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Optimal layout of additional facilities for minimization of domino effects based on worst-case scenarios

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Abstract−Accidents involving domino effects are more serious than other type of accidents. Although there have been studies on such accidents, it is still difficult to examine the actual factors and causes since the domino effect is influenced nonlinearly by factors involving flame, overpressure, and flying objects. We considered the case of adding new facilities to an existing system in a given site. The layout of new facilities suggests positions that minimize the domino effects, based on nonlinear optimization taking domino factors into account. We quantitatively calculated the domino risk of each facility through the concept of combined domino factors (flame, overpressure, and missile). Also, we identified variations of domino damage extent of the target system through comparison of the impacts of domino effect when additional facilities were installed. Simulated annealing was adopted for searching optimal positions. As a case study, we applied the proposed method to the case of adding DME storage tanks in the existing LPG charging facilities. The presented framework of the quantitative assessment of domino risk and safety standard for the layout of additional facilities would be useful for proper layout design for improved accident prevention.

Key words: Domino Effect, Domino Factors, Optimal Layout, Simulated Annealing

INTRODUCTION

1. Research on Domino Effect

A fire/explosion/missile load generated by a single accident in an industrial site can cause secondary and higher order accidents in other units [1]. This situation is known as a “domino effect.” The representative accident is an LPG explosion accident at Mexico City in 1984 (Deaths: 650, Injuries: 6400). This accident occurred because an 8 inch pipe connecting spheres had ruptured, and the escaping gas formed a cloud covering an area of 200 m*150 m. The cloud then drifted towards a flare tower, caught fire and precipitated the BLEVE. This led to the failure of one vessel after another, with most exploding vessels causing nearby vessels to fail. A block of 200 houses built mostly of wood, cardboard, and metal sheets was demolished by these fireballs. Masses of fragments of tanks and pipes, some of them weighing 40 ton, were blown into air and landed as far as 1,200 m away [2]. In Korea, there was an explosion accident of an LPG charging station at Bucheon in 1998 (Death: 1, Injuries: 83, Property damage: 10 million dollars). The direct cause of the incident was concluded as the faulty joining of the couplings of the hoses in the butane unloading process from the tank lorry into the underground storage tank. Before the BLEVE (boiling liquid expanding vapor explosions) occurred, the released butane caused a pool fire that was ignited by an unknown ignition source. During 20 min, about 4.5 tons of butane was released and burned, heating up nearby LPG cylinders and two tank lorries parked at the unloading area [3]. Accidents involving the domino effect caused tremendous damage, but scant research has been performed due to its low occurrence frequency. Although numerous studies have been reported, they seldom give any advice or guidelines designed for preventing the domino effect and properly mapping the specific locations of each facility, because most researches on domino effects have focused on analysis after the accident [4].

Safety aspects have been considered, so far, in a rather simplified way by allocating equipment items with respect to the minimum allowable distances between them [5]. Among previous studies, Lee et al. proposed a guideline designed for preventing the domino effect in building explosive facilities [4]. Lee et al.’s paper suggests the positions that can minimize the domino effect using a nonlinear approach and a computer-aided module [4], but has limitation in applications because of insufficiency of considerations of domino factors (fire, pressure, and missile) and assuming the same risk of all facilities. Recently, the methodologies based on the index-approach were proposed to solve optimal layout considering safety factors [6,7]. Index approach suggested good guidelines in this area. But, this method has the problem of subjectivity, results reappearance, and easy-to-use because use factors have a qualitative or semi-quantitative feature. Thus, there is need for an approach combining facilities layout and quantitative risk assessment.

Aforementioned researches focused on generating a safe layout for the design of new process plants. However, revamping and modifications of process plants or existing facilities are more prevalent, e.g., upgrading of existing LPG stations into DME-LPG stations. In that case, this research suggests a systematic way to design inherently safer configurations by finding out optimal locations of new equipments installed in the existing configurations.

2. Theoretical Background

2-1. What is the Domino Effect?

Article 8 of the Seveso II Directive 96/82/EC uses the term “dom-

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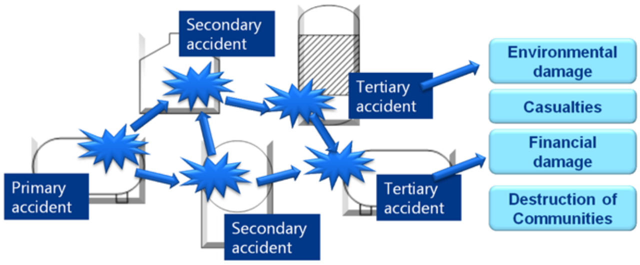

Fig. 1. Scheme of domino effect.

Table 1. Accidental events related to the domino effect [10]

Domino factor	Accidental event
Heat radiation & Fire impingement	Pool fire, Jet fire, Flash fire, Fireball, VCE (vapor cloud explosion)
Overpressure	Condensed phase explosion, Confined explosion, Physical explosion, BLEVE (boiling liquid expanding vapor explosions), VCE
Fragment projection	Condensed phase explosion, Confined explosion, Physical explosion, BLEVE

ino effects" to denote the existence of "establishments or groups of establishments where the likelihood and the possibility or consequences of a major accident may be increased because of the location and the proximity of such establishments, and their inventories of dangerous substances." Control of Major Accident Hazard (COMAH) of UK defined the domino effect as "a loss of containment incident on a major hazard installation which has resulted either directly or indirectly from a containment incident at an adjacent or nearby major hazard installation. The two events must occur either concurrently or in close sequence and the hazard range from the domino event must extend beyond that of the initiating event." The generalized definition provided by the AIChE-CCPS as "an incident which starts in one item and may affect nearby items by thermal, blast or fragment impact," causing an increase in consequence severity or in failure frequencies [8].

Current safety research has led to a variety of methodologies to assess the significance of domino effects at hazard sites. The factors relevant to domino escalation and various direct and indirect mechanisms for obtaining a domino accident (caused by the domino effect) have been determined [4]. From the definition, we know that the domino effect is triggered by three main types of primary accidents such as flame (thermal effect), overpressure (pressure effect), flying objects (missile effect), or a combination of those. Toxic release was excluded from the present analysis because this physical effect does not result directly in a loss of containment or in the damage of secondary equipment [9].

2-2. Simulated Annealing

SA is a method for solving unconstrained and bound-constrained optimization problems. The method models the physical process of heating a material and then slowly lowering the temperature to decrease defects, thus minimizing the system's energy.

At each iteration of the simulated annealing algorithm, a new point is randomly generated. The distance between the new point and the current point, or the extent of the search, is based on a probability distribution with a scale proportional to the temperature. The algorithm accepts all new points that lower the objective, but also, with a certain probability, points that raise the objective. By accepting points that raise the objective, the algorithm avoids being trapped in local minima, and is able to explore globally for more possible solutions. An annealing schedule is selected to systematically decrease the temperature as the algorithm proceeds. As the temperature decreases, the algorithm reduces the extent of its search to converge to a minimum [10]. Herein, we used the SA in the optimization toolbox, part of the MATLAB package.

PROPOSED ANALYSIS TECHNIQUE

1. Overall Framework

This research focused on arranging additional facilities on a rectangular site with already existing industrial facilities. The problem is to determine the optimal location of each additional facility while minimizing domino effects. The factors are considered the three major causes of domino effects and distances between facilities. We calculated domino factors (flame factor, overpressure factor, and missile factor) based on worst-case scenarios for a quantitative representation of facilities' risk.

The cause of a domino effect can be determined by various influences: material quality of facilities, nearby environment, meteorological conditions, and so on. In this research, only the three major factors (flame, overpressure, and missile) causing a domino effect was considered so as to minimize the influence of uncertainty. However, in the case of the safety device and type of target equipment, we considered as weight and standard because these factors can quantify through literature and calculation. Safety devices have been divided into fire (active: fire sprinkler and water curtain, Passive: thermal insulation and fire wall) and pressure (active: form sprinkler, passive: Barricade, pressure relief valve, and blast wall) protection measures.

We selected well-known standards for simplification of the methodology. Cozzani et al. proposed escalation criteria according to type of target equipment (see Table 2). If we know the required in-

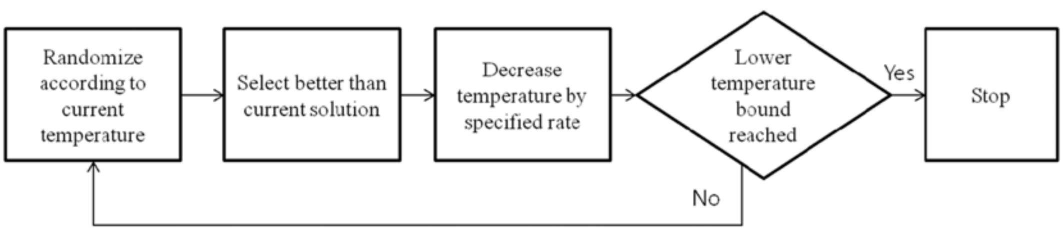

Fig. 2. The simulated annealing algorithm.

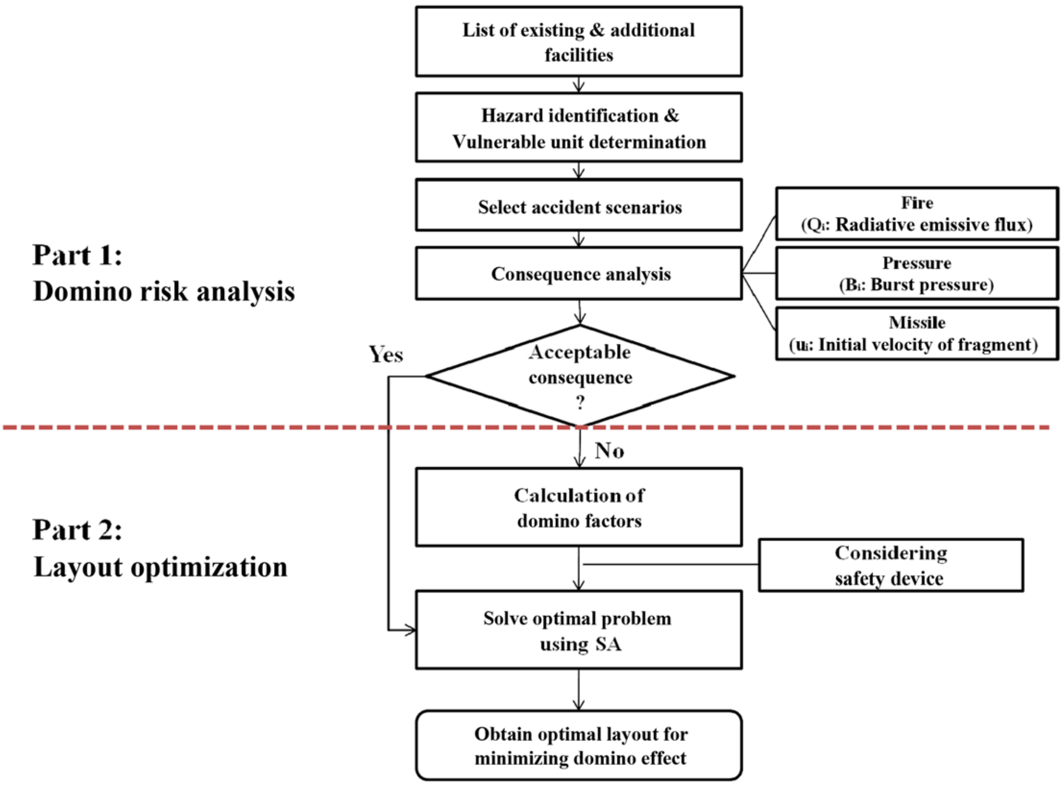

Fig. 3. Proposed algorithm.

formation about target equipment, we will use Cozzani's criteria. But, if we do not have the required information about target equipment, we will use general criteria using in the various software and literatures. Experimental studies have suggested that a heat load of 37 kW/m^2 is sufficient to cause damage in other installations operating under normal operating conditions. A study of past accidents suggests that an overpressure of 0.7 atm is necessary to cause damage and fatality. A velocity higher than 75 m/s has sufficient potential to penetrate the target unit provided that it collides with the unit [1].

The proposed algorithm consists of two steps (see Fig. 3): first, analysis of domino risk on existing and additional facilities, and second, search the optimal layout using SA and domino factors. The procedure includes the following steps:

1-1. Domino Risk Analysis

(1) Perform hazard identification on the existing facilities and additional facilities using the past accident DB [2,11,12] or selection of pertinent process units based on DOW Fire&Explosion index [13].

(2) Select feasible accident scenarios for the vulnerable equipment likely to impact a potential domino effect using ETA (event tree analysis) and perform the consequence analysis about each scenario. Herein, we assumed to generate rupture or large leak size (50-150 mm) as worst-case scenarios. In the case of fire scenario, we considered fireball, pool fire, and jet fire. In the case of flash fire, we did not consider as domino factor because the domino accidents by flash fire were not recorded [14]. And we selected the maximum value among these scenarios. In the case of overpressure and missile, we calculated the burst pressure of the facilities and the initial velocity of fragment based on m_{TNT} regardless accident scenarios.

(3) Determine whether consequence analysis exceeds the standard of domino effect (refer to Table 2 or if specific criteria do not have this table, refer to radiation>37.5 kW/m^2, overpressure>0.7 atm, and initial velocity of fragment>75 m/s) or not.

1-2. Layout Optimization

(4) Calculate the domino factors on flame, overpressure, and missile using the suggested formulation in section 3. The value of flame factors' domino risk is emissive power. The value of overpressure's domino risk is the initial burst pressure. The value of missile factors' domino risk is the initial velocity of fragments. And, safety devices can be considered to mitigate the domino effect as multiplied with factors of domino risk.

(5) Search optimal coordinates using SA based on the domino factors and distance.

Table 2. The specific escalation criteria for various primary scenarios [9]

Scenario		Target equipment category	Escalation criteria
Fire	Fireball	Atmospheric	100 kW/m^2
	Jet fire	Atmospheric	15 kW/m^2
		Pressurized	40 kW/m^2
	Pool fire	Atmospheric	15 kW/m^2
		Pressurized	40 kW/m^2
Overpressure		Atmospheric	0.22 bar
		Pressurized	0.31 bar

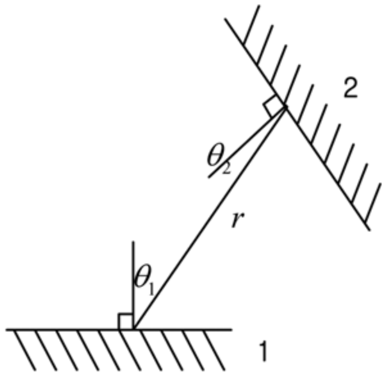

Fig. 4. Relationship between the distance and the emissive flux.

2. Domino Factors

Lee et al. [4] obtained the optimal layout with the assumption that each facility has an equal risk. However, this approach had limitations to site real application. Herein, we calculate the domino factors based on the function of consequence (potential domino risk) and probability (influencing probability according to distance). The proposed methodology quantitatively calculates the risk of each facility through the concept of domino factors and improves the site application.

2-1. Flame Factor (F)

Thermal effect modeling is widely used in chemical plant design and quantitative risk assessment [4]. In thermal effects, it has been reported that the radiation transferred between two parallel surfaces is proportional to $1/r^2$ by assuming 2-dimensional space and that $\theta_1=\theta_2$.

$$F \propto \frac{1}{r^2} \qquad (1)$$

where r is distance between facilities.

The potential flame risk of facilities is represented by an emissive power (Q) and divided into three models (fireball, jet fire, and pool fire). Specific calculation procedure for flame factor is presented in Fig. 5.

where R_f: radiative fraction of the heat of combustion
0.3 for vessels bursting below the relief of set pressure
0.4 for vessels bursting at or above the relief set pressure
D_{fmax}: maximum diameter (m)=$5.8m_f^{1/3}$
t: duration (s)
$0.45m_f^{1/3}$ for m_f<30,000 kg
$2.6m_f^{1/6}$ for m_f>30,000 kg

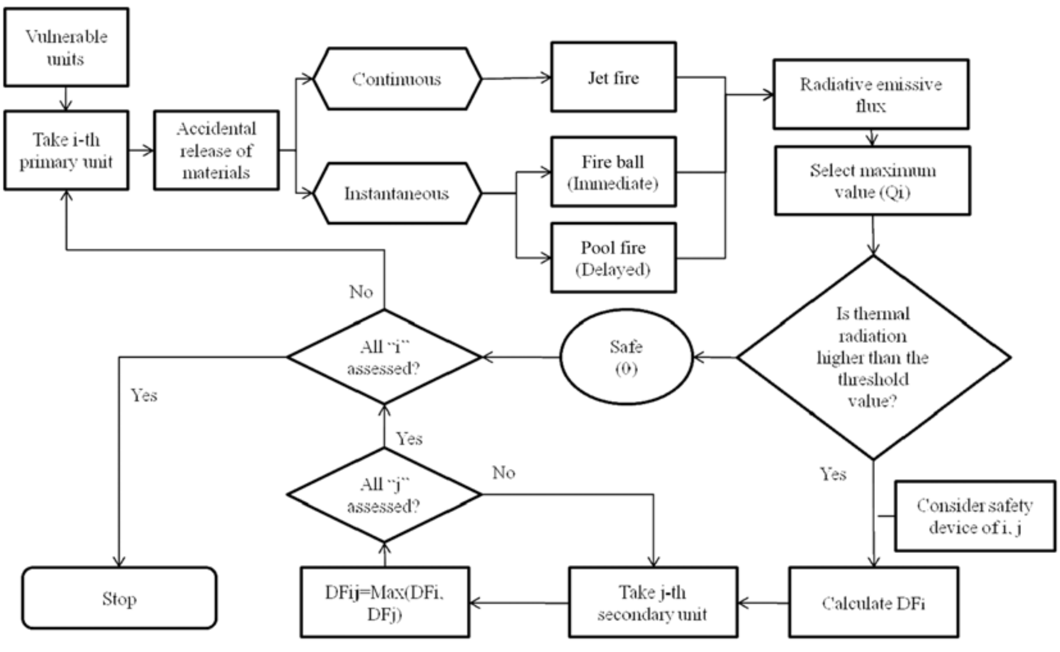

Fig. 5. Procedure for flame factor calculation.

Table 3. Equation for various fire scenarios

Scenario	Emissive flux	Effective distance of flame	Reference
Fireball	$Q=\frac{R_f m_f Hc}{\pi D_{fmax}^2 f}$	$r_{max}^2=\frac{2.2\tau_a RHcm_f^{2/3}}{4\pi_{criteria}}$	Roberts and Hymes [8]
Pool fire	$Q=\frac{\delta m_b HcS_p}{2\pi R_p L_f+S_p}$	$r_{max}^{0.09}=Q_{criteria}F_{view}2.02P_w^{-0.09}$	TNO pool fire model [16]
Jet fire	$Q=\frac{F_s m' Hc}{S_j}$	$r_{max}^{0.09}=Q_{criteria}F_{view}2.02P_w^{-0.09}$	Yellow book [16]

F_s: Fraction of the generated heat radiated from the flame surface$=0.21e^{-0.00323u_j}+0.11$

m′: mass flow rate (kg/s)

$$=C_d\rho_{ambient}A_h\sqrt{\frac{2p_{process}}{\rho_{process}}\times\frac{k}{k-1}\times\left[1-\left(\frac{p_{ambient}}{p_{process}}\right)^{(k-1)/k}\right]}$$

R_p: equilibrium radius of pool (m)$=\frac{D_{pmax}}{2}=\sqrt{\frac{v_L}{\pi y_L}}$

Lf: length of flame (m)$=84R\left[\frac{m_b}{\rho_1\sqrt{2gR}}\right]^{0.61}$

In this research, we propose a flame factor considering distance and emissive power (DF) between facilities. The first part of the equation below considers the flame effect between existing facilities (e) and (j). This part has a fixed value. The second part considers the flame effect between additional facilities (i) and existing facilities (j). The last part considers the flame effect between additional facilities. In other words, the layout of additional facilities is obtained from the minimum flame factor value (F), which is calculated in terms of distance and the emissive power relation of all facilities.

$$F=\sum_{i=1}^{m+n-1}\sum_{j=i+1}^{m+n}\frac{1}{r_{ij}^2}DF_{ij}=\left[\left(\Sigma_{e=1}^{m-1}\Sigma_{z=e+1}^{m}\frac{1}{r_{ez}^2}DF_{ez}\right)+\left(\Sigma_{a=1}^{n}\Sigma_{e=1}^{m}\frac{1}{r_{ae}^2}DF_{ae}\right)+\left(\Sigma_{a=1}^{n-1}\Sigma_{k=a+1}^{n}\frac{1}{r_{ak}^2}DF_{ak}\right)\right] \quad (2)$$

where F=flame factor

$I=E+A=\{1,\ldots,m\}+\{1,\ldots,n\}=\{1,\ldots,m+n\}$, $i\in I$, set of all facilities

$J=\{i+1,i+2,\ldots,n\}$ $j\in I$, set of all facilities

$r_{ij}=[(x_i-x_j)^2+(y_i-y_j)^2]^{1/2}$, rectilinear distance between i and j

$E=\{1,2\ldots,m\}$, $e\in E$, set of existing facilities

$Z=\{e+1,e+2,\ldots,m\}$, $z\in E$, set of existing facilities

$A=\{1,2\ldots,n\}$, $a\in A$, set of additional facilities

$K=\{a+1,a+2,\ldots,n\}$, $k\in A$, set of additional facilities

$DF_{ij}=\max(Q_i, Q_j)$

2-2. Overpressure Factor

The simple approach to a quantitative assessment of overpressure damage to facilities is also based on distance [4]. It is proposed that the probability of secondary equipment failure always has the highest value in the center of an explosion, which decreases with the square of the distance. In addition, the potential pressure risk for facilities can be assumed as the initial burst pressure because the overpressure extent of facility is mainly influenced by burst pressure of the facility. Herein, if it is assumed that expansion occurs isothermally and that the ideal gas law applies, the initial burst pressure can be calculated by using the TNT equivalency method and the ideal gas law. Specific calculation procedure for overpressure factor is presented in Fig. 6.

$$P\propto\frac{1}{r^2} \quad (3)$$

$$m_{TNT}=\frac{\varphi m_f\Delta Hc}{E_{TNT}} \quad (4)$$

$$m_{TNT}=4\times10^{-5}V\times\left(\frac{B}{P_1}\right)\times R\times T0\times\ln\left(\frac{B}{P_2}\right) \quad (5)$$

$$r_{max}=ze_{criteria}\times m_{TNT}^{1/3} \quad (6)$$

where m_{TNT}: explosion energy flux (kg-TNT)

φ: explosion efficiency (0.01-0.1)

E_{TNT}: explosion energy of TNT (4,686 kJ/kg)

V: volume of compressed gas (m^3)

B: burst pressure of the vessel (bar)

P_1: standard pressure (1 bar)

R: gas constant (1.987 kcal/kg-molK)

T_0: Standard temperature (273 K)

P_2: pressure of the expanded gas (bar), 1 bar is assumed generally

In this research, we proposed a pressure factor considering burst

Table 4. Criteria value of scaling law for r_{max} calculation

	Scaled overpressure (bar)	ze: Scaled distance ($m/kg^{1/3}$)
Atmospheric	0.22	8
Pressurized	0.31	6
The others	0.7	4.5

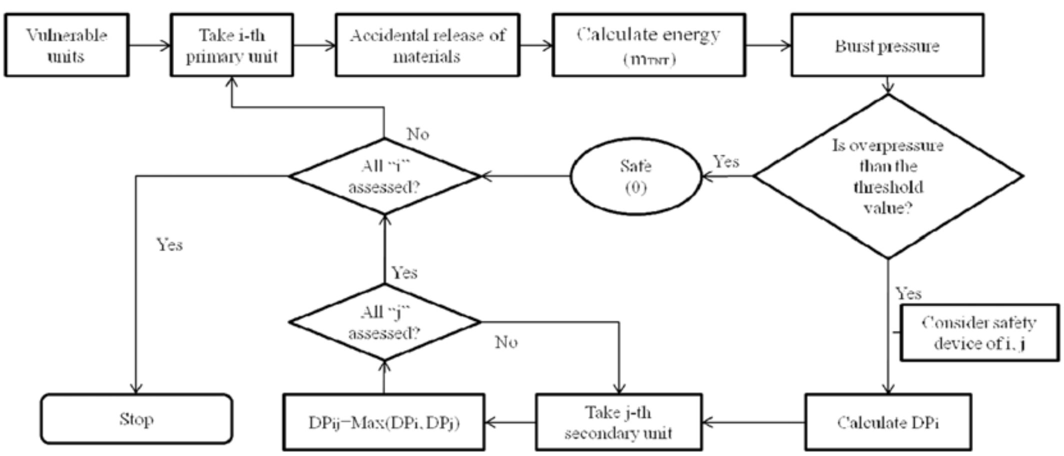

Fig. 6. Procedure for overpressure factor calculation.

pressure (DP) and distance between facilities. The first part of the equation below considers the overpressure effect between existing facilities (e) and (j). This part has the fixed value. The second part considers the overpressure effect between additional facilities (i) and existing facilities (j). The last part considers the overpressure effect between additional facilities. In other words, the layout of additional facilities is obtained from the minimum overpressure factor value (P) that is calculated in terms of the relation between all facilities.

$$P=\sum_{i=1}^{m+n-1}\sum_{j=i+1}^{m+n}\frac{1}{r_{ij}^2}DP_{ij}=\left[\left(\Sigma_{e=1}^{m-1}\Sigma_{z=e+1}^{m}\frac{1}{r_{ez}^2}DP_{ez}\right)+\left(\Sigma_{a=1}^{n}\Sigma_{e=1}^{m}\frac{1}{r_{ae}^2}DP_{ae}\right)+\left(\Sigma_{a=1}^{n-1}\Sigma_{k=a+1}^{n}\frac{1}{r_{ak}^2}DP_{ak}\right)\right] \quad (7)$$

where P is overpressure factor and DP_{ij} is max (B_i, B_j)

2-3. Missile Factor

The number of missiles produced by the fragmentation of a pressure vessel is a function of not only the size, shape, and content of the pressure vessel, but also the manner in which it fails. A probabilistic approach for flying objects can be derived using an exponential function with the arbitrary positive real number z [4], and the potential missile risk for facilities can be assumed as the initial velocity of the fragment. Herein, the initial velocity of the fragment was calculated using Baum's empirical formula [8]. In this research, we proposed a missile factor considering the exponential function and initial velocity of the fragment. The exponential function represents the probability of a fragment having a range greater than a_{ij}. z represents an arbitrary positive real number for solving for the flying distance of the fragments. The studies about the z value represented various values according to given conditions: 0.006 (derived from the graphical information) [17], 0.004 (the data from Mexico City accident) [5], and 0.03 (about 4000 propane tanks) [18]. We selected 0.004 as the z value because of its wide use around the world. Specific calculation procedure for missile factor is presented in Fig. 7.

$$M\propto e^{-zr} \quad (8)$$

$$u=2.05\sqrt{\frac{BD_f^3}{w}} \quad (9)$$

$$r_{max}^2=\frac{u^2-u_{criteria}^2}{2wg} \quad (10)$$

where z: arbitrary positive real number, (0.004)

u: initial velocity of the fragment (ft/s)

B: burst pressure of the vessel (psig)

D_f: Fragment diameter (inch), $D_f=(FS/\pi)^{1/2}$

w: Weight of the fragment (lb), w=Wv/N

Wv: mass of vessel (lb)

N: Number of fragments, N=−3.77+0.0096 (vessel capacity (m^3))

FS: fragment surface area ($inch^2$)

In this research, we proposed the missile factor considering initial velocity of the fragment (DM) and distance between facilities. The first part of the equation below considers the missile effect between existing facilities (e) and existing facilities (j). This part has a fixed value. The second part considers the missile effect between additional facilities (i) and (j). The last part considers the missile effect between additional facilities. In other words, the layout of additional facilities is obtained from the minimum missile factor value that is calculated taking account of the relations between all facilities.

$$M=\sum_{i=1}^{m+n-1}\sum_{j=i+1}^{m+n}e^{-br_{ij}}DM_{ij}=[(\Sigma_{e=1}^{m-1}\Sigma_{z=e+1}^{m}e^{-br_{ez}}DM_{ez})+(\Sigma_{a=1}^{n}\Sigma_{e=1}^{m}e^{-br_{ae}}DM_{ae})+(\Sigma_{a=1}^{n-1}\Sigma_{k=a+1}^{n}e^{-br_{ak}}DM_{ak})] \quad (11)$$

where M is missile factor, b is arbitrary positive real number (>0), and DM_{ij}=max(D_i, D_j)

2. Optimization Problem Formulation

The general problem of allocating additional facilities can be modeled in a nonlinear way. Even though the general layout problem considers costs of land, piping, and pumping, in case of allocating additional equipment to the existing layout inherently, these costs do not change much compared to the cost due to possible accidents,

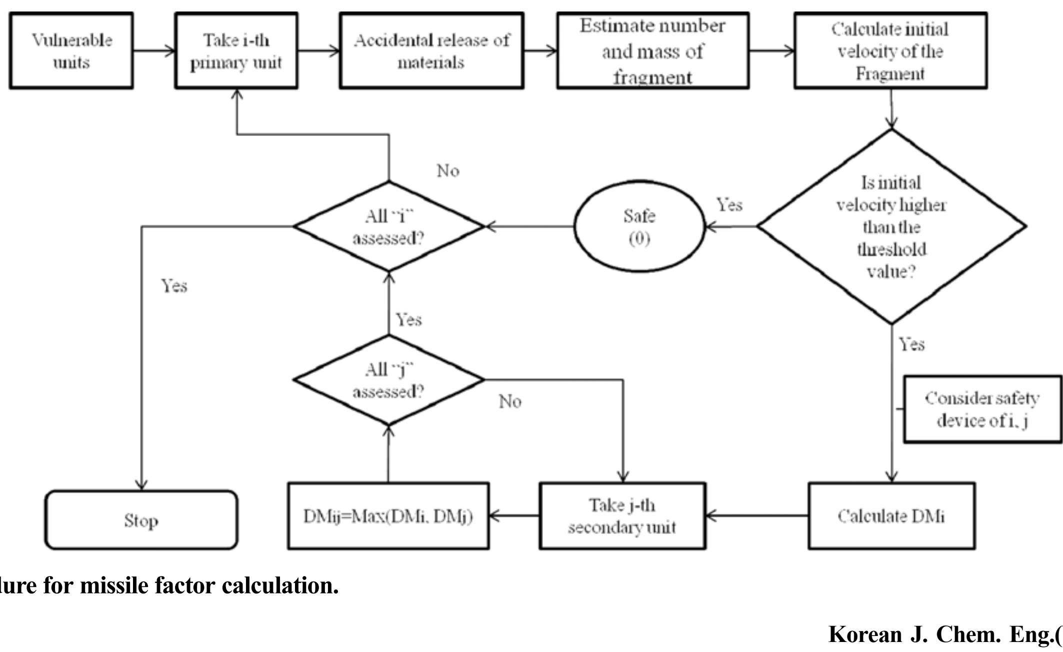

Fig. 7. Procedure for missile factor calculation.

and generating an optimal solution based on the safety alone can guarantee the layout optimal in the safety point-of-view as well as the process operation point of view.

The objective function is the minimizing domino effect D. The D function consists of F (flame factor), P (overpressure factor), and M (missile factor). Each factor has been calculated as function of consequence (potential domino risk) and probability (influencing probability of each factor). The α, β, and γ have been intoduced to make an objective function. F, P, and M have been calculated the absolute values for causing domino effect of each factor. For expressing an objective function, each factor has been changed the relative standard [see Fig. 8]. For a simple example, we assume to have F=500, P=1000, and M=10. And, we have α=10, β=50, γ=2 as the domino parameters. The domino parameters have been calculated as a standard value (minimum value) for optimal layout of each factor and converted absolute value into relative value. F calculated 50 times domino risk compared with standard value, P had 20 times, and M had 5 times. In brief, P has large value among domino factors, but the objective function has largely influenced F value when domino parameters have been applied. In conclusion, the α, β, and γ represent the parameters to make an objective function to make each factor dimensionless and of equal influence. Herein, all domino factors were assumed to have equal impact, while overpresure presented more impact in other research [1]. Different influence of impact factors can be introduced by adjusting the α, β, or γ value.

In this study, each facility was assumed to have the same shape and only the coordinates of the center point of the objects were considered. Altitudinal effects were not considered, and for simplification the installation directions of facilities and the possible direction of explosion were not considered. Overlap between facilities and the radius of the facilities were not considered, because by heuristic principles, a larger distance between the facilities would guarantee a smaller likelihood of domino effects [4].

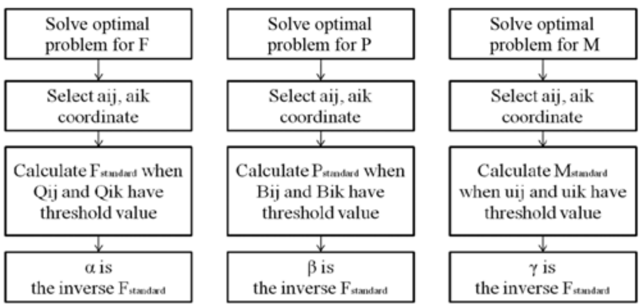

Fig. 8. Procedure for domino parameter calculation.

Objective function

$$\text{minimize } D=\Sigma_{i=1}^{m+n-1}\Sigma_{j=i+1}^{m+n}(\alpha F_{ij}, \beta P_{ij}, \gamma M_{ij}) \quad (12)$$

Subject to

I=E+A={1,…,m}+{1,…,n}={1,…,m+n}, $i \in I$, set of all facilities

J={i+1,i+2,....,n} $j \in I$, set of all facilities

$r_i=(x_i, y_i)$, $0 \le x_i \le X$, $0 \le y_i \le Y$ ((X, Y) is the coordinate, corresponding to the site size)

$r_{ij}=[(x_i-x_j)^2+(y_i-y_j)^2]^{1/2}$, rectilinear distance between i and j

$f(\alpha F_{ij}, \beta P_{ij}, \gamma M_{ij})$=select $(\alpha F_{ij}, \beta P_{ij}, \gamma M_{ij})$ based on max(r_{max} of DF, r_{max} of DP, r_{max} of DM)

α: relative impact of flame parameter

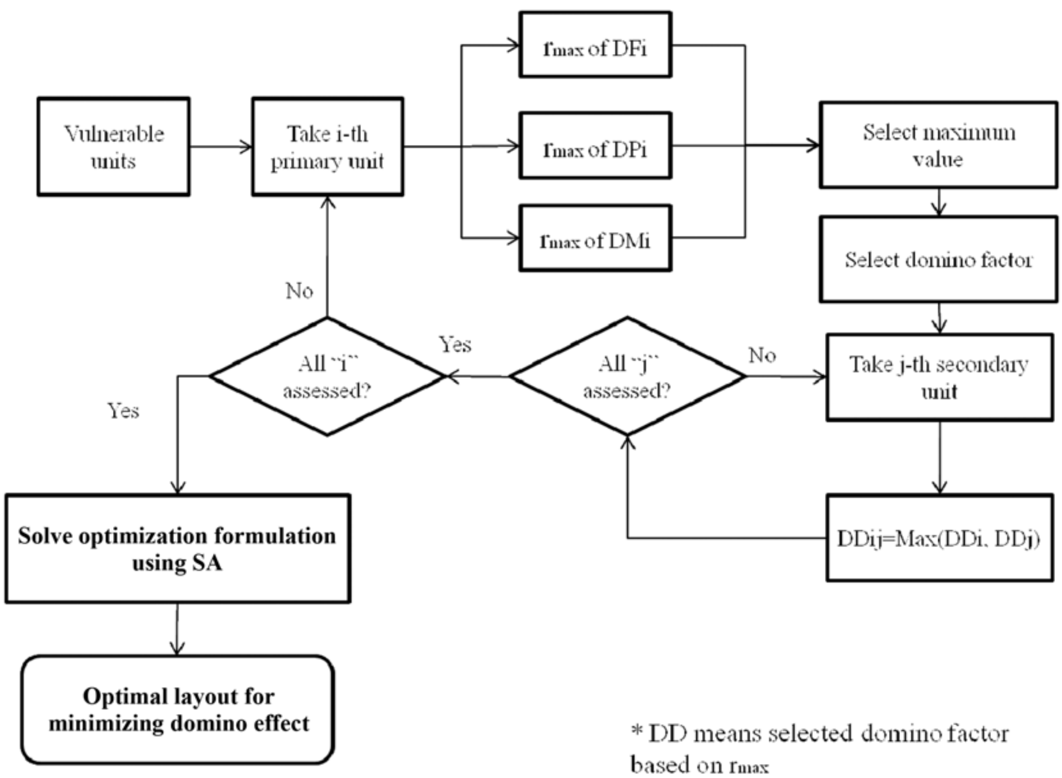

Fig. 9. Procedure for objective function calculation.

β: relative impact of pressure parameter
γ: relative impact of missile parameter
r_{ij}: satisfy the regulation about concerning facilities (e.g., minimal safety distance between facilities, safety distance from the boundary of the site etc.)
$r_{ij} \le r_{max}$: $r_{ij} = r_{max}$ means that above distance of r_{max} don't generate domino effect. r_{ij} don't exceed effective distance of domino factors for saving installation cost

CASE STUDY AND DISCUSSION

We performed a case study based on a proposed methodology. KOGAS is undertaking a "DME exhibition supply project." Part of this project is installing an additional DME storage tank on an existing LPG charging station. The layout considering safety of additional DME tanks has been the main concern of this project. We took this as the case study.

First, we performed hazard identification and selected accident scenarios using ETA on the existing LPG station. In the existing station, four vulnerable facilities were selected as exceeded items according to the domino criteria. We considered two cases, in which one (Case 1: DME 5 ton) or two (Case 2: DME 5 ton, DME 10 ton) DME tanks will be installed in this LPG charging station. Database (see Table 5) was constructed to base on the P&ID (Piping and Instrumentation Diagram) and PFD (Process Flow Diagram). Construction material and thickness were assumed using the proper values. And, safety device in this case was not considered because we did not know whether it existed or not. The required database is as follows.

The domino factors were calculated on four vulnerable facilities and additional facilities (see Table 6). We searched the optimal layout for each factor using domino factors and simulated annealing. As the constrained conditions, we considered site size (120 m*100 m) and safety distance from the boundary of the station (20 m). The simulation results were as follows. In case 1, flame and missile factors had the same coordinate ([20,20]: Fig. 10, 12), while the overpressure factor had different coordinates ([20,80]: Fig. 11). These results show that different factors had different domino impact in their facility. In case 2, all factors had the same coordinate (5 ton tank: [20, 80], 10 ton tank: [20,20]).

We searched the optimal layout considering the three factors, and calculated domino parameters by each factor. First, each parameter value was calculated to express one objective function (see Table 7). The objective function (D) searched using three domino factors (see Table 4), domino parameters, and SA. In case 1, the optimal layout had the same coordinates as the overpressure factor ([20,80]:

Table 5. Facilities database

CASE		Item	Storing material	Quantity (kg)	Diameter (mm)	Construction material	Thickness (mm)	Coordinate
CASE 1	CASE 2	Propane tank	Propane (Pressurized)	40000	2800	Carbon steel	19	50,70
		Butane tank	Butane (Pressurized)	40000	2600	Carbon steel	19	50,30
		Pump	Propane (Pressurized)	155 (320 *l*/min)	400	Carbon steel	19	80,80
		Compressor	Propane (Pressurized)	175 (360 *l*/min)	450	Carbon steel	19	90,25
		Tank1	DME (Pressurized)	5000	1300	Carbon steel	19	Being Determined
		Tank2	DME (Pressurized)	10000	1800	Carbon steel	19	Being Determined

Table 6. Calculated results of domino factors

	Propane tank (1)	Butane tank (2)	Pump (3)	Comp. (4)	Tank1 (5)	Tank2 (6)
Radiative emissive flux (kW/m^2)	394	390	156	159	174	195
Burst pressure (bar)	2290	2600	664	668	1811	1811
Velocity of fragment (m/s)	1844	1890	448	459	1125	1341

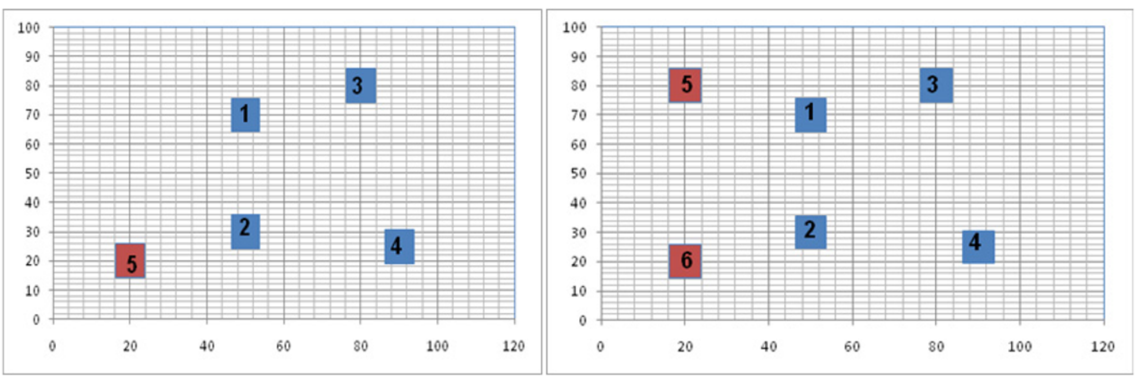

Fig. 10. Layout of additional facilities for case 1 & 2 considering flame factor.

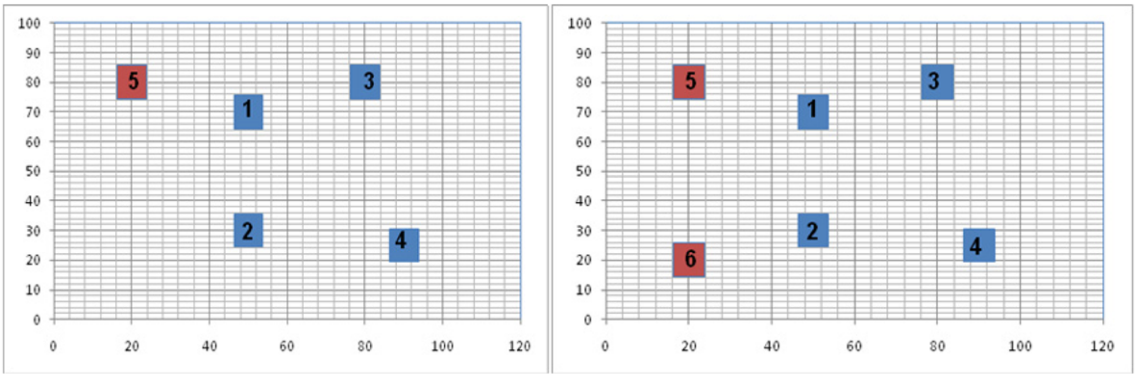

Fig. 11. Layout of additional facilities for case 1 & 2 considering pressure factor.

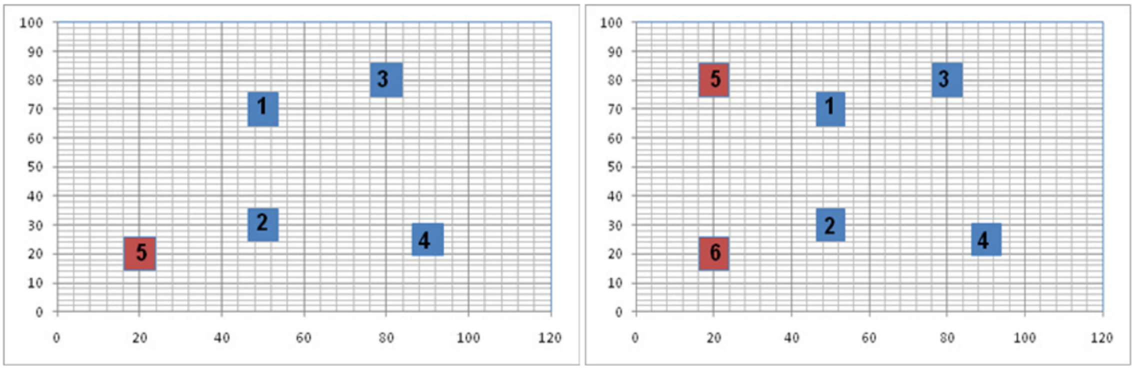

Fig. 12. Layout of additional facilities for case 1 & 2 considering missile factor.

Table 7. Calculation results of domino parameters

Domino parameter	α	β	γ
Case 1	16.2866	833.3333	0.0048
Case 2	6.2461	370.3704	0.0021

Fig. 13_left). Generally, the results have a different layout comparison of each factor with combination of all factors. However, we obtained similar layout in this case due to the existing facilities leaning to the one side. This result means that the layout of additional facility had an important influence on the overpressure factor compared to the flame and missile factors. In case 2, the optimal layout had same coordinate with all factors (5 ton tank: [20,80], 10 ton tank: [20,20]).

We determined the variation of the domino effect through the objective function value (D) when additional facilities are installed in the existing system. "Variation rate" means the relative risk change of the domino effect according to additional facilities:

$$\text{Variation rate (\%)} = \frac{\text{D of additinal facilities} - \text{D of existing facilities}}{\text{D of existing facilities}} \times 100$$

The damage probability increased 25% over the domino effect

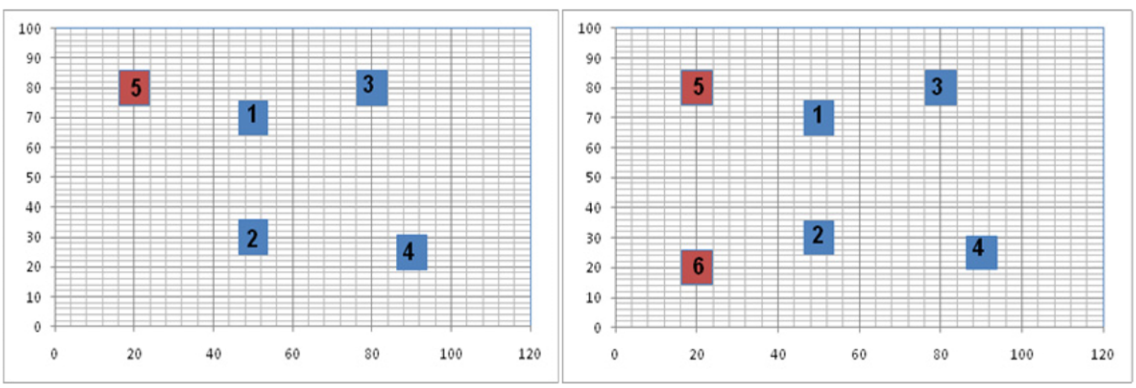

Fig. 13. Layout of additional facilities for case 1 & 2 considering three domino factors.

Table 8. Comparison of D value in existing facilities and additional facilities

	Existing facilities	One tank addition (Case 1)	Two tank addition (Case 2)
D	1443.27	1805.90	2190.50
Variation rate	-	25.38	52.14
Relative rate to case 1	-		21.34

of the existing system when one additional facility was installed. The damage probability of the addition of two tanks increased 52% over the domino effect of the existing system, and increased 21% over the domino effect of one tank installation. Proper layout design and safety measures to prevent accidents should be prepared based on this result.

CONCLUSION

Accidents caused by domino effects have a low frequency of occurrence but generate serious damage when they do occur. Thus, it is important to consider domino effects in the design of facilities layouts. However, former studies related to domino effects have been inclined to post-accident analysis. This paper proposes an algorithm that can effectively arrange additional facilities on an arbitrary plant site for minimized domino effects. We quantitatively calculated the risk of each facility through the concept of domino factors, calculated considering the potential domino risk of each facility and the distance. We also introduced the domino parameters concept to make an integrated objective function. After formulating a nonlinear optimization problem considering domino effects, SA was performed to find the optimal layout with minimized domino effects, based on quantitative risk factors for the installation of additional facilities. Thus, we identified safety variations of the target system through comparison of the domino effect impact when additional facilities were installed. Our research focused on the quantitative approach to solve domino problems, and the proposed method has the following merits:

- Can be worked out quickly, thus providing a swift means of safety assessment
- Provision of the quantitative net scores of domino risk enabling easy interpretation of the results: Net scores enabling comparison of domino risk posed by available alternatives, helping in decision-making
- No requirement of high levels of expertise from the user
- Domino factors quantifying the domino risk was identified as the essential element to reduce the subjectivity in the related decision making.

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NOMENCLATURE

α : flame parameter
β : pressure parameter
γ : missile parameter
ρ_a : air density (1.2 kg/m^3 at 20C and 1 atm)
δ : fraction of energy converted to radiation
φ : explosion efficiency
τ_a : atmospheric transmissivity
a_i : i-th facility vector, $a_i=(x_i, y_i)$
B : Burst pressure of the vessel [bar]
D_f : Fragment diameter [inch]
D_{fmax} : maximum diameter of fireball [m]
D_{pmax} : maximum diameter of pool [m]
E_{TNT} : explosion energy of TNT [4686 kJ/kg]
F : flame factor
FS : fragment surface area [$inch^2$]
F_s : fraction of the generated heat radiated from the flame surface
F_{view} : point source of view factor [m^2]
g : acceleration of gravity [9.8 m/s^2]
Hc : Heat of combustion [kJ/kg]
I : set of i (additional facilities)
J : set of j (existing facilities)
Lf : Length of flame [m]
M : missile factor
M_{TNT} : explosion energy flux (kg-TNT)
m' : mass flow rate [kg/s]
m_b : mass burning rate [kg/m^2s]
m_f : mass of spilled or contained material [kg]
N : number of fragments
P : overpressure factor
P_1 : standard pressure [1 bar]
P_2 : pressure of the expanded gas [bar]
P_w : water partial pressure [N/m^2]
Q : radiative emissive flux [kW/m^2]
R : gas constant [1.987 kcal/kg-molK]
R_f : radiative fraction of the heat of combustion
R_p : equilibrium radius of pool [m]
r : fistance between facilities [m]
S_j : surface area of jet fire [m^2]
S_p : surface area of pool [m^2]
T_0 : standard temperature [273 k]
t : durations [seconds]
u : Initial velocity of the fragment [ft/s]
V : volume of compressed gas [m^3]
V_L : volumetric liquid spill rate [m^3/s]
W : weight of the fragment [lb]
Wv : mass of facility [lb]
y_L : liquid burning rate [m/s]
z : arbitrary positive real number

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