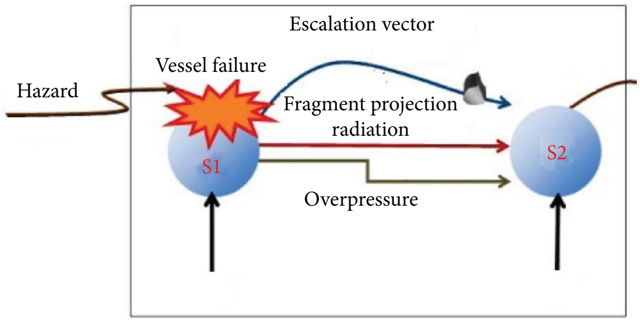

Figure 1: Different escalation vectors in tanks containing hazardous chemicals.

sprays in pressurized tanks [17, 18]. Despite the importance of the two cited approaches, there is another fundamental approach that prevents the domino effect from achieving process safety aiming to reduce hazards in the predesign phase [19, 20]. This approach aims to prevent the domino effect and determine safety distances as a key strategy in defining effective actions to prevent the domino effect. Integrating inherent safety criteria with active and passive protection strategies is a promising path toward preventing accidental domino events in the chemical and process industry. Indeed, if active and passive controls are not applicable or the escalation vector exists after taking these actions, inherent safety can limit the effects. Limitation of effects of the escalation vector must be relevant to the threshold value of potential target equipment. This principle suggests two sets of actions: (1) appropriate design of possible targets of intensifier accidents such as using underground tanks that are not exposed to radiation of fire flame and (2) taking the suitable safety distance [21].

Usually, countries determine the safety distance between tanks and equipment of the chemical storage tanks to prevent these accidents. Safety distances are determined according to characteristics and the content of chemical substances. For instance, in Korea, the safety distance for 2,000–3,000 kg flammable substance storage is 106 m. This distance equals 827 m for more than 100,000 kg of flammable chemical substance storage. It must be noted that this distance equals to 50 and 45 m at temperatures of lower than 21°C and temperatures between 21 and 70°C [22]. According to studies, countries that consider higher safety distance are less likely to experience domino accidental events [23, 24]. This issue becomes more important when reviewing the recent accidents in chemical industries, especially the oil and gas industries. One possible theory is that safety standards are not taken into account in these industries, or the standards are not appropriately defined. In other words, accurate and specified consequence analysis is not carried out in these industries to prevent such incidents.

In the present study, the probability of the domino effect will be analyzed according to fire and explosion scenarios, as well as the calculation of escalation vectors and considering the values of damage thresholds to pressurized and atmospheric tanks.

2. Methodology

The case study is a part of the storage tank site of Kangan Petro Refining Co. (KPRC), including six tanks. Figure 2 indicates serial images of the region being studied and the arrangement of chemical storage tanks.

Figure 2: Storage tank layout and separation distances in the case study.

It should be noted that tanks 1–4 are in operation and the other two tanks, including tanks 5 and 6, are under construction. Since these two tanks are part of the executive plans of KPRC, in order to achieve more realistic results, these tanks have been considered in the present study.

2.1. Identifying Primary Scenarios. There are two vulnerability scenarios to the tank to calculate inherent safety distances and simulate the accidents, including fracturing and leakage of tanks. According to the logic model predicting the consequences of chemical release suggested by CCPS, four possible primary scenarios led to an accident, including tank leakage and formation of vapor cloud explosion (VCE), tank fracture and creation of fireball, tank leakage and formation of jet fire, and tank leakage and creation of pool fire.

2.2. Determining Escalation Vectors. Events that cause high-energy release led to a set of propagated and harmful accidents of domino type that usually occur due to damage to atmospheric or pressurized industrial equipment. The intensity of each escalation vector depends on total energy (or substance) that is probability released from the primary system (reactor, storage tank, etc.). The primary scenario is the main factor in the severity assessment of each escalation vector. Escalation vectors and radius for primary scenarios are indicated in Table 1. This table shows experimental results if studying more than 100 domino effects [25, 26].

2.3. Damage Threshold and Determining Safety Distance. The minimum distance defined as a suitable metric standard to minimize escalation hazards is called the safety distance, while the probability of escalation effects is taken into account [27]. Given that a minimum distance between separating units is required to prevent the escalation effect, this distance can be determined according to the damage threshold. Threshold values employed in the categorization of process equipment in the present approach are determined by reviewing past accidents and equipment damage models. This Table 1 is the results of analyzing more than 100 domino effects studied and assessed by Cozzani et al. [25].

In accidents where the fire is the primary scenario and damage is likely to propagate to other units (secondary), radiation can damage the target unit. Accordingly, the intensity of the escalation vectors depends on fire features which rely on fire scenario parameters.

Table 1: Escalation vectors for categorization of different primary scenarios and intensity assessment criteria of escalation vectors

Primary scenario	Escalation vector	Equipment category	Threshold value	Escalation vector
Fireball	Heat radiation	Atmospheric pressurized	15 kW/m^2 50 kW/m^2	Fireball radius
Jet fire	Heat radiation	Atmospheric pressurized	15 kW/m^2 50 kW/m^2	The distance at which heat radiation equals the threshold value
Pool fire	Heat radiation	Atmospheric pressurized	15 kW/m^2 50 kW/m^2	The distance at which heat radiation equals the threshold value
Vapor cloud explosion	Overpressure ($F \geq 5$; $M_f \geq 0.35$)	Atmospheric pressurized	22 kPa 16 kPa	The distance at which peak pressure equals the threshold value
BLEVE	Overpressure fragment projection	Atmospheric pressurized any	22 kPa 16 kPa Undefined	The distance at which peak pressure equals the threshold value Fragment projection Fragment impact Maximum projection distance
Mechanical explosion	Overpressure fragment projection	Atmospheric pressurized any	22 kPa 16 kPa Undefined	The distance at which peak pressure equals threshold value Maximum projection distance

Table 2: Safety distance for escalation.

Primary scenario	Escalation vector	Equipment category	Threshold value	Safety distance
Fireball	Heat radiation	Atmospheric pressurized	15 kW/m^2 50 kW/m^2	Fireball radius 0
Jet fire	Heat radiation	Atmospheric pressurized	15 kW/m^2 50 kW/m^2	Flame length + 50 m Flame length + 25 m
Pool fire	Heat radiation	Atmospheric pressurized	15 kW/m^2 50 kW/m^2	Pool border + 50 m Pool border + 15 m
VCE	Overpressure ($F \geq 5$; $M_f \geq 0.35$)	Atmospheric pressurized	22 kPa 16 kPa	$R = 1.75$ $R = 2.10$
BLEVE	Overpressure fragment projection	Atmospheric pressurized any	22 kPa 16 kPa Undefined	$R = 1.80$ $R = 2.10$ Undefined
Mechanical explosion	Overpressure fragment projection	Atmospheric pressurized any	22 kPa 16 kPa Undefined	$R = 1.80$ $R = 2.10$ Undefined

Damages caused by explosion waves in process equipment originated from mixed interactions, such as pressure wave reflection, flow separation, tensile forces, and mechanical forces. On the other hand, damages to equipment far distances generally depend on overpressure peaks and positive impulse in industrial explosions, while tensile forces can be neglected. In addition, most of approaches related to the damage severity have been calculated at the maximum pressure peak. According to Table 1, the distance obtained in threshold is a scale to escalation vectors for each overpressure scenario. Safety distances can easily be calculated using the proposed model.

The primary scenario is crucial in assessing escalation vectors and safety distance according to the above cases. A separate subject is addressed regarding inherent safety distances in Table 2.

2.3.1. Inherent Safety Distances for the Fireball Scenario. The fireball scenario is related to pressurized gases liquefaction, though it is also possible for the pressurized gases. The fireball duration is normally limited (5–20 s), though the radiation effects of the fireball are taken into consideration in this section. The escalation vector intensity depends on the fireball size, which is estimated using Equation (1) [28]:

$$R_c = 2.9\, \mathrm{m}_f^{(1/3)}. \quad (1)$$

R_c is the fireball radius (m), and m_f is the tank content (kg). Equation (1) provides the required separation distances or the inherent safety distances to prevent damage spread to the atmospheric equipment.

2.3.2. Inherent Safety Distances for the Jet Fire Scenario. In the jet fire, the escalation vector intensity depends on the flame length maximum by assuming the distance between the ignition source and the escalation location as the maximum distance.

In the first step, the jet fire diameter is as follows:

$$D_{eq} = D_o \sqrt{\frac{\rho_o}{\rho}}, \tag{2}$$

D_o is the hole diameter (m); ρ is the leaking material density (kg/m^3); ρ_o is the ambient air density (kg/m^3).

Since the CFD is a conventional method for calculating the fire parameters, the researchers have used various methods to solve these equations. Thereby, here, the least-squares numerical method, which is a common method in solving problems and mathematical equations, which is used due to simplicity in this study. Therefore, the flame length and height in the jet fire are as follows:

$$\log(\mathrm{H}_{\text{flame}}) = 1.24 + 0.21(\log(m^0)) + 0.68(\log(\mathrm{D}_{equ})), \tag{3}$$

$$\log(\mathrm{L}_{\text{flame}}) = 1.18 + 0.35(\log(m^0)) - 0.04(\log(D_{equ})), \tag{4}$$

$m^0$is the spread rate based on kg/s. Since this parameter is generally obtained empirically through the experiments, it has been assumed to be 10 kg/s.

2.3.3. Inherent Safety Distances for the Pool Fire Scenario. Even though escalation due to pool fire is usually the consequence of the unit involved in the flames, constant radiation makes it possible for the flame to escalate as the damage spreads beyond the target tank. Therefore, the escalation vector intensity is related to a pool fire region and the distance of the fire surface. Also, the spread possibility depends on the radiation intensity and fire duration. The inherent safety distances may be defined based on the distance from the pool edge: as an illustration, 50 m from the pool edge in the atmospheric equipment and 15 m from the pressurized equipment. In order to calculate the pool diameter, we can use the following equation:

$$\frac{H}{D} = 42 \times \left(\frac{\dot{y}}{\rho_a \sqrt{gD}}\right)^{0.61}, \tag{5}$$

where D is the liquid pool diameter which is in meter, $\dot{y}$ is the material mass combustion rate per area unit (kg/m^2· s), and ρ is the material density (kg/m^3).

The material combustion rate is calculated using Equation (6):

$$\dot{y} = 1.27 \times 10^{-6} \rho \frac{\Delta H_C}{\Delta H^*}, \tag{6}$$

ΔH^* is the required heat for the evaporation of 1 kg of material (kJ/kg):

$$\Delta H^* = \Delta H_V + \int_{\mathrm{T}_S}^{\mathrm{T}_{BP}} \mathrm{C}_P \mathrm{dT}, \tag{7}$$

where ΔH_V (kJ/kg) is the latent heat of evaporation of the material, C_p (kJ/kg) is the heat capacity of the material, T_{bp} (°C) is the normal boiling point of the material, T_s (°C) is the ambient temperature, and L_V is the specific latent heat.

2.3.4. Inherent Safety Distances for the Vapor Cloud Explosion (VCE). The escalation vector intensity regarding the VCEs is related to the explosion wave, depending on the distance from the excessive pressure, which is equivalent to the threshold values for the damage via overpressure. The estimated explosion energy or the explosion strength is calculated using the QRA approximation.

It should be noted that these calculations of propagating cloud include (1) semispherical, homogeneous, and stoichiometry concentration and (2) the combustion energy average, which was considered from the combination of the hydrocarbon fuel, and it is equivalent to 3.6 MJ/m^3. In brief, the safety distance is calculated according to Table 2.

2.4. Determining the Hazard Indexes. In order to define the distances of the provided inherent safety escalation above, we can define a set of indexes for defining hazards escalation. Although complex analyses are needed for damaging the equipment via various physical effects, we can simply display the hazard escalation by using this set of objective indexes. In this study, the indexes are defined as follows.

The domino chain potential (DCP) index that was defined as the affected regions of the escalated impacts is calculated based on the escalation vector intensity using Equation (8):

$$\mathrm{DCP}_i = \pi \begin{pmatrix} \mathrm{p}_i, \mathrm{t}_i \\ \max(\mathrm{D}_{\mathrm{ISh},i,j}) \\ h, j = 1 \end{pmatrix}^2, \tag{8}$$

DCP_i is the domino chain potential index for the ith initial unit, and $D_{ISh,i,j}$ is the inherent safety for the hth scenario concerning one type of objective jth. In order to determine the worst state, the maximum inherent safety distance should be chosen from the items below:

(i) The p_i probable scenarios with the probability that the ith unit is a potential trigger;
(ii) The t_i possible types from the objective unit which is probable to play a role in the scenario.

The DCP index thus denotes a leading indicator of the domino hazard potential of the unit making the escalation vector. Indeed, this index is a preliminary screening identifying the potential domino hazard sources among the most hazardous escalation sources (the units that have more hazards in initiating an escalating incidence).

In order to evaluate the escalating hazard between two units, the *domino chain actual DCA hazard index* was defined:

Table 3: List of storage tanks considered in the case study.

Storage tank ID	Substance	Type	Volume (m^3)	Inventory (ton)
1	C5+	Atmospheric	10,000	6,304
2	C5+	Atmospheric	10,000	6,304
3	Propane	Atmospheric	52,000	30,117
4	Butane	Atmospheric	26,000	15,621
5	Propane	Atmospheric	52,000	30,117
6	Butane	Atmospheric	52,000	31,200

$$\mathrm{DCA}_{h,i,j} = \frac{\mathrm{D}_{\mathrm{ISh},i,j}}{D_{i,j}}.\alpha_{h,i}, \quad (9)$$

$\mathrm{DCA}_{h,i,j}$ is the hazard index for the *h*th preliminary scenario from the *i*th unit with the assumption that there is a trigger domino surrounding *j*th unit.

$\mathrm{D}_{\mathrm{ISh},i,j}$ Is the inherent safety distance for *h*th scenario, $D_{i,j}$ is the actual separation distance between the i unit and j unit, and $\alpha_{h,i}$ is the inventory parameter of the *h*th scenario.

The inherent safety distance for the hth scenario ($D_{IS\ h,\ i,\ j}$) will be calculated by using the explained approach above; the determined data and the actual distance of the equipment ($D_{i,\ j}$) will be calculated by having the plan design. Suppose the separation distances and the plan designs are unavailable (as an illustration, the preliminary plan design steps). In that case, the conventional safety distances are used to estimate the expected hazard chain. These scales are investigated and determined based on real experiments and incidents. These distances are reported in several studies, i.e., Cozzani et al. [25].

The inventory parameters $\alpha_{h,i}$ are considered in calculations for some of the preliminary scenarios where their hazard escalation depends on the inventory and the preliminary unit equipment.

In jet fires or pool fires, the minimum time is required to reach secondary targets and damage them, and domino accidental events occur. Accordingly, a material or critical inventory is the minimum amount of flammable substance that fire could not propagate to secondary targets and cause damage. Therefore, the inventory parameter for jet and pool fires according to the inventory *j*th unit, critical inventory for the hth escalation scenario, is defined by Equation (10):

$$\alpha_{h,i}\begin{Bmatrix} 1 + \log_{10}\left(\dfrac{I_{\mathrm{i}}}{\mathrm{CI}_{h,i}}\right) & \text{if } \mathrm{I}_i \geq \mathrm{CI}_{h,i} \\ 1 & \text{if } \mathrm{I}_i < \mathrm{CI}_{h,i} \end{Bmatrix}. \quad (10)$$

For all other scenarios with no critical parameter, $\alpha_{h,i}$ is considered equal to 1.

In order to obtain more brief expressions of critical primary units concerning domino damages in a certain plan, a unit *domino actual hazard index* (UDI) is defined according to Equation (11):

$$\mathrm{UDI}_i = \sum_{j=1}^{\mathrm{u_i}} \max_{h=1}^{\mathrm{m}_i} \left(\mathrm{DCA}_{h,i,j}\right), \quad (11)$$

u_{i} is the total number of considered units for possible escalation caused by the *i*th unit, and m_{i} is the total number of primary escalation scenarios of the *i*th unit, which is likely to trigger escalation.

The UDI index ranks escalation sources according to higher hazards in a plant.

TDI is the *target domino hazard index* and is similar to UDI, except that it is focused on the domino target and can be calculated by Equation (12):

$$\mathrm{TDI}_j = \sum_{\mathrm{i}=1}^{q_j} \max_{h=1}^{\mathrm{m}_i} \left(\mathrm{DCA}_{h,i,j}\right), \quad (12)$$

TDI_j is the target domino hazard index defined for *j*th target. q_j Is the total number of units considered for possible escalation scenarios of the *j*th unit as a target, which is defined in the UDI Equation. This index is assessed for a target unit during a plan in actual hazard screening. Higher values of TDI are calculated for the majority of primary scenarios on which escalation to the target unit depends. Accordingly, target ranking is employed for target units for which the probability of accidental domino events is higher so that units requiring active and passive protection for prevention of escalation are identified. It is evident that TDI can also be calculated for external units (e.g., in adjacent industrial units) to assess escalating hazards around other facilities.

2.5. Findings. As indicated in Figure 1, six tanks are studied in this research, among which four are under operation and two others are under construction. Material type and level of content are cited in Table 3. Besides, Table 4 indicates the distance and exact position of tanks from each other in terms of m.

Due to the dependence and relationship between escalation vectors to primary scenarios, the primary scenario is first determined. Besides, as mentioned earlier, this issue is determined experimentally according to information gathered by researchers in previous studies. The inherent safety distance is calculated after determining the escalation vector according to the relevant scenarios. The results pertinent to safety distances and details of scenarios considered for each

Table 4: Separation distances between storage tanks.

Storage tank ID (m)	Storage tank (1)	Storage tank (2)	Storage tank (3)	Storage tank (4)	Storage tank (5)	Storage tank (6)
1	—	28	127	209	97	158
2	28	—	74	155	75	114
3	127	74	—	28	97	70
4	209	155	28	—	155	98
5	97	75	97	155	—	27
6	158	114	70	98	27	—

Table 5: Assumed scenarios considered and calculated for inherent safety parameters for each storage tank.

Storage tank ID	Primary scenario	Physical effect	Safety distance	$D_{IS,A}$ (m)	$D_{IS,p}$ (m)	CI (T)	α
1	Fireball	Heat radiation	Fireball radius	535.7	0	Undefined	1
2	Jet fire	Heat radiation	Flame length + 50 m	50.12	25.12	Undefined	1
3	Jet fire Fireball	Heat radiation	Flame length + 50m Fireball radius	150 902	25.07 0	Undefined	1
4	Fireball	Heat radiation	Fireball radius	725	0	Undefined	1
5	Pool fire	Heat radiation	—	52.2	17.2	Undefined	1
6	VCE	Overpressure	—	1.75	2.10	Undefined	1

tank are provided in Table 5. The radius of fireball for tank (1) containing 6,304-ton material is calculated according to Equation (1). It is assumed that the radius of fireball is equivalent to inherent safety distance. Accordingly, the inherent safety distance for fireball is calculated as follows:

$$R_C \approx D_{IS} = 2.9(m_t)^{\frac{1}{3}} = 2.9(6{,}304{,}000)^{\frac{1}{3}} = 535.7 \text{ m}. \tag{13}$$

It should also be noted that the escalation vector for atmospheric and pressurized equipment are not equivalent. Given that the tanks being studied are atmospheric, only the escalation vector of atmospheric tanks is calculated. In pool fire, the inherent safety distance with fire boundary is considered + 50. For instance, for tank (5) containing 30,117,000 kg propane, the pool radius is calculated as follows:

$$\begin{aligned}\Delta H^* = \Delta H_V + \int_{T_S}^{T_{BP}} C_P dT = 356 \text{ kJ/kg}\\ + \int_{35}^{-42} C_P dT = 356 \text{ kJ/kg} + 30{,}117{,}000\\ \times \frac{1.68 \text{ kJ}}{\text{kg.K}}(-42-35)\text{K} = 4\times 10^{10}.\end{aligned} \tag{14}$$

The next step is to calculate the burning rate of the liquid thick in the pool. The burning rate of material is calculated according to Equation (6):

$$\begin{aligned}\dot{y} &= 1.27\times 10^{-6}\rho\frac{\Delta H_C}{\Delta H^*}\\ &= 1.27\times 10^{-6}\times 2.01(\text{kg/m}^3)\times\frac{50.35\times 10^3\left(\frac{\text{kJ}}{\text{kg}}\right)}{4\times 10^{10}\left(\frac{\text{kJ}}{\text{kg}}\right)}\\ &= 3.2\times 10^{-12}\left(\frac{\text{kg}}{\text{m}^2}.\text{s}\right).\end{aligned} \tag{15}$$

The third step is to calculate the diameter of the burning pool. Pool diameter is calculated through Equation (5):

$$\frac{H}{D} = 42\times\left(\frac{\dot{y}}{\rho_a\sqrt{gD}}\right)^{0.61} \xrightarrow{H=2D} D \approx 2.2 \text{ m}. \tag{16}$$

It is assumed that in the pool fire, inherent safety distance is equivalent to pool diameter, meaning +50 m, in atmospheric equipment. Accordingly, the inherent safety distance in pool fire for tank (5) is obtained to be approximately 52.2 m. The inherent safety distance for jet fire in tank (3) containing propane is calculated in several steps listed as follows. In the first step, the diameter of the jet fire is determined according to Equation (2):

$$D_{eq} = D_o\sqrt{\frac{\rho_o}{\rho}} = 80\times 10^{-3}\times\sqrt{\frac{1}{493}} = 3.6\times 10^{-3} \text{ m}. \tag{17}$$

Therefore, flame length and height in the jet fire are calculated according to Equations (3) and (4):

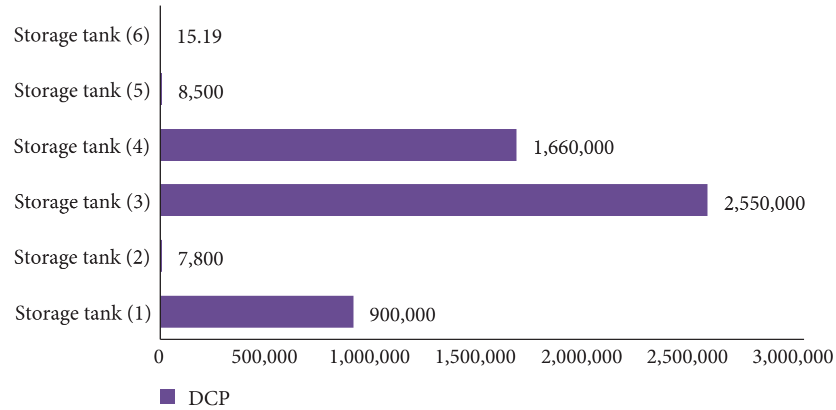

Figure 3: Domino chain potential (DCP) index for the storage tanks considered in the case study.

Table 6: Values of the domino chain actual hazard index (DCA) for the storage tanks considered in the case study.

Primary unit	Primary scenario	Target unit					
		Storage tank (1)	Storage tank (2)	Storage tank (3)	Storage tank (4)	Storage tank (5)	Storage tank (6)
Storage tank (1)	Fireball	—	19.1	4.2	2.5	5.5	3.4
Storage tank (2)	Jet fire	1.79	—	0.67	0.32	0.6	0.43
Storage tank (3)	Jet fire	0.39	0.67	—	1.78	0.51	0.71
	Fireball	7.1	12.2		32.2	9.2	12.9
Storage tank (4)	Fireball	3.4	4.7	25.9	—	4.7	7.4
Storage tank (5)	Pool fire	0.54	0.7	0.54	0.34	—	1.93
Storage tank (6)	Vapor cloud explosion	0.01	0.01	0.02	0.02	0.06	—

$$m \approx 14\ \log(H_{\text{flame}}) = 1.24 + 0.21(\log 30, 117, 000)) -0.68(\log(0.0036)), \tag{18}$$

$$\log(L_{\text{flame}}) = 1.18 + 0.35(\log(30{,}117{,}000)) -0.04(\log(0.0036)) \approx 50\ \text{m}. \tag{19}$$

In a jet fire, the inherent safety distance for tank (3) containing propane is +50 m flame long. Accordingly, the inherent safety distance for tank (3) is 150 m. Table 5 indicates the results obtained by calculating the inherent safety distance for each assumed scenario pertinent to each tank.

2.6. Calculating the Hazard Index and Determining the Critical Tank. The DCP index is obtained according to inherent safety distance using Equation (8). For instance, DCP for tank (3) is calculated as follows:

$$\begin{aligned} \text{DCP}_{(3)} &= \pi \left(\begin{matrix} p_{(3)}, t_{(3)} \\ \max\left(\text{D}_{\text{ISh},(3),j}\right) \\ h, j = 1 \end{matrix} \right)^2 \\ &= \pi\,(\max\,(150; 25.07; 902; 0))^2 \\ &= \pi\,(902)^2 = 2.55 \times 10^6 \text{m}^2. \end{aligned} \tag{20}$$

The results obtained by calculation of the DCP value of each unit are indicated in Figure 3. DCP values for units are ranked according to the potential of the domino effect, regardless of the position, actual location, and inherent safety distance.

Accordingly, the DCP index can be used as a primary screening in escalation hazards. In this study, tank (3) is considered the most critical unit.

According to the inherent safety design and content parameter, and also the data in Table 4 that are separation distances, the values of UDI, DCA, and TDI are calculated. According to Equation (9), the DCA value is calculated for both tanks (3) and (4) as follows:

$$\text{DCA}_{\text{fb},3,4} = \frac{\text{D}_{\text{ISfb}3,4}}{\text{D}_{3,4}} \cdot \alpha_{\text{fb},3} = \frac{902}{28} \times 1 = 32.2. \tag{21}$$

Results obtained by calculation of the DCA value for both tanks are indicated in Table 6.

Indeed, the DCA index ranks and determines the escalation scenarios that are likely to happen in both units and tanks. For instance, the DCA values for tank (6) with the stochastic scenario of vapor cloud for each tank is less than 1. Indeed, when this scenario happens, simultaneous escalation

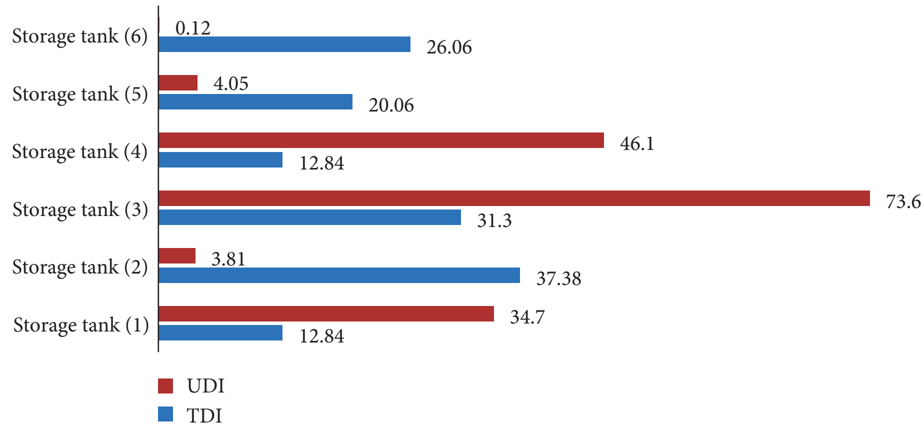

FIGURE 4: Domino hazard indices (UDI and TDI) for the storage tanks considered in the case study.

of tank (6) and any other tank is not possible, and this tank is not included in case a crisis happens in this scenario. On the other hand, the DCA value for tank (3) with the fireball scenario is always higher than 1. Accordingly, none of the tanks are safe in this inherent position map if this scenario happens. In summary, if the fireball scenario happens for tank (3), none of the inherent tanks are safe, and this unit is considered critical. It must be noted that the primary scenarios are selected randomly at the beginning. For instance, a fireball scenario in pressurized atmospheric tanks under the studied conditions is extremely rare. However, in order to obtain more acceptable results, it seems that all scenarios must be taken into account. Regardless of all primary calculations in simulation, an attempt is made to analyze more realistic scenarios. Accordingly, the jet fire scenario will be addressed in the following, which is considered as the scenario of a more critical unit [3] at the beginning. Another point is that the software results were employed as data in the indexing process to obtain more acceptable and accurate results. It is because data obtained by software are more accurate than analytical data, and more items are involved in obtaining software results, while process analytical calculations are simpler and more general.

Equations (11) and (12) are used to calculate UDI and TDI, respectively. For instance, the UDI index for tank (3) is calculated as follows:

$$\begin{aligned} \mathrm{UDI}_{(3)\mathrm{tank}} &= \sum_{j=1}^{u_{(3)}} \underset{h=1}{\overset{m_i}{\max}}\left(\mathrm{DCA}_{jf,(3),j};\mathrm{DCA}_{fb,(3),j}\right) \\ &= \max(0.39; 7.1) + \max(0.67; 12.2) \\ &\quad + \max(1.78; 32.2) + \max(0.51; 9.2) \\ &\quad + \max(0.71; 12.9) = 73.6. \end{aligned} \tag{22}$$

Accordingly, other values for UDI are also calculated. Besides, the TDI for tank (3) is calculated as follows:

$$\begin{aligned} \mathrm{TDI}_{(3)} &= \sum_{i=1}^{q_{(3)}} \underset{h=1}{\overset{m_i}{\max}}\left(\mathrm{DCA}_{h,i,3};\mathrm{DCA}_{h,i,j}\right) \\ &= 4.2 + 0.67 + 25.9 + .54 + 0.02 = 31.33. \end{aligned} \tag{23}$$

Figure 4 indicates the results obtained by calculating the UDI and TDI.

The UDI (a case study tank) represents a unit's capacity to damage target units or other tanks and create a domino effect. In the case study, this value must be less than 6. Similar to UDI, TDI must also be less than the total number of units. Thereby, according to the results, Figure 3 demonstrates more critical resources of a domino effect for both capacity and capability of damage target units and the number of vulnerable targets. As shown, tank (3) with maximum UDI is the primary fireball scenario, and jet fire is the most critical tank in the harmfulness and starting a domino effect. Tank (2) with maximum TDI is the most critical target unit in the exposure to escalation effects.

3. Conclusion

In the last few decades, domino incidents have been studied and analyzed by researchers from various aspects. In this study, the inherent safety model was used, which is a framework for determining the safety intervals of process industries. This model is defined based on hazard indicators. These indicators can be used as a criterion to assess the probability of the domino phenomenon.

To investigate the possibility of domino effects, after determining the location map, separation distances and specifications of each tank were determined. A list of possible scenarios was considered for each of the tanks, and inherent safety distances were calculated using related mathematical equations. DCP, DCA, UDI, and TDA parameters called hazard index parameters were calculated as domino probability criteria.

The most critical unit was determined according to the determined DCP index. Based on the DCA index, the critical units were determined with DCA values greater than one. In the event of an accident (tank 3 containing propane), there is a possibility of the initiation of a domino with the default scenario. Values smaller than one with default scenarios display low-risk units that are not prone to a domino effect.

In this study, tank 6 was identified with the hypothetical scenario as the least dangerous unit in the initiation of a domino in the event of an accident. After determining the UDI and TDA indices, the most critical unit with the hypothetical scenario was determined as unit 3.

Indicators, respectively, indicate the risk of injury due to the launch of a domino accident from the mentioned unit to other units and the risk of injury due to the launch of a domino from other units to the unit. If the UDI values (worst case scenario) are the same, the TDI index can be used to determine the most critical unit. The use of the technique to case study showed that the set of hazard indexes provided valuable data on the potential hazard of escalation events.

Data Availability

The data used to support the findings of this study can be obtained from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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