

An Improved Hybrid Genetic Algorithm for Chemical Plant Layout Optimization with Novel Non-overlapping and Toxic Gas Dispersion Constraints*

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Abstract New approaches for facility distribution in chemical plants are proposed including an improved non-overlapping constraint based on projection relationships of facilities and a novel toxic gas dispersion constraint. In consideration of the large number of variables in the plant layout model, our new method can significantly reduce the number of variables with their own projection relationships. Also, as toxic gas dispersion is a usual incident in a chemical plant, a simple approach to describe the gas leakage is proposed, which can clearly represent the constraints of potential emission source and sitting facilities. For solving the plant layout model, an improved genetic algorithm (GA) based on infeasible solution fix technique is proposed, which improves the globe search ability of GA. The case study and experiment show that a better layout plan can be obtained with our method, and the safety factors such as gas dispersion and minimum distances can be well handled in the solution.

Keywords plant layout, non-overlapping constraints, toxic gas dispersion, genetic algorithm

1 INTRODUCTION

Plant layout is complex, in which the land, funding, security and other factors should be considered. The spatial arrangement of all process units in a given area should maximize the use of land and minimize the construction funds, costs for material transportation between units, *etc.* Toxic or explosive gas usually exists in a chemical plant. The leakage of such dangerous gas may lead to poisoning or explosion, such as BP Texas City incident (2005) and Bhopal disaster (1984), causing great property damage. Therefore, a proper layout plan should take security factors into consideration and minimize the damage to units and people when an unexpected incident occurs.

In the past, the distribution of buildings in a plant usually follows some simple rules, *e.g.*, arranging the units in their order in the process with sufficient distances to reduce the material transportation between units [1–4]. The results may be different by different designers and it is time consuming to find a comprehensive plan. The relationship and constraints between buildings will be very complicated when the number of sitting facilities increases, which makes the arrangement more difficulty. Another strategy is based on graphs theory [5]. In this method, buildings are simplified as rectangles, and the result based on simple common sense is used as an initial solution. The method of graphs theory is used for further work. Programming techniques are applied in solving the layout problem. The facility layout problem is formulated as a quadratic assignment problem (QAP) and several algorithms have been proposed to solve the layout problem [6, 7]. Then the QAP is extended to

generate the mixed-integer programming (MIP) model [8, 9], in which the non-overlapping constraints and pipe cost are considered but the security factor is neglected. Security factors include gas leakage and explosion, and these models are always non-linear. When the security factor is considered, the layout problem will convert to a mixed-integer nonlinear programming (MINLP). Currently, few researches are based on MINLP. Penteado and Ciric [10] introduced the concept of property damage into the security factor. Patsiatzis *et al.* [11] gave a security factor including the Dow Fire and Explosion Index. An approach based on the worst-case scenario was proposed by Ovalle *et al.* [12], in which the gas dispersion models and the wind direction were introduced into the constraints.

The model mentioned above can be described as an optimization problem with large number of variables subject to large number of constraint equations. Traditional optimization algorithms such as steepest descent method and interior point method are strongly dependent on gradient information and it is difficult to find the optimal solution if the feasible regions are discontinuous. Genetic algorithm (GA) is widely used in solving constrained optimization problems and control strategies in chemical engineering [13–16]. Because it is a stochastic search algorithm with outstanding globe search ability, the genetic algorithm is used here in dealing with plant layout problem. Another reason is that the coordinates of facilities can be easily coded as genes in GA.

In this study, we mainly focus on the MINLP model for plant layout proposed by Roman *et al.* [17] and Lee and Grossmann [18]. The gas leakage factor is introduced as constraints and a new non-overlapping

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constraint based on facility projection is proposed, which reduces the number of variables significantly. In order to obtain the optimal solution, the genetic algorithm is improved by an infeasible solution fix technique, which will enhance the globe search ability and increase the search speed.

2 GAS DISPERSION AND NON-OVERLAPPING CONSTRAINTS

The gas leakage problem in chemical plant is usually defined as a continuous process, and in our study we start from a passive dispersion under a constant condition. In this section, new constraint equations for gas dispersion are proposed and a new non-overlapping constraint based on facility projection is used to simplify the plant layout model.

2.1 Gas leakage constraints

Conventional models are used in the passive dispersions. In the Pasquill-Gifford model [19], the passive dispersion for a continuous spill over the ground is

$$C = \sum_{i=1}^n C_i(x, y, z, t - t_i) \quad (1)$$

$$C_i(x, y, z, t - t_i, H_e) = \frac{2Q}{(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z} \exp \left[-\frac{[x - v(t - t_i)]^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2} \right] \times \left\{ \exp \left[-\frac{(z - H)^2}{2\sigma_z^2} \right] + \exp \left[-\frac{(z + H)^2}{2\sigma_z^2} \right] \right\} \quad (2)$$

where t_i is the time interval, in which the smoke released represent the mass flow rate of emission Q ($\text{kg} \cdot \text{s}^{-1}$), $\sigma_y = 0.04x / \sqrt{1 + 0.0001x}$, $\sigma_z = 0.016x / \sqrt{1 + 0.0003x}$, $\sigma_x = \sigma_y$, H is the height of the emission source. σ_x , σ_y , and σ_z are the dispersion parameters determined by the atmospheric stability and experimental equations.

When the emission source and related parameters are known, the maximum dangerous distance, defined as $D_{\min}^{\text{dang}}$, can be calculated with Eqs. (1) and (2). By the characteristic of passive dispersion and the solutions from Computer Fluid Dynamics (CFD) program, we can approximate the region of gas leak as a narrow oval and the source angle of the length and the width is 15° , as shown in Fig. 1. We define that the safe distance between the emission source and the sitting facility is larger than $D_{\min}^{\text{dang}}$ or the angel is larger than 7.5° . The constraint equations are expressed as

$$\begin{cases} |\mathbf{v}_{s,j}| \geq D_{\min}^{\text{dang}} & \theta < 7.5^\circ \\ |\mathbf{v}_{s,j}| > d & \theta \geq 7.5^\circ \end{cases} \quad (3)$$

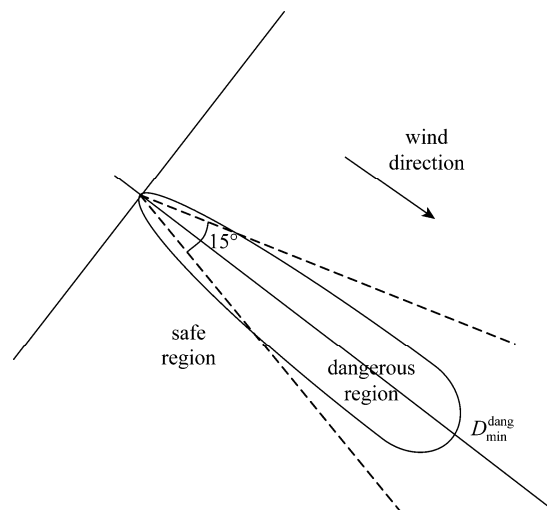


Figure 1 Safety areas under harmful gas dispersion

where $\mathbf{v}_{s,j} = (x_s - x_j, y_s - y_j)$, $\cos \theta = \mathbf{v}_{s,j} \cdot \mathbf{v}_{\text{wind}} / (2|\mathbf{v}_{s,j}| \cdot |\mathbf{v}_{\text{wind}}|)$, x_s , y_s , x_j and y_j are coordinates of facilities s and j , and θ refers to the angle of $\mathbf{v}_{s,j}$ and the wind direction.

Then, this formulation can be transformed to

$$|\mathbf{v}_{s,j}| \geq \frac{D_{\min}^{\text{dang}} + d}{2} - \frac{D_{\min}^{\text{dang}} - d}{2} \times \frac{|\theta - 7.5|}{\theta - 7.5} \quad (4)$$

$$d = \sqrt{(x_s - x_j)^2 + (y_s - y_j)^2} + \text{st} \quad (5)$$

where d is the common non-overlapping constraint distance, and st is the street width.

2.2 Improved non-overlapping constraints

Two facilities cannot occupy the same physical space. Considering two facilities s and k , in the study of Roman *et al.* [17], the non-overlapping constraint is described as that facility s could be layout anywhere on the West region (named "W") or on the East region (named "E") or at the center, and in the last case it would lay either in the North region (named "N") or the South (named "S"), as indicated in Fig. 2.

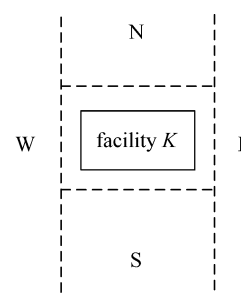


Figure 2 Non-overlapping constraints

The non-overlapping disjunction is [17]

$$\left| \begin{array}{l} x_s \leq x_k - D_{s,k}^{\min,x} \vee x_s \geq x_k + D_{s,k}^{\min,x} \\ x_s \geq x_k - D_{s,k}^{\min,x} \\ x_s \leq x_k + D_{s,k}^{\min,x} \\ y_s \geq y_k + D_{s,k}^{\min,y} \vee y_s \leq y_k - D_{s,k}^{\min,y} \end{array} \right| \quad (6)$$

where $D_{s,k}^{\min,x} = \frac{Lx_s + Lx_k}{2} + s$, $D_{s,k}^{\min,y} = \frac{Ly_s + Ly_k}{2} + st$,

x_s , y_s , x_k and y_k are the coordinates of facilities s and k , Lx_s , Ly_s , Lx_k and Ly_k are the length and width of s and k , $D_{s,k}^{\min,x}$ and $D_{s,k}^{\min,y}$ are the minimum separation between s and k .

Because the above constraint is a disjunctive formulation, it is not directly accepted by commercial computer codes. In the study of Roman *et al.* [17], the convex hull formulation is used to convert the above disjunctive model in an MINLP. An apparent weak point is that too many additional variables (thirteen) are needed to form an MINLP for each two facilities. The number of variables for even a simple plant layout problem will be very large, increasing the difficulty of solution.

Here we study the projection of two facilities and a new non-overlapping constraint is proposed by considering the projection of i and j . Their projections in x -direction and y -direction are defined as S_x and S_y , as shown in Fig. 3.

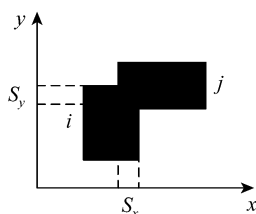


Figure 3 Projection of overlapping of facilities

The two facilities will occupy the same physical space only if $S_x > 0$ and $S_y > 0$. Thus the non-overlapping constraint is

$$(S_x > 0 \wedge S_y < 0) \vee (S_x < 0 \wedge S_y > 0) \vee (S_x < 0 \wedge S_y < 0) \quad (7)$$

Reformulating the disjunction as an inequality, we have

$$|S_x| + |S_y| > S_x + S_y \quad (8)$$

where $S_x = Lx_i / 2 + Lx_j / 2 - (x_j - x_i)$, $S_y = Ly_i / 2 + Ly_j / 2 - (y_j - y_i)$, Lx_i , Ly_i , Lx_j and Ly_j are the length of i and j .

The advantage of non-overlapping constraint based on projection is that there is no integer and additional variables in the equations, reducing the number

of variables from thirteen to four. For a non-linear model, the complexity of solution is reduced significantly.

3 ISFT_HGA

Plant layout can be defined as an optimization problem with large number of variables and constraints. However, when using standard genetic algorithm to solve constrained optimization problems with large and strict constraints, it may also have some trouble in finding feasible and optimal solution. Thus, an approach using infeasible solution is proposed in this study.

3.1 Infeasible solution fix technique

For improving the search ability of GA, Michalewicz [20] first proposed a novel idea that indicates the importance of infeasible individuals, as they may contain valuable gene fragment. Use of these infeasible individuals will effectively maintain the diversity of the population. Meanwhile, the feasible region of some optimization problems is not continuous so that the search process is likely to stay in one of the feasible regions if only feasible solutions are considered, leading to a local optimal solution. Optimal solutions to some of the constrained problems are on or near the boundary of the feasible region. Selection on the infeasible solution can drive the population to and over the boundary, enhancing the exploration. Thus using infeasible solution can improve the global search ability.

Inspired by the use of infeasible individuals, an infeasible solution fix technique (ISFT) is proposed here, in which a certain number of feasible and infeasible individuals are selected to execute crossover operation so as to acquire good individuals from the offspring. The specific way to select certain number of individuals for ISFT will be discussed in Section 3.3. The arithmetical crossover is taken in ISFT. With the experimental studies, it is shown that the proposed method has a great probability to find a better solution than traditional crossover operator.

3.2 Configuration of population components

In order to introduce the infeasible solution fix technique into GA, the individual number of mating pool and the number of feasible and infeasible individuals selected should be configured as follows.

Table 1 gives different types of individuals, their size and symbol. The initial population size is pop and the parameter of ISFT is α . Parameter α is the ratio of the numbers of feasible and infeasible individuals selected from the population. The feasible solutions selected here are the optimal solutions in the population and the infeasible solutions selected are the worst individuals. Apparently α should be less than 50% and complete offspring component can be obtained by Eq. (9). Fig. 4 demonstrates the flow chart of generation

Table 1 Symbol and population size of different individual types

Individual type	Symbol	Population size
initial population	ini_pop	pop
mating pool	mat_pool	$(1-2\alpha)\text{pop}$
feasible solution for ISFT	ISFT_fes	$\alpha \cdot \text{pop}$
infeasible solution for ISFT	ISFT_infes	$\alpha \cdot \text{pop}$
individual generated by ISFT	ISFT_new	$\alpha \cdot \text{pop}$
individual generated by mating pool	Std_new	$(1-2\alpha)\text{pop}$
offspring	newpop	pop

of new population. The number of each kind of individuals in the population can be determined with the population size and α given.

$$\text{newpop} = \text{std_new} + \text{ISFT_new} + \text{ISFT_fes} \quad (9)$$

3.3 Steps of ISFT_HGA

Since genetic algorithm always has local search problem, the steepest descent method is introduced here to improve the local search ability. The infeasible solution fix technique-based hybrid genetic algorithm (ISFT_HGA) is obtained by using the infeasible solution fix technique and the steepest descent method based on the standard GA. The algorithm is described as follows.

Step 1 Initialize pop, crossover rate, mutation rate, and α .

Step 2 Generate pop number of individuals randomly in the search space.

Step 3 Sort the priority of the individuals in the population and select $\alpha \cdot \text{pop}$ number of feasible and $\alpha \cdot \text{pop}$ number of infeasible individuals for the ISFT procedure.

Step 4 Apply the standard crossover operator for the mating pool.

Step 5 Perform the ISFT procedure.

Step 6 Apply the steepest descent method for the new feasible individuals to improve the local search. For the optimal solution in every generation, perform

an extra local search to expand the search space.

Step 7 Apply the mutation operator for the individuals and generate the offspring.

Step 8 Go to Step 3 if the termination criteria are not satisfied with the offspring.

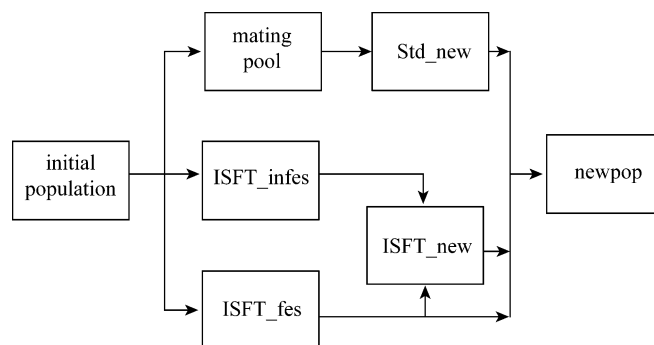
It should be noted that, when initializing the parameters of algorithm, one should make sure that proper values of popsize and α are set so that their product is an integer. In the use of ISFT, more techniques of crossover can be used if the computational cost is tolerated, such as multi-point crossover and uniform crossover, which will increase the opportunity to find a better solution.

4 EXPERIMENTS AND COMPARISON

4.1 Experiment and discussion on parameter α

The ratio of individuals selected from the population, α , plays an important role in the feasible-infeasible individual crossover method. Higher probability for getting more outstanding individuals is based on the number of individuals selected from the population, but more individuals mean more computations. Thus how to set a proper α value to make the method effective with relatively less computations is worth to test.

In this experiment, we set α equal to 5%, 10%, ..., and 35%, and the standard test function g04 is taken. The optimal solution of g04 is -30665.539 . The parameters used are: ini_pop 100, crossover rate 0.5, and mutation rate 0.05. The arithmetical crossover and uniform mutation are taken, so the fitness function evaluations (FFEs) for different α are 50, 200, 450, 800, 1250, 1800, and 2450. Fifty independent experiments for each α are taken, and the result is shown in Fig. 5 and Table 2. The average of objective function value is getting close to the optimum with the increase of α and stays stable at about -3.04×10^4 when α is 27%. The best, standard deviation and worst values also present better results with the increase of α . FFEs are the important evaluation criteria for the computation cost of an evolutionary algorithm. Because the number of individuals generated by ISFT becomes larger with the increase of α , the FFEs will increase

**Figure 4** Flow chart of the generation of new population

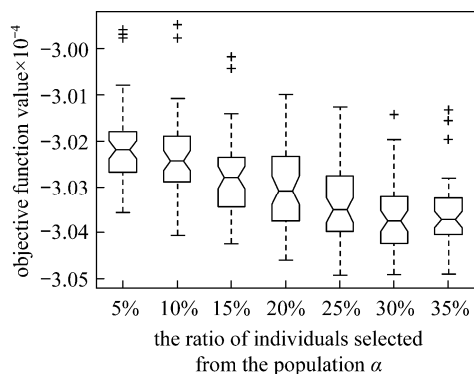


Figure 5 Variation of objective function value versus α

Table 2 Results with different α

α	Results with different α			
	Best	Mean	St. dev	Worst
5%	-30356.47	-30209.81	91.32	-29960.37
10%	-30406.11	-30232.88	87.65	-29948.63
15%	-30423.32	-30278.51	89.13	-30017.47
20%	-30458.95	-30304.21	88.12	-30099.38
25%	-30491.41	-30333.17	86.21	-30127.14
30%	-30489.92	-30365.02	75.12	-30142.79
35%	-30489.92	-30355.15	83.44	-30132.79

rapidly with the effect of ISFT improved. The main purpose of using ISFT in our approach is to help the search crossing over the boundary of feasible region to other areas and improve the population diversity, as mentioned in Section 3.1. The steepest descent method is the main measure used to improve the local search ability. As the computational cost is one of our concerns, the value of α in this paper is set at 15%, which is the compromise between the effect of ISFT and computational cost.

4.2 Case study for plant layout

Experiments for a plant layout are carried out. The case is from Ref. [12] for the convenience of comparison. In Section 4.1 we only take the geometrical distribution into consideration, and in this section the gas dispersion in a facility is added as a safety factor in the constraints. The parameters of ISFT_HGA are: ini_pop 80, crossover rate 0.5, mutation rate 0.05, and α 15%. The population size, crossover and mutation rate used are empirical values.

The case can be described as follows. Four facilities are already installed and their type, size, exact position and number of people inside are given in Table 3. Then, five new facilities will be accommodated in a square land with 1500 m side length. Their sizes and number of expected people in each facility are shown

Table 3 Characteristics of installed facilities

Facility	L_x/m	L_y/m	X/m	Y/m	People
maintenance workshop	25	20	52.5	35	10
office	30	20	20	15	15
process	30	50	20	55	0
service facility	20	15	50	12.5	5

in Table 4 and the interconnections between the facilities are given in Table 5. The pipe and land costs are USD 60.8 m^{-1} and USD 16.0 m^{-2} , respectively.

Table 4 Characteristics of new facilities

Facility	L_x/m	L_y/m	People
storage	60	60	1
compressors room	30	15	0
control room	15	15	15
storage tanks	20	50	0
residual water treatment station	35	20	1

Table 5 Facility interconnectivity

From	To
residual water treatment station	process service facility offices
process	storage tanks compressor room
storage tanks	residual water treatment station process

4.2.1 Case study based on geometrical distribution only

The results are shown in Tables 6, 7 and the schematic distribution is shown in Fig. 6.

Table 6 Comparison of HGA and Reference [12] (a)

	ISFT_HGA		Result from [12]	
	X/m	Y/m	X/m	Y/m
storage	95	80	170	42
compressor room	85	12.5	95	37.5
control room	27.5	92.5	87.5	12.5
storage tanks	50	75	125	47
residual water treatment station	87.5	35	62.5	60

Table 7 Results comparison of HGA and Reference [12] (b)

	Total pipe length/m	Occupied area/ m^2	Total cost /USD
ISFT_HGA	476.95	14950	268198.56
Result from [12]	576.24	17425.0	313835.39

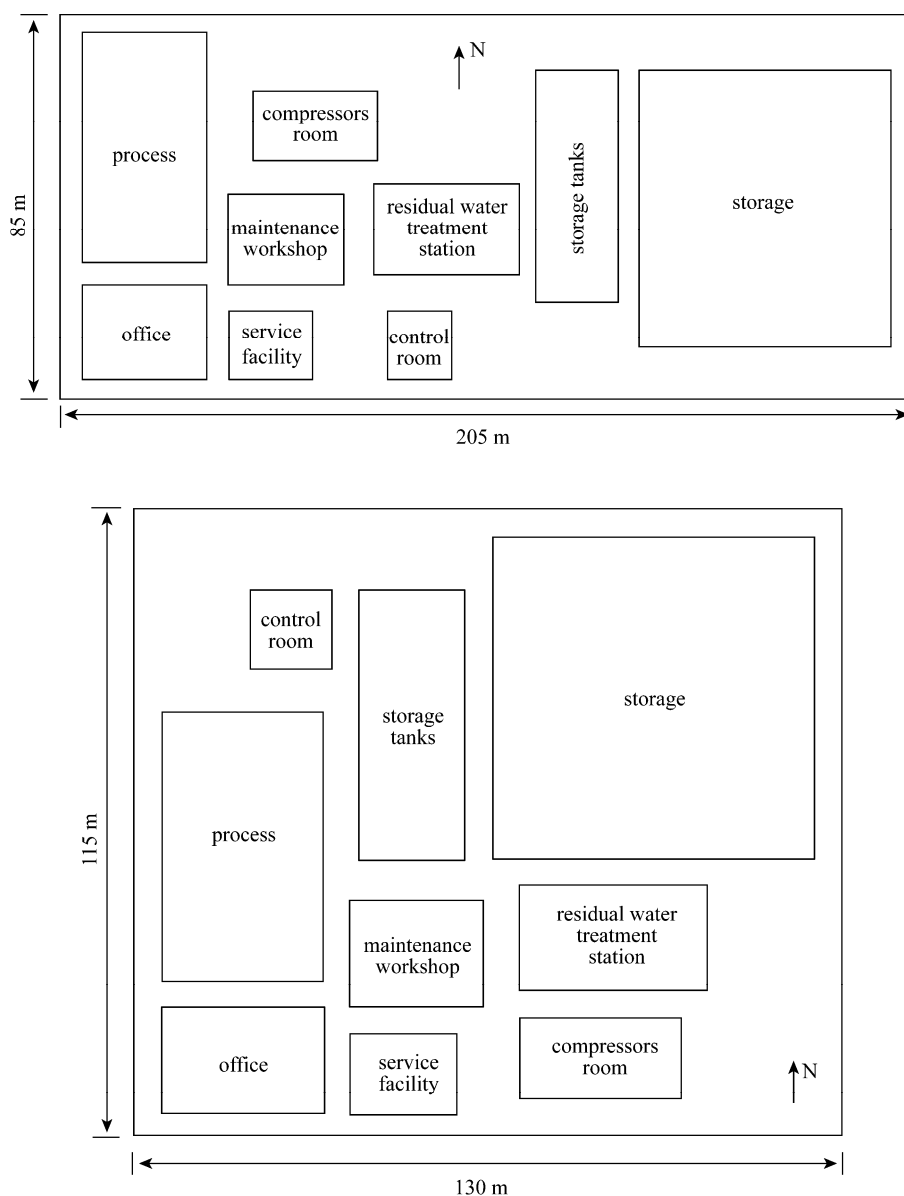


Figure 6 Results from reference [12] and ISFT_HGA

According to Reference [12], the general algebraic modeling system (GAMS) is used to solve this model, using the solvers BARON. In Table 4, our results obtained by improved GA are obviously better than those of Ovalle *et al* [12]. The land cost and pipe length are less, indicating a better layout plan. The algorithm used in GAMS is the branch and bound method, with which it consumes more time and it is more difficult to find the globe minimum values than the GA. The improvement on the non-overlapping constraint also makes the constraint equations more simpler, so that the search of algorithm mainly focus on the violation of non-overlapping and minimum occupied area.

4.2.2 Case study based on additional safety factor

Here we consider the minimum distances and gas

dispersion in addition. The minimum distance is a safety distance between potentially dangerous source and normal facility, and it is proper to consider it with the gas leakage factor. In this experiment we use the distances suggested in GB50160-2008 [21] and Table 8 shows the required minimum distances. The following equation represents the minimum distance constraint

$$(x_i - x_j)^2 + (y_i - y_j)^2 \geq d_{\min}^2 \quad (10)$$

where x_i , y_i , x_j and y_j are coordinates of i and j , and $d_{\min}$ is the minimum distance.

In this case, the storage tank is taken as the potential leak source and the plant is in Beijing. From the meteorological data, the dominant wind direction in Beijing is Southeast wind in summer and Northwest wind in winter, and winter is consider here, with wind

Table 8 Minimum distances between facilities suggested in GB50160-2008

	Office	Storage	Compressor room	Control room	Storage tanks	Residual water treatment station
office				15(82.8)		15(44.5)
storage tanks			25(28.5)	45(45.5)	35(36)	
compressor room	15(31.6)					
control room			15(18.0)			15(46.5)
storage tanks			60(86.3)	60(94.6)		
residual water treatment station		45(29)	35(35.3)		25(25.6)	

Note: The data in parentheses are the results obtained by our method.

velocity $2 \text{ m}\cdot\text{s}^{-1}$ and temperature $5 \text{ }^{\circ}\text{C}$. With the assumption that the leakage substance is hydrogen sulfide (H_2S), mass flow rate is $7 \text{ kg}\cdot\text{s}^{-1}$, the height of the emission source is 5.29 m , and the gas concentration under minor injuries is $0.035 \text{ kg}\cdot\text{m}^{-3}$, the calculated $D_{\min}^{\text{dang}}$ by the Pasquill-Gifford model is about 100 m . The results are shown in Tables 9, 10 and the schematic distribution is shown in Fig. 7. The maintenance workshop and office are safe from the H_2S release as they are not in the downwind direction. The control room is in the downwind direction but the distance from the storage tank is much larger than $D_{\min}^{\text{dang}}$, being less harmful to the people in it. The distance between facilities is shown in Table 8. Most of the distances obtained satisfy GB50160-2008 except the distance between the residual water treatment station and storage, 29 m , which is less than the suggested distance 45 m , so it is a flaw of the plan. Since most of the distances between facilities meet the requirement,

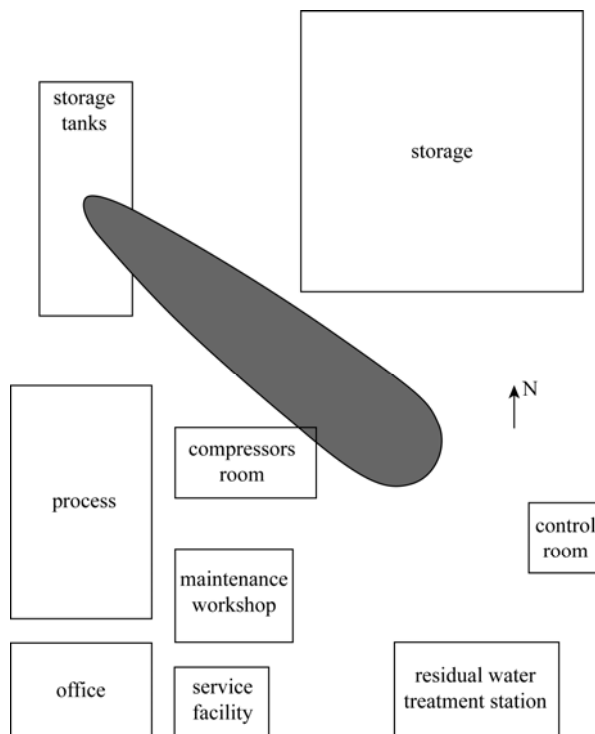
Table 9 Results obtained by HGA (a)

	X/m	Y/m
storage	97	129
compressor room	55	62.5
control room	124	46
storage tanks	21	119
residual water treatment station	104.5	14

Table 10 Results obtained by HGA (b)

Total pipe length/m	Occupied area/ m^2	Total cost/USD
556.07	22386	391985.056

this layout plan can reduce the potential damage when explosion or gas leak incident occurs. In the calculation,

**Figure 7** Results by improved GA based on minimum distances and security factor

the occupied area and pipe length are also considered, which is property factors.

5 CONCLUSIONS

Improvements on the plant layout model based on MINLP are proposed in this work. A new non-overlapping constraint disjunction is based on facility projection, and the number of variables is the same when reformulated as a non-linear problem. This makes the whole model simpler. In handling of gas dispersion, new constraint equations are developed, which accurately demonstrate the relationship between the emission source and sitting facility. Also, an improved genetic algorithm based on an infeasible solution fix technique is proposed, which improves the globe search ability. In the experiments, a plant layout case from literature is used. In the case study based on geometrical distribution only, the results obtained by our method give a better layout plan than that in the reference, with lower land cost and pipe length. In the case based on safety factors including minimum distance and toxic gas dispersion, the layout plan obtained gives a proper distribution, preventing the people in the facility from the toxic gas and meeting the requirement for minimum distances between facilities as suggested in GB50160-2008.

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