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An Industrial Area Layout Optimization Method Based on Dow's Fire & Explosion Index Method

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In the process of plant and industrial area layout design, safety issue is very important and cannot be ignored. Dow's Fire & Explosion Index (F&EI) Method is an accurate and widely used approach to evaluate plant safety. Researches using Dow's method on layout problem is mature in plant level, but very few works are focus on the industrial area level. This paper determines the layout of industrial area based on the safety evaluation of plant resulting from Dow's method. In this work, the risk of industrial area is determined through F&EI of each plant evaluated from Dow's method. An objective function is established to consider the risk of the industrial area, the risk of each plant, the distance between plants and the purchase cost of each plant. In addition, we consider the problem as a discrete layout problem, and it is solved by genetic algorithm. By optimizing the problem, safer industrial area layout can be obtained. This new layout design method considered safety evaluation from the view of whole industrial area. Because Dow's method was established on the basic of a great deal of engineering practices, the method we proposed can be more practical compared with others. The case study is used to illustrate the feasibility and effectiveness of the industrial area layout method we proposed.

1. Introduction

Layout design of industrial area is a key stage in the process of chemical engineering design. It directly affects the capital cost, operating cost, energy consumption and safety of industrial area. The layout design of industrial area is a fertile field for further study. Dow's Fire & Explosion Index Method (1994) is a systematic method to evaluate safety, which was developed by The Dow's Chemical Company. From the publication of first edition in 1964, the 7th edition is the latest one now. The Dow's method can evaluate and quantify the potential risk of fire, explosion and reaction of process unit and materials contained step by step. The evaluation and quantification is based on the statistics of past accident, the inherent property of materials and existing protection measure for running. Dow's method has been proved to be accurate and reliable, and been widely considered as one of the most important risk index.

The layout design of industrial plant and area is a complex and significant problem. In early time, layout was determined by experiment and intuitive sense. But now many theories and approaches have come up to achieve safer and more economical running of factory. Koopmans and Beckmann (1955) firstly presented layout problem, which aim at increasing benefits for factory. An MINLP approach, in which the impact and cost of protection device is taken into consideration, is developed by Penteado and Ciric (1996) to determine the layout of facilities within a plant, which is relatively complete. Caputo et al. (2015) put forward a mathematical layout model solving by genetic algorithm (GA), in which the evaluation of safety is only based on the peak pressure of facility and relative distance. Patsiatzis and Papageorgiou (2002) combine Dow's method with layout problem to determine the layout of facilities within a plant. Xu et al. (2013) add the constraint of Non-overlap of plants and obtain the layout of industrial area, in which Pasquill-Gifford dispersion model is involved to evaluate the consequence of toxic gas leak and assess safety. All the connection of pipeline is point to point, until Wu and Wang (2017) firstly developed an approach to work out the shortest length of pipeline network in an industrial area, such as steam pipeline network, which is more complicated and practical than the situation of point to point. After that, Wu et al. (2016) determined the layout of an industrial area, taking pipeline network within industrial area into consideration and evaluating the safety using Vapour Cloud Explosion (VCE) model. Previous researches in layout in industrial area level are based on the prediction of consequence of accident. That is not targeted and rough, because we know that plants with advanced control system and good protection device is safer than the plants without these certainly, even they are the same processes. In this work, Dow's method, which is systematic and targeted, is applied to the layout design in industrial area level.

2. Methodology

2.1 Problem statement

In this work, an industrial area including several plants is given. Each plant includes several or just one process units (the partition depends on Dow's method). Each process unit includes several facilities, which generally, just one of these facilities is the main facilities, and others are accessory facilities, such as a reactor and its raw material storage tank and feed pump. Before design, some information, which includes the free space of industrial area and the process technology, operating conditions, manufacture process, protection device and the cost of every plant, should be given. The free space of industrial area will be divided into several equal quadrates whose quantity depends on the number of plants waiting for allocation. The plants will be treated as points which have no size and will be put in the center of the quadrates. What has been done in this work is to determine the layout of these plants in industrial area to make the whole area as safe as possible.

2.2 Dow's Fire & Explosion Index

The safety of plants is evaluated using Dow's Fire & Explosion Index Method. According to Dow's method, every plant should be divided into several process units first, which is based on manufacture process and operating conditions. Then the Material Factor (*MF*), General Process Hazards Factor (F_1), Special Process Hazards (F_2), Process Control Credit Factor (C_1), Material Isolation Credit Factor (C_2) and Fire Protection Credit Factor (C_3) are obtained, which respectively depend on the material that process unit dealing with the operating condition of process unit, whether including special process, control technique, isolation level and fire-fighting equipment. Each factor has several subitems, and the value of each factor is worked out based on the value of these subitems. For each value of subitem, Dow's method has detailed criterion to make sure that the result is systematic and targeted. With these factors, the Process Unit Hazards Factor can be calculated as below:

$$F = F_1 \times F_2 \tag{1}$$

Where F is the Process Unit Hazards Factor, F_1 is General Process Hazards Factor, F_2 is Special Process Hazards Factor.
The Process Unit Hazards Factor indicate the hazard level of process technology and operating conditions. It is distinct that high temperature, high pressure and large quantity of flammable and explosive material in process can obviously increase the hazard level of the process unit, while low temperature, low pressure and small amount is reverse.
The Fire & Explosion Index can be calculated as below:

$$F\&EI = MF \times F \tag{2}$$

Where *F&EI* is the Fire and Explosion Index, *MF* is the Material Factor. *F&EI* indicate the inherent safe level of the process unit. The lower this index is, the safer this process unit is in inherence, which means the handling material and the operating condition is safe. And *F&EI* is independent of protection device. The Material Factor is the most fundamental parameter of Dow's method, which is a measure of the intrinsic rate of potential energy release from fire or explosion produced by combustion or chemical reaction.
Then the Loss Control Credit Factor can be calculated as below:

$$C = C_1 \times C_2 \times C_3 \tag{3}$$

Where C is Loss Control Credit Factor, C_1 is Process Control Credit Factor, C_2 is Material Isolation Credit Factor, C_3 is Fire Protection Credit Factor.
The Loss Control Credit Factor indicate the level of prevention and protection device. The lower it is, the better the prevention and protection device of this process unit is.
Then the corrected F&EI can be obtained as below:

$$Corrected\ F\&EI = F\&EI \times C \tag{4}$$

Corrected F&EI indicates the actual hazards level of the process unit.

2.3 Full Area Hazards Level

The Hazards Index (*HI*) is proposed to indicate how dangerous a plant is. It is the sum of the *corrected F&EI* of each process unit in this plant, as shown below.

$$HI_i = \sum_{j=1}^{n} Corrected\ F\&EI_j \tag{5}$$

Where HI_i is Hazards Index of *i*-th plant, $Corrected\ F\&EI_j$ is Corrected F&EI of *j*-th process unit in *i*-th plant, *n* is the quantity of process unit in *i*-th plant.

For plant A and plant B whose relative location is given, the hazards level of plant B caused by plant A is determined at the same time. And this hazards level is positively associated with the Hazards Index of plant A and the cost of plant B, while is negatively associated with the distance between plant A and plant B. So the index Hazards Level (*HL*) and the formulation below is proposed to indicate the hazards level of plant B caused by plant A.

$$HL_{A,B} = \frac{HI_A \times k_B}{d_{A,B}} \tag{6}$$

Where $HL_{A,B}$ is the hazards level of plant B caused by plant A, HI_A is the Hazards Index of plant A, k_B is the cost (RMB /10^6) of plant B, $d_{A,B}$ is the distance (m) between plant A and plant B.

For a certain layout of industrial area, the Hazards Level of whole area caused by plant A can be described as the sum of Hazards Level of every plant caused by plant A, which is shown below.

$$HL_A = \sum_{i=1}^{n} HL_{A,i} \tag{7}$$

Where HL_A is the hazards level of full area caused by plant A, $HL_{A,i}$ is the Hazards Level of plant *i* caused by plant A, *n* is the quantity of plants within the industrial area.

Each plant can threaten the safety of full industrial area, so the Full Area Hazards Level can be obtained by formulation below:

$$FHL = \sum_{i=1}^{n} HL_i \tag{8}$$

Where *FHL* is the Full Area Hazards Level, which indicate the magnitude of hazards of the whole industrial area. High *FHL* means the layout of industrial area is unreasonable and unsafe, while low *FHL* means the layout reduce the hazards of the entire industrial area. Next, an effect algorithm is used to work out a layout which has the lowest *FHL*.

2.4 Solving algorithm

Genetic algorithm (GA) is used in this work to obtain the solution. GA is a kind of heuristic algorithm which can obtain the relatively optimal solution of a certain problem. Selection, crossover, mutation and other method is involved in GA to search optimal solution, which means GA imitate the evolution process of biology in nature. GA has been widely used in all areas, and has been widely considered one of the most effective solving algorithm.

In this methodology, for a certain industrial area, HI of every plant is worked out manually under the strict implementation of Dow's method. Then they are input into GA. GA randomly generates multiple sets of binary code firstly, and each set of code, called individual, represents a kind of layout. Then GA calculates the FHL of every individual. The individual with highest FHL will be eliminated, while the individual with lowest FHL will get into the next generation directly. Other individuals will exchange some parts of code and get into the next generation. Then some individuals mutates in some position of code (if it was 0, then becomes 1; if it was 1, then becomes 0). After that, a new generation is obtained. GA calculates FHLs of the new generation, and repeat what mentioned above, until a preset value of generation number is reached.

There are other heuristic algorithm, like Simulated Annealing Algorithm (SA). But GA has a parallelism property and spends shorter solution time comparing with other algorithms. Parallelism property means the calculation of FHLs of individuals is independent from each other. So we can calculate an individual in a logical core and calculate several individuals simultaneously by using a multicore processor. This can greatly shorten solution time, while other algorithms cannot.

3. Case study

3.1 Basic data

An actual oil refinery is studied as a case to illustrate the working principle of the layout method we proposed. As the number of plants waiting for arrangement is 9, the free space is divided into 9 equal small quadrates. These plants are arranged as 3 × 3, and the length of each quadrate side is 200 m. Every plant is treated as point, which will be put in the center of quadrate. Information about the plants of process technology, operating condition, manufacturing process, protection device and cost is obtained previously. The cost of plants is shown in Table 1, in which the cost of tank farm includes the cost of construction and the value of stored product.

Table 1: The cost of plants

Number of plants	Name of plants	Cost (10^6 RMB)
1	Atmospheric and vacuum distillation plant	93
2	Catalytic cracking plant	85
3	Tank farm	100
4	Air separation plant	10.8
5	Gasoline hydrogenation plant	50
6	Power station	30
7	Hydrogen production plant	70
8	sewage treatment plant	35
9	Control room	65

3.2 Dow's Fire & Explosion Index

The Dow's method is strictly implemented to evaluate the safety of every plant. Every plant is divided into several process units, and the results is:

Atmospheric and vacuum distillation plant is divided into primary tower, atmospheric furnace, atmospheric tower, vacuum furnace and vacuum tower.

Catalytic cracking plant is divided into reaction regeneration, fractionating, absorption tower, reabsorption tower, desorption tower and stabilizer tower.

Tank farm is divided into crude oil storage tank, gasoline storage tank, kerosene storage tank and diesel storage tank.

Air separation plant includes condensation-evaporator only.

Gasoline hydrogenation plant is divided into prehydrogenation reactor, hydrogenation reactor, stripping tower, reabsorption tower, furnace and stabilizer tower.

Power station includes boiler only.

Hydrogen production plant is divided into compressor, hydrogen desulfurization reactor, reaction furnace, stripping tower, middle shift reactor and PSA.

Besides, sewage treatment plant and control room will be evaluated as a whole respectively.

Then the safety of each process unit is evaluated based on Dow's method strictly, and the results is shown in Table 2.

From the result of safety evaluation using Dow's method in Table 2, it can be seen that the most dangerous plants are catalytic cracking plant and gasoline hydrogenation plant, while the air separation plant is relatively safe (except control room and sewage treatment plant). Although material that air separation plant deals with is incombustible, the F&EI of air separation is not 0. Actually because the temperature of condensation-evaporator of air separation plant is much lower than the melting point of some hydrocarbon, so solid hydrocarbon will accumulate in it. They may be ignited by unknown mechanism in some condition. So air separation plant is still dangerous and the F&EI exists.

Although tank farm contains a lot of material that is flammable and explosive, the hazards level is still relatively low, because the material is not in a handling process. In addition, protection and prevention is good. The points mentioned above are consistent with result of human analysis, which illustrates that the result based on Dow's method is actual and dependable.

Table 2: The result of safety evaluation using Dow's method

Name of plant	Process unit	MF	F_1	F_2	F&EI	C	Corrected F&EI	Plant HI
Atmospheric and vacuum distillation plant	Primary tower	16	1.25	5.83	93.34	0.79	73.73	393.38
	Atmospheric furnace	16	1.25	7.09	113.38	0.81	91.39	
	Atmospheric tower	16	1.25	6.29	100.71	0.79	79.55	
	Vacuum furnace	14	1.25	6.81	95.28	0.79	75.26	
	Vacuum tower	14	1.25	6.64	92.99	0.79	73.45	
Catalytic cracking plant	Reaction regeneration	14	1.45	6.80	95.16	0.73	69.27	539.25
	Fractionating	16	1.25	7.17	114.72	0.81	92.47	
	Absorption tower	21	1.25	5.78	121.34	0.79	95.85	
	Reabsorption tower	21	1.25	5.06	106.23	0.79	83.91	
	Desorption tower	21	1.25	5.36	112.49	0.79	88.86	
	Stabilizer tower	21	1.25	6.56	137.86	0.79	108.90	
Tank farm	Crude oil storage tank	16	1.25	4.31	69.00	0.69	47.72	143.47
	Gasoline storage tank	16	1.25	4.60	73.65	0.69	50.93	
	Kerosene storage tank	10	1.25	3.24	32.41	0.69	22.41	
	Diesel storage tank	10	1.25	3.24	32.41	0.69	22.41	
Air separation plant	Condensation-evaporator	29	1.25	3.51	101.79	0.79	80.40	80.40
Gasoline hydrogenation plant	Prehydrogenation reactor	21	1.55	7.00	147.10	0.79	116.20	525.58
	Hydrogenation reactor	21	1.75	6.60	138.65	0.74	102.98	
	Stripping tower	16	1.25	4.11	65.75	0.79	51.94	
	Reabsorption tower	21	1.25	5.06	106.23	0.77	81.40	
	Furnace	21	1.25	3.99	83.75	0.77	64.17	
	Stabilizer tower	21	1.25	6.56	137.86	0.79	108.90	
Power station	Boiler	21	1.75	6.39	134.17	0.79	105.99	211.97
Hydrogen production plant	Compressor	21	1.25	4.25	89.22	0.79	70.47	405.68
	Hydrogen desulfurization reactor	21	1.45	4.45	93.52	0.81	75.38	
	Reaction furnace	21	1.65	5.94	124.69	0.77	95.54	
	Stripping tower	21	1.25	2.37	49.70	0.79	39.26	
	Middle shift reactor	21	1.55	4.22	88.57	0.79	69.96	
	PSA	21	1.25	3.49	73.38	0.75	55.07	
Sewage treatment plant	Sewage treatment plant	0	0	0	0	0	0	0
Control room	Control room	0	0	0	0	0	0	0

3.3 Result and discussion

The problem was solved in MATLAB platform using GA. The population size is set as 500 and generation was 1000. The optimized result is shown as Figure 1a. Figure 1b and Figure 1c show the cost of plant and the Hazards Index in the optimal arrangement.

From these figures, it can be seen that 4 most dangerous plants, which are catalytic cracking plant, gasoline hydrogenation plant, hydrogen production plant and atmospheric and vacuum distillation plant, are placed in 4 corner of the petrochemical industrial area respectively, which can make the hazard level of other plants caused by these 4 plants as low as possible. The sewage treatment plant has the lowest Hazards Index, which means the hazard level of surrounding plant caused by sewage treatment plant is zero, so it can minimize the full area hazards level to put sewage treatment plant in the center of petrochemical industrial area.

The tank farm is the most expensive plant (including the cost of construction and the value of stored product). If placed in the diagonal position (3th row, 3th column), it will be furthest from the catalytic cracking plant (the most dangerous plant). But at the same time, it will be relatively near to the gasoline hydrogenation plant (the second most dangerous plant). The algorithm intelligently put the tank farm in the position of second row third column, which is relatively far from the two most dangerous plants simultaneously to make a balance.

The cost of air separation plant is the lowest, resulting in the position between the two most dangerous plants. As the two most dangerous plants is put in the left of industrial area, the cost of plants increase in turn from left to right roughly.

This case illustrates how the method we proposed determine the layout of petrochemical industrial area clearly, and proves the method to be effective to reduce the hazards and risk of whole industrial area.

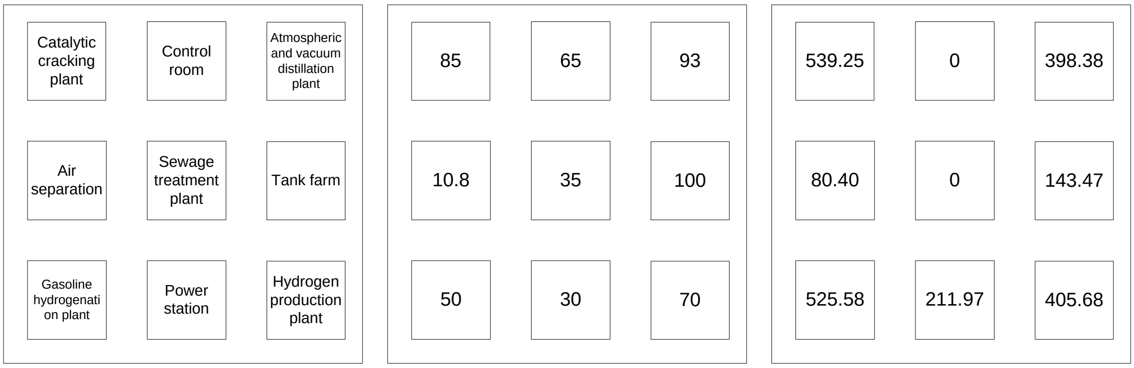

Figure 1a: (a) Optimized layout, (b) the cost of plants (10^6 RMB), and (c) the Hazards Index of plants.

4. Conclusion

A systematic, accurate and scientific method based on Dow’s Fire & Explosion Index Method is proposed to determine the layout of industrial area to reduce the hazards of whole area. In this work, Dow’s method is firstly applied to the layout problem of industrial area level to evaluate the safety of plants. Then Full Area Hazard Level (FHL) is proposed to indicate the hazard level of whole industrial area. FHL takes the layout of the area and the safety evaluation of every plant using Dow’s method into consideration, so that it can distinguish good layout from bad one. GA is used to solve this problem. In the case study, the method we proposed designs the layout of the whole industrial area reasonably. The design separates the expensive plants from the dangerous plants, to reduce hazards and enhance safety. If there are multiple dangerous resource, the method can intelligently arrange the plants to make a balance. And the dangerous plants are pointed out, so that we can enhance management of them in daily operation. This illustrates that the method is effective and practical. And this design takes all process technic and protection devices into consideration, so the method we proposed is more accurate than others.

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