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# Optimization for Allocating the Explosive Facilities in Order to Minimize the Domino Effect Using Nonlinear Programming

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**Abstract**−Accidents caused by the domino effect in chemical plants or the petrochemical industry are generally more serious than any other accident. But it is difficult to examine the true factor because the domino effect is influenced by many nonlinear factors. The immediate causes of the domino effect are the peak overpressure, flying objects, and flame. Nonlinearity is inherent in all three causes. However, it is believed that a systematic and mathematical approach can minimize the incidence of the domino effect. We considered the case where there were n-explosive facilities in a given arbitrary rectangular facility site. This paper suggests the positions that can minimize the domino effect using a nonlinear approach. The method initiated an arbitrary number of facilities in addition to the original position, and can search for the position to minimize the domino effect. This paper presents a new computer-aided module, MiniFFECT (MINImization of domino eFFECT).

Key words: Domino Effect, MiniFFECT, Nonlinear Approach, Gradient Method, Explosive Facility

## INTRODUCTION

An incident that begins in one facility can affect nearby facilities (e.g., storage tanks containing explosive materials, high temperature reactors) by flame (thermal effect), peak overpressure (pressure effect) and flying objects (missile effect). This phenomenon is called the domino effect. All chemical installations are closed systems. An explosion in such a system can produce second and third explosions, which may directly cause injuries to people or damage structures. Furthermore, they may increase the effects of accident by destroying or disabling the surrounding chemical process equipment and initiating accidents.

Three major factors of domino effect have been examined continuously. A procedure for analyzing the flight of a missile from the explosion of cylindrical vessels was reported by Hauptmanns [2001]. The quantities used to assess the domino effects caused by overpressure were reported by Cozzani and Salzano [2004], who used probit analysis. There have also been many studies on flame.

Domino effect analysis software, DOMIFFECT, and the risk assessment tool, TORAP, which consider three factors and assess the risk boundary were developed by Khan et al. [1998a, 2001].

Although various studies have been reported, most do not give any advice for building explosive facilities safely. In the case of arranging those facilities in a restrictive rectangular surface, there may be a condition for minimizing the domino effect.

This paper presents a computer-programmed-module MiniFFECT (MINImization of domino eFFECT), which enables one to determine the optimal position for minimizing the domino effect in explosive facilities using nonlinear programming methods. We considered the three major factors of the domino effects: thermal, overpressure and missile effect.

## STUDY OF THE DOMINO EFFECT

### 1. Definition of Domino Effects

The basic guidelines for preventing major accidents in Europe were stipulated in the Seveso 1996 Directive. Article 8 of this Seveso II Directive uses the term domino 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." Current safety research has led to a variety of methodologies to assess the significance of domino effects from major 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. In order to build a good method, the concept of domino effects needs to be well defined.

Although there is no generally accepted definition of domino effects, many authors have provided suggestions. An overview of the current definitions identified in a review of the relevant documents is as follows.

Lees [1980] defined the domino effects as "a factor to take account of the hazard that can occur if leakage of a hazardous material can lead to the escalation of the incident, e.g. a small leak which fires and damages by flame impingement a larger pipe or vessel with subsequent spillage of a large inventory of hazardous material."

Bagster and Pitblado [1991] defined the domino effect as "a loss of containment of a plant item which results from a serious incident on a nearby plant unit." The third Report of the Advisory Committee on Major Hazards [Health and Safety Commission, 1984] reported it as "the effects of major accidents on other plants on the site or nearby sites." Delvosalle [1996] suggested that the domino

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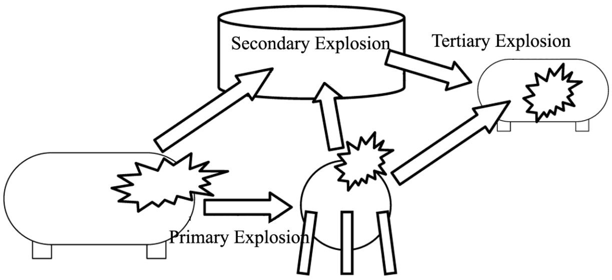



**Fig. 1. Typical phase of the domino effect.**

effect is "a cascade of events in which the consequences of a previous accident are increased by following one(s), spatially as well as temporally, leading to a major accident."

The generalized definition provided by Delvosalle [1996] has the advantage of allowing for the introduction of a mathematical approach to solving domino accident optimization problems. According to this definition, a domino effect implies a primary accident in a primary installation (this event might not be a major accident), inducing one (or more) secondary accident(s), concerning secondary installation(s). This (these) secondary accident(s) must be a major one(s) and must extend the damage caused by the primary accident. Therefore, the domino effects act in a chain, involving a number of installations. Consequently, each installation represents a direct (or an indirect) threat to all installations in a chemical industrial area [Renier et al., 2004].

Fig. 1 shows the characteristics of the domino effects mentioned above.

## 2. Three Major Factors of the Domino Effect

2-1. Flame (Thermal Effect)

Thermal effect modeling is widely used in chemical plant design and Quantitative Risk Assessment (QRA). This modeling considers two surfaces, 1 and 2, of which the first is radiating with an emissive power $E_1$ (Fig. 2). The radiant intensity falling in a small element of surface, $dA_2$, on surface 2 is obtained by calculating the amount of energy from a small element of the surface, $dA_1$, which is transmitted through the solid angle subtended by $dA_2$ at $dA_1$:

$$dq = I_n dA_1 \cos\theta_1 \cdot \frac{dA_2 \cos\theta_2}{r^2} \tag{1}$$

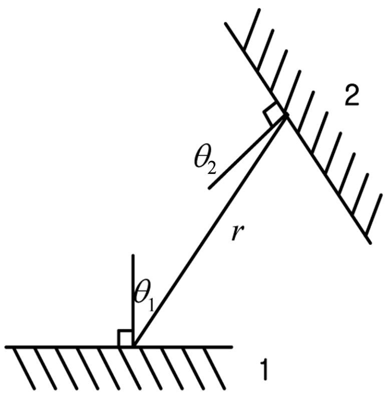



**Fig. 2. Derivation of relationship between the distance, r, and the radiant flux, q.**

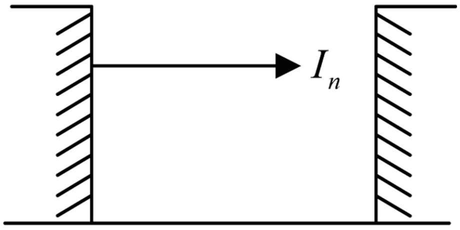



**Fig. 3. Situation where each facility faces each other.**

The incident radiant flux at $dA_2$ can then be defined as

$$dq = \frac{d}{dA_2} = I_n dA_1 \cos\theta_1 \cdot \frac{\cos\theta_2}{r^2} \tag{2}$$

However, $(dA_1\cos\theta_1)/r^2$ is the solid angle subtended by $dA_1$ at $dA_2$. Accordingly, the following equation can be obtained by integrating over $A_1$, and setting $I_n=E/\pi$:

$$q = E \cdot \int_0^{A_1} \frac{\cos\theta_1 \cos\theta_2}{\pi r^2} dA_1 \tag{3}$$

However, because it is assumed that each facility is in 2-dimensional space, $\theta_1=\theta_2=0$ (Fig. 3). It can be concluded that the relationship between the distance r and the heat intensity $I_n$ is

$$I_n \propto \frac{1}{r^2} \tag{4}$$

In addition, it was reported that the radiation energy received is proportional to $1/r^2$ [AIChE CCPS, 1999].

2-2. Peak-Overpressure (Blast Effect)

The simple approach for a quantitative assessment of the damage to equipment caused by overpressure is also based on the distance.

It is proposed that the probability of the failure of secondary equipment is always highest in the center of an explosion, which decreases with the square of the distance. This behavior has some weak points but for simplification, the following relation can be assumed [Dougal, 1998]:

$$\Delta P \propto \frac{1}{r^2} \tag{5}$$

where $\Delta P$ is the peak overpressure, and r is the distance between two facilities.

2-3. Flying Objects (Missile Effect)

The number of missiles produced by the fragmentation of a pressure vessel is a function not just the size, shape and content of the pressure vessel but also the manner in which it fails. A probabilistic approach will be helpful for examining the missile effect. An example of a probabilistic approach for flying objects can be derived from the graphical information reported by Holden and Reeves [1985]. It is possible to derive the following expression for the probability range relationship.

$$P = e^{-0.006r} \tag{6}$$

, where P is the probability of a fragment having a range greater than r meters.

Another equation for end projectiles, which was obtained from the data from Mexico City, was reported by Pietersen [1988] as follows:

$$P=e^{-0.004r} \tag{7}$$

and by Birk [1996] for 400 liter propane tanks:

$$P=e^{-0.03r} \tag{8}$$

There are more equations besides the equations shown above. Therefore, in this article, the arbitrary positive real number k was used, which gives the following equation:

$$P=e^{-kr} \tag{9}$$

**3. Software for Domino Effects**

Various types of software have been developed for assessing the domino effects as reported by Renier et al. [2004].

In Italy, an area risk assessment study called ARIPAR was carried out before the regulations stated in the Seveso II Directive. The original methodology and algorithm of the program was modified and the latest version was proposed in 2003. ARIPAR version 3.0 implements a probabilistic methodology for assessing the risks of complex industrial areas, including the transport of dangerous substances, to obtain a number of different risk measures [Spadoni et al., 2003].

DOMIFFECT (DOMIno eFFECT) is a software tool developed by Khan and Abbasi [1998a] for domino effect analysis in chemical process industries, and is based on the deterministic models used in conjunction with probabilistic analysis. The tool is based on a systematic domino method, Domino Effect Analysis (DEA), which was also developed by Khan and Abbasi [1998b].

DISMA (DISaster MAnagement) is a tool that was designed for implementing the Seveso II Directive. Uth and Richter [1999] reported the multi-use of the program, which is suitable for Safety Report scenario building, in-site and off-site emergency planning, domino effect calculation and land-use planning. The SHELL SHEPHERD Software is an example of a commercially developed safety toolkit for users to examine the domino effects.

STARS Domino (Software Toolkit for Advanced Reliability and Safety analysis Domino) is an integrated software package that is composed of four modules: 1) Knowledge Base, 2) System Model, 3) Fault Tree and 4) Event Tree. Consequence assessment is carried out by constructing an accidental scenario and simulating the phenomenological events by using the Event Tree as a reference module. There are many tools available to create an event tree and to execute the external calculation models in this module.

DOMINOXL 2.0 [Delvosalle et al., 2002] examines all possible domino effects that can lead to internal and external domino accidents. Subsequently, the most dangerous equipment zones or pipes for a given scenario in a group of chemical plants are determined by adding up the number of primary domino effects per installation, leading to a Dangerousness Factor (DF). Similarly, the most vulnerable equipment zones or pipes are also determined by adding up the number of domino effects for an installation, and then considering a secondary installation for a given protection level. This calculation leads to a Vulnerability Factor (VF). Both the DF and VF are calculated by taking into account a weighting coefficient that is defined by the user. Table 1 presents an overview of the software mentioned and identified above.

However, the studies mentioned above did not deal with the facility location itself. To accomplish this, computer-aided tools or modules are essential and important not only for estimating the risk but also for determining the safe location of an explosive facility.

**Table 1. An overview of the current main software identified in a review of the relevant documents**

| S/W | Use |
|---|---|
| ARIPAR | An area risk assessment study |
| DOMIFFECT | Domino effect analysis in chemical process industries |
| DISMA | Implementing the Seveso II |
| SHELL SHEPHERD | Safety toolkit for users to examine domino effects |
| STARSDomino | A consequence assessment |
| DOMINOXL 2.0 | Enumerating all possible domino effects |

## DECISION PROBLEM

**1. Problem Description**

Consider the relationship between the distance between each facility and the domino effects. From Eqs. (1)-(5), both the thermal effect (flame) and blast effect (peak overpressure) are proportional to $r^{-2}$, and the missile effect (flying objects) is proportional to $e^{-r}$. Problem 1 is to determine the optimal location of each facility whilst minimizing the domino effects. Each facility is the same and the height was not considered (2-dimensional analysis). Overlaps between facilities and the radius of the facility were not allowed because the farther the distance between the facilities is, the smaller the domino effects. There may be more than one or more optimal locations, while the coordinates of the facilities do not look the same but same when rotated. Problem 2 is to identify the individuality between the location considering the thermal and blast effects, and the location considering the missile effect. If those look very similar, there may be only one location that integrates the three major domino effects. Otherwise, a ranking between the three major effects needs to be found and a new integrated equation needs to be constituted with unknown factors.

Suppose that there are the same n-explosive facilities such as storage tanks and high temperature reactors. An arbitrary rectangular facility site is assumed and n-explosive facilities are placed on that site. N-explosive facilities have some initial points and each facility has the same explosion probability. The explosion direction according to the pipeline extension or the barrier in between two facilities was not considered. Once all the initial points are set, the first point moves to the counter direction of the gradient descent. If the new point is better than the previous one, the process is carried on from the previous position. If not, the step size may need to be changed. When the first updated point does not move, the next point is considered. It continues from the first point to the last one. If it is made the end of the first cycle, it turns to the next cycle. These successive cycles will last until all the points cannot move any more.

**2. Nonlinear Formulation**

The general problem of allocating n-explosive facilities can be modeled as a nonlinear program. The following will show that the model is a proper representation of the problem under study, i.e., find if and how a given number of facilities with the same radii can

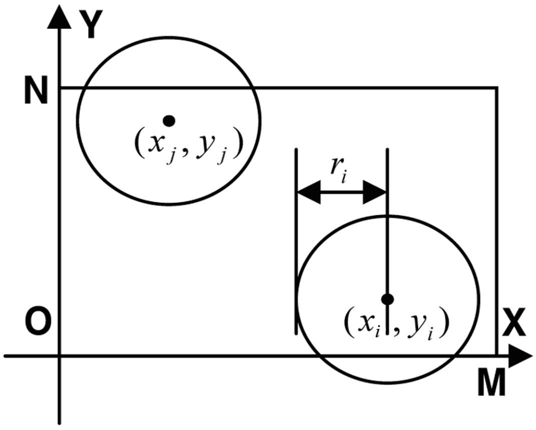



**Fig. 4. Cartesian coordinate system.**

fit into a given rectangular site. The capital letters I and J represent the set of all facilities, and i and j represent an element of I, J, respectively. The coordinates of the $i^{th}$ facility are $(x_i, y_i)$. The Cartesian system is shown in Fig. 4. The following can be expressed by considering the set of different facilities

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

The problem is now modeled as follows:

$$\text{Minimize } P=\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} P_{ij} \tag{10}$$

$$P_{ij}=\frac{1}{\|a_i-a_j\|^2}P_0 \tag{11}$$
(flame, peak overpressure)

$$P_{ij}=e^{-k\|a_i-a_j\|}P_0 \tag{12}$$
(flying objects)

Subject to

$$\|a_i-a_j\|^2\geq(r_i+r_j)^2 \text{ (for } i\neq j) \tag{13}$$

$$0\leq x_i,\ x_j\leq M \tag{14}$$

$$0\leq y_i,\ y_j\leq N \tag{15}$$

$$a_i=(x_i, y_i) \tag{16}$$

$$a_j=(x_j, y_j) \tag{17}$$

In these expressions, $r_i$ is a known real positive number, $(x_i, y_i)$ are unknown coordinates, $i\in I$. $P_0$ is the probability in which the domino effects can originate when the distance is 1. For example, 3 $P_0$ states that domino effects are three times more probable than $P_0$. Therefore, $P_{ij}$ should be reduced as much as possible. However, for the function, $P_{ij}$ is discontinuous in case two or more points are piled up, we should be careful not to diverge.

## MATHEMATICAL DESCRIPTION FOR MINIMIZATION ALGORITHM OF DOMINO EFFECTS

### 1. Gradient Descent Method

Newton's method uses an iterative scheme to determine a point where the gradient vector of the function whose minimum is sought vanishes. A related use of the gradient vector involves finding the directions along which a functional decrease occurs. The direction derivative of a differentiable function, f, is defined as follows:

$$Df(x^0;\ y)=y^T\nabla f(x^0)=\lim_{t\to 0}\frac{f(x^0+ty)-f(x^0)}{t} \tag{18}$$

Consider that all the vectors (directions) $y\in R^n$ such that, for a given point $x^0\in R^n$,

$$y^T\nabla f(x^0)<0 \tag{19}$$

It follows from Eq. (18) that, for sufficiently small positive t,

$$f(x^0+ty)<f(x^0) \tag{20}$$

This means that if the aim is to determine the minimum of f on $R^n$ and the gradient of f does not vanish at some point, $x^0\in R^n$, then a sufficiently small move in the y direction that satisfies Eq. (19) will result in a function decrease. The directional derivative, $Df(x^0; y)$ actually measures the instantaneous increase (if $Df(x^0; y)>0$) or decrease (if $Df(x^0; y)<0$) in the value of f at $x^0$ along the direction y. Therefore, all directions y having the some bounded length, say $\|y\|\leq 1$, can be determined in the particular direction that yields the steepest descent in the value of f at a given point $x^0$ for which $\nabla f(x^0)\neq 0$. The nonlinear programming problem can then be defined.

$$\min_y y^T\nabla f(x^0)=\sum_{j=1}^{n}\frac{\partial f(x^0)}{\partial x_j}y_j \tag{21}$$

subject to

$$\|y\|=\left\{\sum_{j=1}^{n}(y_j)^2\right\}^{1/2}\leq 1 \tag{22}$$

The optimal solution of this problem is as follows

$$y^*=\frac{-\nabla f(x^0)}{\|\nabla f(x^0)\|} \tag{23}$$

Therefore, the steepest descent in the function value is in the direction of the negative gradient. The method of the steepest descent, which was first derived by Cauchy, can be described as follows: Given a point $x^0\in R^n$, compute, for k=0, 1, …, the sequence of points

$$x^{k+1}=x^k-\theta_k^*\nabla f(x^k) \tag{24}$$

where $\theta_k^*>0$ satisfies

$$f(x^k-\theta_k^*\nabla f(x^k))=\min_{\theta_k\geq 0} f(x^k-\theta_k\nabla f(x^k)) \tag{25}$$

In Cauchy's steepest descent method, the global minimum of f is found along the negative gradient direction [Mordecai, 1976].

### 2. Algorithmic Description of the Nonlinear Programming

In order to implement the MiniFFECT algorithm on a PC, a program was written, which can be used to verify the proposed method. The general algorithm can be represented broadly, and Fig. 5 shows a summary of this algorithm. In the following discussion, the pattern $(x_i, y_i)$ is denoted by a vector $X_i$ for brevity, X is a set of $X_i$.

$$X=\{X_1, X_2, \ldots, X_n\} \tag{26}$$

(1) Initially set n facilities points, $(x_1, y_1)$, … $(x_n, y_n)$, hence an initial point X.

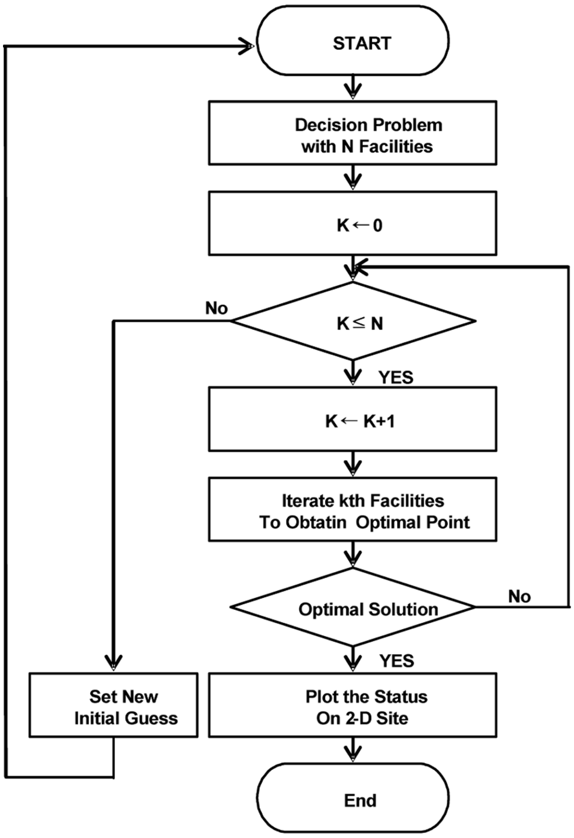



**Fig. 5. General algorithm.**

(a) Let $P_{old}=10^3 P_0$, $\eta=1$;
(b) Let $\eta=1$;
(2) If $\eta<10^{-6}$, go to (5);
(3) Calculate $P(X_i)$;
(4) If $P(X_i)<10^{-6}$, stop; otherwise calculate $\Delta P$,
(a) If $P(X_i)<P_{old}$, $P_{old}\leftarrow P(X_i)$, $X\leftarrow X-\eta(\nabla P)$, go to (2);
(b) If $P(X_i)\geq P_{old}$, $P_{old}\leftarrow P(X_i)$, $\eta\leftarrow 0.9\eta$, $X\leftarrow X-\eta(\nabla P)$, go to (2);
(5) Change the component $(x_i, y_i)$ in X into next component and then go to (1)-(b).
(6) If searching the optimal point is carried to all points, iterate procedures until all the points in set X do not change.

Note that, in the program, the most important loop is (6). A second cycle should be started if some point itself cannot be placed in the optimal status when the first cycle is finished. Such a status is called a local optimum of $i^{th}$ point.

The two core points in the algorithm are as follows. First, when a new position is arrived at by a small step using the gradient method, if it is not better than the previous one, one should return to the previous position according to the algorithm. However, only the step size is reduced without returning. Secondly, the criterion for the probability function value used here $\eta<10^{-10}$ is rather than $|\nabla P|\leq\varepsilon_0$.

Sometimes the algorithm can be faced with an impossible solution, because the probability function P is discontinuous. If some point moved is the same as another point, an impossible status can occur by chance. Therefore, some small number is inserted into the denominator for the sake of convenience.

## 3. Mathematical Description of Nonlinear Programming

From Eqs. (10)-(25), in the problem of allocating n-explosive facilities, we can approach the problem mathematically using nonlinear programming.

P is a known function of the system pattern with 2n independent variables:

$$P=P(x_1, x_2, \ldots, x_n, y_1, y_2, \ldots, y_n) \tag{27}$$

P has the following properties:

(1) it is defined on the entire 2n-dimensional Euclidean space $(0, \infty)^{2n}$, as smooth, continuous/discontinuous, and differentiable at general points;
(2) it is nonnegative, namely $P>0$ in $(0, \infty)^{2n}$;
(3) In practice, P does not have 2n variables because at some instant $2n-2$ variables except for $X_k=(x_k, y_k)$ are temporarily constant.

Therefore, the allocating problem is converted into a problem of optimization the total probability $P=P(x_1, x_2, \ldots, x_n, y_1, y_2, \ldots, y_n)$.

The aim is to determine a minimum with an optimal solution:

$$X^*=(x_1^*, x_2^*, \ldots, x_n^*, y_1^*, y_2^*, \ldots, y_n^*) \tag{28}$$

There is an algorithm for the unconstrained optimization of smooth functions, for example, the well-known method of a gradient descent. It should be noted that the evolution of $(x_1, x_2, \ldots, x_n, y_1, y_2, \ldots, y_n)$ in the gradient method is consistent with the successive updating of the patterns of the facilities on the rectangular site. The mathematical description of the gradient algorithm is as follows:

(1) Randomly define a number of initial points $(x_1^0, y_1^0)$, $(x_2^0, y_2^0)$, …, $(x_n^0, y_n^0)$ within a rectangular M×N dimensional site. Choose a positive number $\eta_0=1$ as the initial step size. The step size changes 0.9 times smaller than the previous step in the case where the movement is successful. Choose a very small positive number $\varepsilon_0$, as the criteria for gradP=$\nabla$P being approximately zero.

(2) Set the initial probability $P^0=P(x_1^0, x_2^0, \ldots, x_n^0, y_1^0, y_2^0, \ldots, y_n^0)$. If no points decrease the current probability, a solution is found, and the computation terminates.

(3) Calculator vector $\partial P/\partial X^k$ at $(x_1^0, \ldots, x_k, \ldots, x_n^0, y_1^0, \ldots, y_k, \ldots, y_n^0)$:

$$\frac{\partial P}{\partial X^k}=\left(\frac{\partial P}{\partial x_1^0}, \frac{\partial P}{\partial x_2^0}, \ldots, \frac{\partial P}{\partial x_k}, \ldots, \frac{\partial P}{\partial x_n^0}, \frac{\partial P}{\partial y_1^0}, \frac{\partial P}{\partial y_2^0}, \ldots, \frac{\partial P}{\partial y_k}, \ldots, \frac{\partial P}{\partial y_1^0}\right) \tag{29}$$

Except the point $(x_k, y_k)$, an extra $n-1$ points are constant, which currently have been updated. A new pattern is calculated from the following gradient method:

$$\begin{aligned}
x_1^k &= x_1^{k-1}-\eta_k\frac{\partial P}{\partial x_1},\\
&\vdots\\
x_n^k &= x_n^{k-1}-\eta_k\frac{\partial P}{\partial x_n},\\
y_1^k &= y_1^{k-1}-\eta_k\frac{\partial P}{\partial y_1},\\
&\vdots\\
y_n^k &= y_n^{k-1}-\eta_k\frac{\partial P}{\partial y_n},
\end{aligned} \tag{30}$$

**Table 2. Iteration results of MiniFFECT according to the various number of facilities**

| No. of facilities | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 13 | 15 | 17 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Iterations (Flame & Ov. press.) | 6 | 15 | 22 | 25 | 70 | 57 | 71 | 67 | 63 | 93 | 94 | 59 | 63 |
| Iterations (Missile effect.) | 7 | 21 | 34 | 46 | 48 | 88 | 98 | 80 | 124 | 121 | 100 | 152 | 182 |
| Dimension | | | | | | | 10×5 | | | | | | |

where the partial derivatives $\partial P/\partial x_i$, $\partial P/\partial y_i$, i=1, 2, …, n are defined at $(x_1^k, x_2^k, \ldots, x_n^k, y_1^k, y_2^k, \ldots, y_n^k)$ in 2n-dimensional space.

If the previous calculated probability is larger than the later one, return to the previous $k^{th}$ point. Always, the probability function P will proceed in a decreasing direction.

## NUMERICAL EXPERIMENT

### 1. Results

A total of 38 examples were used in this study for the purpose of evaluating the algorithm. The number of facilities ranged from 2 to 20 on a 10×5 rectangular site.

Because the probability function P is divided two classes, (1) flame and peak-overpressure and (2) flying objects, the algorithm should determine if the results are the same in each class.

If the results of the two classes are not the same, the two classes should be integrated by using the integration factor. However, the results show that the same position can be allocated for minimizing the probability by considering two classes. It can be seen that some of the results are different from what was expected.

The computer used in the experiment was a Pentium 2.4 GHz. The GAMS nonlinear programming tool was used. Table 2 shows the output iteration results of the representative examples. According to the number of facilities, Figs. 6 and 7 show the geometry of the facilities, each being a result of a successful computation with the proposed algorithm.

1-1. Results of Flame and Peak Overpressure Effects

There were four examples for n=8, 10, 15, 20. Fig. 6 shows how the n-explosive facilities were allocated to minimize the domino effects by considering the flame and peak-overpressure effects.

1-2. Results of Flying Object Effects

There were four examples for n=8, 10, 15, 20. Fig. 7 shows how n-explosive facilities can be allocated in order to minimize the domino effects by considering the flying object effects.

### 2. Examples for Probability Gain

The example cases consist of 15 and 20-facilities on the 10×5 dimensional space which is performed above. Fig. 8 shows the general and common arrangements of 15 and 20-facilities.

Compared with the arrangement of Figs. 6 and 7, the probability gains of the domino effect are shown in Table 3. Probability gain is defined as Eq. (31).

$$\text{Probability Gain} = \frac{\text{General Case Probability}}{\text{MiniFFECT Probability}} \tag{31}$$

According to the brief results of Table 3, the allocation using MiniFFECT can reduce the probability of the domino effect distinctively. These two examples are simple but display the most distinguishing characteristics in this research.

### 3. Discussion

Figs. 6 and 7 show the results of the three major domino effects. Although some figure couples show slight differences and some show the figures upside down, almost all figure couples are matched. It

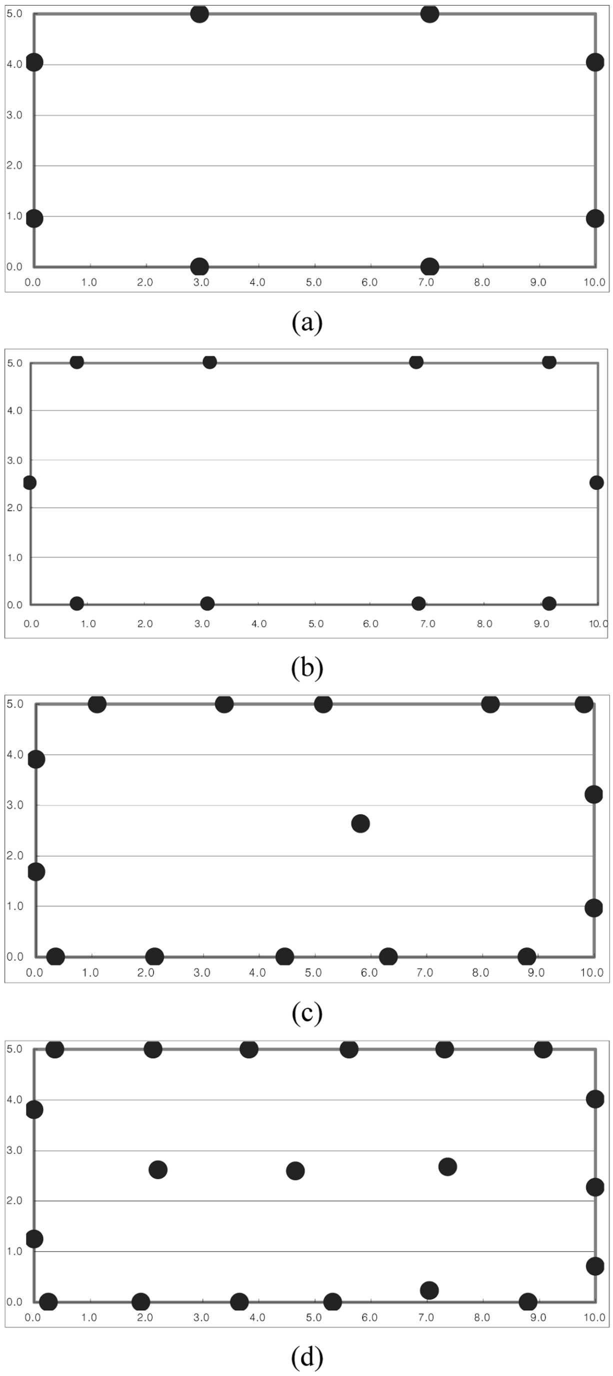
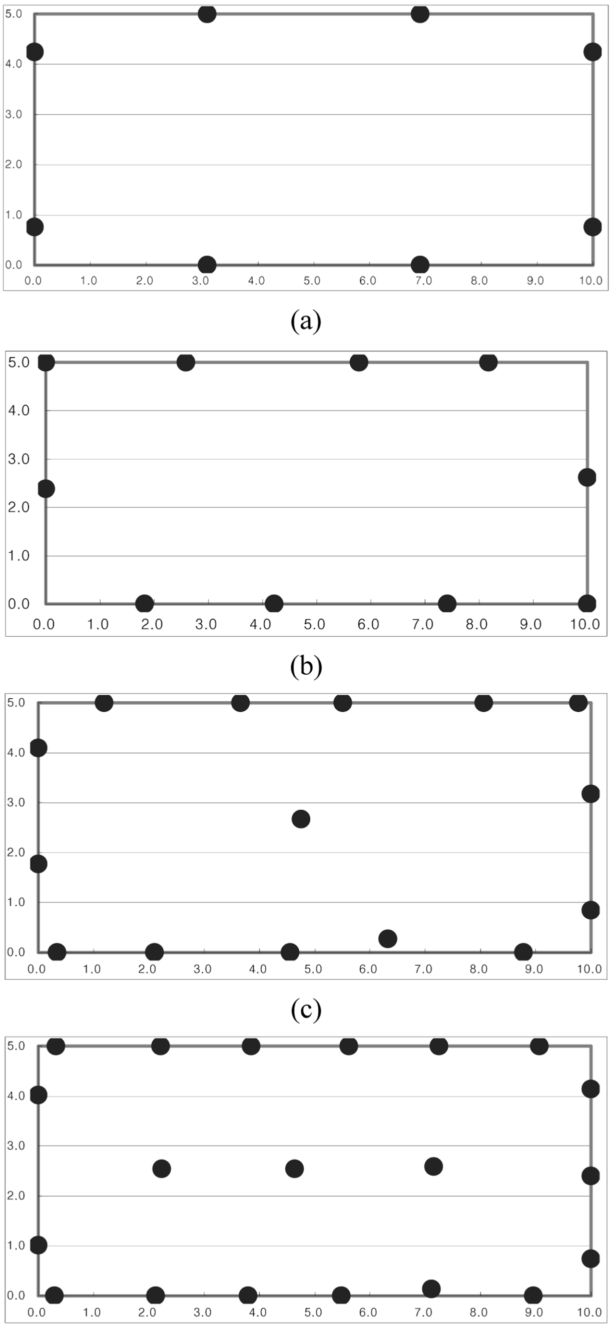


**Fig. 6. Allocation position of the optimal solution by considering the Flame and Peak overpressure effect (shown example for (a) n=8, (b) n=10, (c) n=15, (d) n=20 in regular order).**



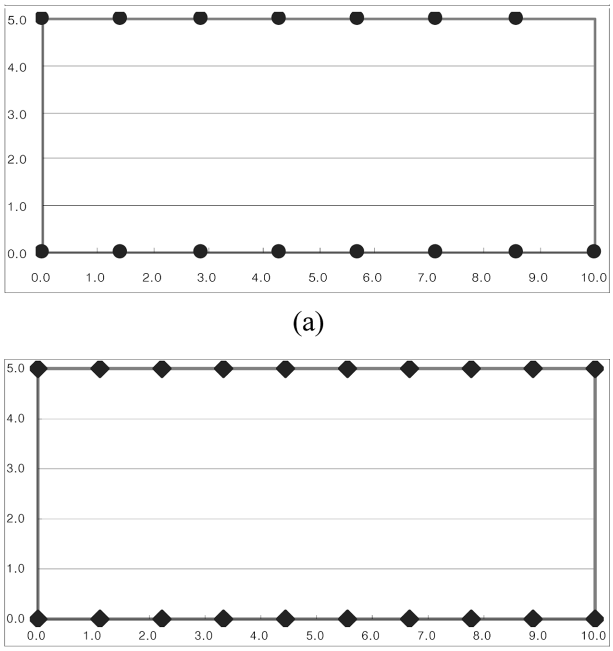

(a) (b) (c) (d)

**Fig. 7. Allocation position of the optimal solution by considering the missile effect (shown example for (a) n=8, (b) n=10, (c) n=15, (d) n=20 in regular order).**

can be seen that these matched results are the optimum solution for the minimization location with the allocating facilities. Table 2 shows only up to 20-facilities, but the proposed module can solve the problems where there are more facilities. Lastly, Table 3 shows that the MiniFFECT module can reduce the incidence of the domino effect.

## CONCLUSIONS

For preventing domino accidents, a fundamental assessment needs




(a) (b)

**Fig. 8. General allocation position for (a) 15 and (b) 20 facilities.**

**Table 3. Probability gains for two cases**

| The number of facilities | MiniFFECT | General case | Probability gain |
|---|---|---|---|
| 15 | $7.55P_0$ | $10.10P_0$ | 1.34 |
| 20 | $9.10P_0$ | $15.61P_0$ | 1.72 |

to be carried out. It is very difficult to assess such events owing to the complex nature of the domino effects. In the last decade, a variety of computer-automated tools have been developed for determining the possibility of domino effects and to provide a risk assessment after accidents. However, these tools do not offer transparent answers for prioritization measures to prevent the domino effect in a complex of chemical facilities. Further research is needed to determine what is the root cause and how the domino effects can be prevented. Judging from this point of view, the computer-aided module MiniFFECT developed in the study is significant. In the case of allocating n-explosive facilities (e.g. storage tank), the MiniFFECT shows the position of each facility with Cartesian coordinates. When explosive facilities are placed in the initial step, n-explosive facilities can be allocated in such a way as to minimize the domino effects by considering the arbitrary size of the building site. This can easily be extended to a large number of facilities and various shapes of site.

This paper proposed a computer-aided nonlinear approach for determining of position of chemical facilities, MiniFFECT. Such a module will be used as part of a decision support system to prevent domino accidents. It is believed that these results will contribute greatly to the safety of the chemical industry.

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## NOMENCLATURE

A : area of the surface
q : radiant flux
$I_n$ : heat Intensity
r : distance
$\Delta P$ : peak-overpressure
P : probability
I : set of i
J : set of j
$P_{ij}$ : probability between $i^{th}$ and $j^{th}$ facilities
$P_0$ : probability that the distance is 1
$a_i$ : $i^{th}$ facility vector ($a_i=(x_i, y_i)$)
$\eta_k$ : $k^{th}$ step size factor

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