fire

Article

Study on Location of Fire Stations in Chemical Industry Parks from a Public Safety Perspective: Considering the Domino Effect and the Identification of Major Hazard Installations for Hazardous Chemicals

Junhao Jiang [1], Xiaochun Zhang [1,*], Ruichao Wei [2], Shenshi Huang [2,*] and Xiaolei Zhang [3]

1 School of Environment Science and Engineering, Guangdong University of Technology, Guangzhou 510006, China; 2112007003@mail2.gdut.edu.cn
2 School of Architectural Engineering, Shenzhen Polytechnic, Shenzhen 518055, China; rcwei@mail.ustc.edu.cn
3 State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei 230026, China; zxlcjc@ustc.edu.cn
* Correspondence: xczhang1@gdut.edu.cn (X.Z.); huangshenshi@szpt.edu.cn (S.H.)

Abstract: In order to select the location of fire stations more scientifically and improve the efficiency of emergency management in chemical industry parks (CIPs), an improved risk calculation model for hazardous chemicals has been proposed by taking the domino effect and the identification of major hazardous installations for hazardous chemicals into account. In the analysis of the domino effect, the Monte Carlo simulation was used. Then, a location model of the fire stations was established with the optimization objectives of minimizing total cost and maximizing total risk coverage. The solving procedure of the location model is based on the augmented ε-constraint method combined with the TOPSIS method. Finally, a green chemical industry park was used as a case study for the validation and analysis of the location model. The results showed that the improved model could protect the high-risk areas, which is beneficial for the location decisions of fire stations.

Keywords: public safety; hazardous chemicals; chemical industry park; fire stations; location model; domino effect

check for updates

Citation: Jiang, J.; Zhang, X.; Wei, R.; Huang, S.; Zhang, X. Study on Location of Fire Stations in Chemical Industry Parks from a Public Safety Perspective: Considering the Domino Effect and the Identification of Major Hazard Installations for Hazardous Chemicals. *Fire* **2023**, *6*, 218. https://doi.org/10.3390/fire6060218

Academic Editors: Tao Chen, Changkun Chen and Jun Fang

Received: 10 May 2023
Revised: 18 May 2023
Accepted: 22 May 2023
Published: 27 May 2023

1. Introduction

Chemical industry parks (CIPs) are important aspects in achieving a carbon-neutral and green transformation and a high-quality development of the chemical industry. However, CIPs often have potential accident regions composed of hazardous installations, such as hazardous chemical storage tanks, chemical reaction equipment, and production or storage sites. In these areas, the hazardous installations are concentrated, and the consequences of accidents are serious. The production and manufacturing processes in CIPs always involve hazardous substances (toxic, flammable, or explosive), which may lead to major accidents, such as a chemical leakage or the spread of toxic substances and their derived fire and explosion accidents [1]. These initial accidents may spread to the surrounding equipment and facilities, leading to a more serious domino effect [2]. S.P. Kourniotis et al. [3] conducted a statistical analysis of 207 major chemical accidents; their analysis demonstrated that a domino effect occurred in about 39% of the chemical accidents. Indeed, the domino effect can yield catastrophic consequences. For example, the "3.21" chemical explosion in Jiangsu Province, China, in 2019 was caused by the spontaneous combustion of nitrate waste, which eventually led to massive fires and explosions in several storage tanks and warehouses. This chemical explosion resulted in 78 deaths and 716 injuries [4]. Therefore, the potential risk of accidents in CIPs, especially those that may trigger a multilevel domino effect, must be taken into account when conducting emergency management, emergency planning, and risk prevention measures.

The emergency rescue facility in CIPs is an important part of emergency management and emergency response activities, providing various emergency resources (e.g., emergency vehicles, personal protective equipment, etc.) after an accident [5]. In practice, the location of emergency rescue facilities should be determined in advance to ensure emergency preparedness before an accident [6]. China has issued the relevant national standard "Fire Prevention Code of Petrochemical Enterprise Design (GB50160-2008, 2018 Edition)" [7] to guide the emergency management and risk reduction of chemical enterprises. This code describes the basic requirements for the installation of emergency rescue facilities such as fire stations and special mission fire stations. However, each chemical industry park has different potential risks and corresponding risk measures; therefore, quantitative risk assessment of CIPs is needed, and the location decision of facilities must be based on it [8]. De Lira-Flores et al. [9] applied quantitative risk analysis and assessment in the layout planning of hazardous chemical storage tanks in a chemical processing plant, and a mathematical model was built with the aim of finding out the optimal layout of storage tanks and the related safety facilities. Men et al. [10] established an emergency facility location model considering cost, coverage level, and rescue distance, and they accounted for the domino effect in their model. Du et al. [11] analyzed the risks associated with the accident probability and the domino effect in the proposal of emergency resources in a chemical industry park, and they established a hierarchical emergency resource allocation model. Zhao and Ke [12] proposed a method to select the location of chemical emergency facilities based on the results of empirical risk models. Zahiri and Suresh et al. [13] combined the empirical risk model and historical data to solve the siting selection of a hazardous chemical transportation emergency center.

The reasonable location of fire stations could improve the efficiency of emergency management and emergency response in CIPs while reducing the cost of facility construction and emergency rescue operations [10]. Although the multi-level domino effect of hazardous chemical accidents in CIPs has been widely studied, and risk analysis methods have been widely applied in selecting the locations of fire stations, there are still few studies on the location selection of fire stations given the increased risk caused by the multi-level domino effect. Moreover, the traditional risk assessment models used in previous studies cannot characterize the risk differences in different areas of CIPs with a low population density, which will have adverse effects on the emergency management and emergency response activities.

In light of the abovementioned problems, this paper proposes an improved risk calculation method of hazardous chemicals in CIPs—which take into account the domino effect and the identification of major hazardous installations for hazardous chemicals—with the aim of making a more objective assessment of the risk levels of different regions in chemical industry parks. Second, based on the above risk model and grid graph theory, a fire station location model is established, which minimizes the total construction cost and maximizes the sum of the risks covered by the grid. This model can solve the mismatch problem between the risk assessment and emergency response in chemical industry parks with a low population density and catastrophic chain accidents.

2. Risk Assessment Considering Domino Effect and the Identification of Major Hazardous Installations for Hazardous Chemicals

2.1. Risk Analysis and Assessment

Quantitative risk assessment (QRA) usually includes the following main steps: accident scenario identification, probability (frequency) estimation, accident consequence assessment, and risk quantification [14]. Accident scenario identification can be derived from commonly used risk identification methods, such as the event tree approach. In terms of probability (frequency) estimation, this study used Monte Carlo simulation to estimate the accident probability of a hazardous installation under the domino effect. For the accident consequence assessment and quantification, the accident consequence analysis model was used for the quantitative calculation of the escalation probability and personnel death probability. In addition, to facilitate the quantification of risk, a grid-based spatial representation method was used in this study, dividing the study area into $m \times n$ grids with equal-distance steps, denoted as $\Omega = m \times n$, and the distance steps of the grid could be set according to the actual situation.

The definition of risk is the following: risk = probability (frequency) of an accident $\times$ accident consequences [14]. In quantitative risk assessment, individual risk only represents the level of risk at a given location, without regard to the physical presence of an individual, and social risk is generally measured by the product of individual risk and the population density within the region [15], as shown in Equation (1). However, unlike the high population density in cities, the population density in CIPs tends to be low [16], and the result of the product of individual risk and the population density in the region where it is located does not differ significantly. Thus, the social risk calculated using Equation (1) may not be used to establish the regional risk.

$$R = \sum_{m} p_{\Omega,death,m} \cdot p_{accident,m} \cdot \varphi_{\Omega} \tag{1}$$

where R is a mathematical description of the traditional definition of risk. $p_{\Omega,death,m}$ is the consequence of an accident, i.e., the death rate of individuals in a given region Ω caused by an accident m at major hazard installations for hazardous chemicals. $p_{accident,m}$ is the probability of an accident m at major hazard installations for hazardous chemicals. φ_{Ω} is the population density in the region Ω.

In the Chinese national standard "Identification of Major Hazard Installations for Hazardous Chemicals (GB18218-2018)" [17], the identification process of major hazard installations for hazardous chemicals in CIPs considers the correction factor of exposed persons, which better reflects the impact of hazard installations on surrounding persons than directly considering the regional population density. In this regard, the classification index of major hazard installations for hazardous chemicals is introduced in this study, and the coefficient ϕ_m of major hazard installations for hazardous chemicals is defined, as shown in Equations (2) and (3), to further assess the risk of CIPs with low population density attributes. In the process of identifying the major hazard installations for hazardous chemicals, the correction factor of exposed persons is considered, and the number of resident populations within 500m from the plant boundary of the major hazard installations for hazardous chemicals is determined, which can better reflect the potential risk-receiving groups in the area compared with the regional population density. According to Equations (2) and (3), the Identification of Major Hazard Installations for Hazardous Chemicals (GB18218-2018), and the relevant data from hazardous chemical storage units, the level of major hazard installations for hazardous chemicals of each hazardous chemical storage unit and the corresponding coefficient of major hazard installations for hazardous chemicals could be calculated, as shown in Table 1. It should be emphasized that it is not possible to consider all the chemical hazards involved in the chemical industry park in the risk assessment, while previous studies [18–20] considered the major hazard installations as the main aspects of the risk evaluation of the chemical industry park. The major hazard installations region of the chemical industry park should be designated as the key emergency protection area of the chemical industry park [21]. Therefore, major hazard installations for hazardous chemicals deserve more attention than non-major hazards, and it is reasonable to focus on or give priority to major hazard installations in emergency planning with limited inputs. In this study, only major hazard installations for hazardous chemicals are considered in the risk calculation, and major hazard installations are identified for the units in which they are located according to their hazardous characteristics and quantities.

$$r = \alpha \left(\beta_1 \frac{q_1}{Q_1} + \beta_2 \frac{q_2}{Q_2} + \ldots + \beta_n \frac{q_n}{Q_n} \right) \tag{2}$$

$$\phi_m = 5 - r \tag{3}$$

where r denotes the classification index of major hazard installations for hazardous chemicals. α is the correction factor of exposed persons outside the plant area of the major hazard installations of the hazardous chemical. $\beta_1, \beta_2, \ldots, \beta_n$ denotes the correction factor corresponding to each hazardous chemical. $q_1, q_2, \ldots, q_n$ denotes the actual amount of each hazardous chemical in ton. $Q_1, Q_2, \ldots, Q_n$ denotes the critical amount corresponding to each hazardous chemical in tons. The values of α, β, and Q are detailed in the Chinese national standard.

Table 1. Correspondence between the level and coefficient of major hazardous installations for hazardous chemicals.

Level$r$	Coefficient ϕ_m
Level 1 ($r = 1$)	4
Levle 2 ($r = 2$)	3
Level 3 ($r = 3$)	2
Level 4 ($r = 4$)	1

The information related to all locations in the study area is represented by the coordinates of the grid in which they are located, and the Euclidean distance calculation is used for the distances. Under this premise, this study evaluates the integrated risk generated by each hazard installation for hazardous chemicals in the chemical industry park in the event of accidents. Based on the traditional risk framework, the risk of hazard installations for hazardous chemicals in CIPs is defined, and an improved risk model is proposed, the specific mathematical expression of which is shown in Equation (4):

$$R' = \sum_m p_{\Omega,death,m} \cdot p_{domino,accident,m} \cdot \phi_m \tag{4}$$

where $p_{domino,accident,m}$ denotes the probability of accident m of hazard installations for hazardous chemicals under the influence of domino effect. ϕ_m denotes the coefficient of major hazard installations for hazardous chemicals defined in this study. The risk model applies to both production facilities and storage facilities involving major hazard installations for hazardous chemicals in chemical industry parks, and it is only applicable to the cases where major hazard installations for hazardous chemicals are given priority.

2.2. Estimation of Accident Probability of Hazard Installations for Hazardous Chemicals Considering Domino Effect

In this study, the Monte Carlo simulation method proposed by Abdolhamldzade et al. [22] was used for the estimation of the hazard installations accident probability for hazardous chemicals under the influence of the domino effect, which has unique advantages in simulating the interaction of subsystems within a complex system. After inputting parameters such as the number of hazard installations for hazardous chemicals, accident probability (frequency), escalation probability, and the number of simulation iterations, the accident probability of hazard installations for hazardous chemicals under the first-level domino effect could be estimated based on the domino effect of "the probability of an initial accident is greater than the probability of escalation" and through the theory of random numbers. The process is specified as follows: The risk identification is conducted or an accident tree is made. The probability (frequency) of the initial accident occurring is then determined. If the escalation probability between the initial accident and the subsequent storage tank is greater than a random number R, the initial accident is considered to cause the subsequent tank to fail, and thus the domino effect occurs. The related calculation of the high-level domino effect could be done in the same way. Among them, the occurrence probability of an initial accident could be derived from historical accident statistics. The escalation probability is determined after the accident scenario and the initial accident are determined. The Monte Carlo simulation is highly applicable to the domino effect system with uncertainty and complexity [23], and its calculation process and steps are shown in Figure 1.

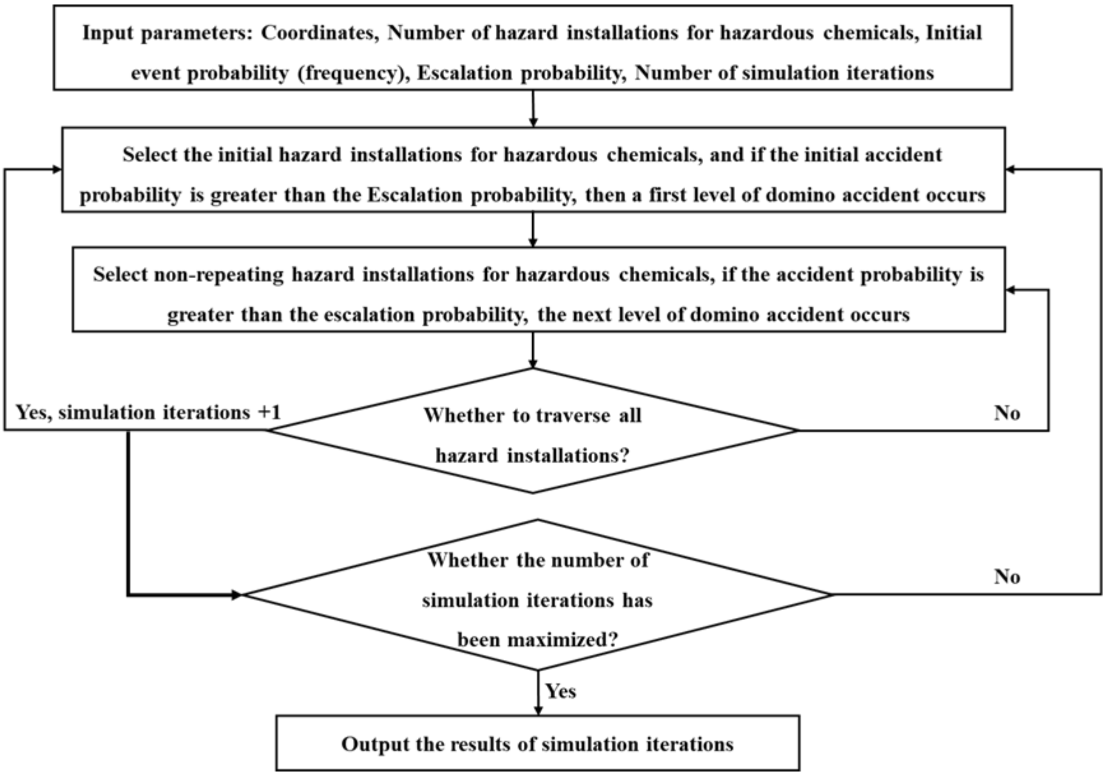

Figure 1. Flow chart of Monte Carlo simulation method to estimate the probability of hazard installations for hazardous chemicals accidents.

3. Mathematical Model for Locating Fire Stations

3.1. Description of the Problem

Assume that the set of emergency rescue demand points (production units or storage units of hazardous chemicals are considered demand points, which are hazardous chemical storage tank regions in this study) in a chemical industry park is S, $\forall s \in S$, and the set of candidate fire stations is I, $\forall i \in I$. D_{is} is the Euclidean distance between the candidate fire station i and the demand point s. C_i is the construction cost of the candidate fire stations, which consists of the fixed construction cost of the facility, the acquisition cost of rescue vehicles accommodated in the facility, and their unit prices are assumed to be 5 million RMB and 500,000 RMB, respectively. S_i is the supply of emergency resources for the candidate fire station, which is generally supplied according to a 20% margin [24]. R_s is the demand for emergency resources. RES_i is the maximum emergency resource capacity of the candidate fire station. X_i takes the value 1 when the candidate fire station i is identified for construction and 0 when the opposite is true. Y_{is} takes the value 1 when the fire station s provides emergency services for the demand point and 0 when the opposite is true. They are all decision variables of type 0–1.

This study constructed a bi-objective mathematical model for locating fire stations, with the optimization of minimizing the total construction cost and maximizing the total risk coverage. The risk caused by domino effect accidents and the identification of major hazard installations for hazardous chemicals are taken into account in this mathematical model. At the same time, the mathematical model also considers the quality differences of emergency services and describes them using a decay function, which is a function of the distance between the fire stations and the demand points.

3.2. Construction of the Mathematical Model

The probability of more than two major accidents occurring simultaneously in a chemical industry park is relatively low. Therefore, this study follows the previous definition of simultaneous accidents of two or more hazard installations for hazardous chemicals, i.e., they occur simultaneously within a relatively short period, and the emergency response process for hazardous chemical accidents usually lasts for a considerable period [11], so that the required emergency resources for all regions where accidents occur need to be prepared within a short period. In addition, the following conditions are assumed and set in this study:

1. This study did not consider the effect of road traffic conditions and vehicle travel status on time;
2. Each candidate fire station met the safety requirements to provide emergency rescue to the point of need;
3. The total risk covered by the emergency response facilities in providing emergency services to the demand points was expressed as the sum of the risk values of the grid they pass through on the line segment connected by two, denoted as CR_{is}. Meanwhile, the decay function is used to express the quality difference of the emergency services [25], as shown in Equation (5):

$$\psi = e^{-kD_{is}^{\gamma}} \tag{5}$$

where, D_{is} is the distance between the candidate fire station i and the demand point $s(\mathrm{m})$. k and γ denote the sensitivity factor of the decay function ψ. They take values in the range of [0, 0.5] and [2, 5];
4. Among all the emergency resources required for hazardous chemical accidents, the amount of foam required to handle hazardous chemical accidents in the normal mission fire station, special mission fire station, or enterprise fire station was selected as a representative emergency resource for calculation.

The amount of foam fluid required for a particular storage tank area is shown in Equation (6) [17]:

$$R_s = \omega \frac{\alpha A q t}{1000\beta} \tag{6}$$

where R_s is the amount of foam (m^3), i.e., the emergency resource requirement in this study. ω is the operational factor, which is determined according to the actual situation, and which takes the value of 1.5 in this study. α is the proportion of foam, which is set to 6%. β is the foam multiplier, which is set to 6.25. A is the area that needs emergency disposal (m^2), which is generally the size of the liquid surface. q is the supply strength of foam $(\mathrm{L}/(\mathrm{min}{\cdot}\mathrm{m}^2))$, which is set to 12. t is the continuous supply time of foam (min), which is set to 60 in this study.

Based on the abovementioned assumptions, the following mathematical model for locating emergency rescue facilities is established:

$$MaxZ_1 = \sum_{i\in I}\sum_{s\in S} Y_{is}\cdot\psi\cdot CR_{is} \tag{7}$$

$$MinZ_2 = \sum_{i\in I} X_i\cdot C_i \tag{8}$$

s.t.

$$\sum_{i\in I} Y_{is}\cdot S_i \geq R_s, \forall s \in S \tag{9}$$

$$\sum_{s\in S} Y_{is}\cdot S_i \leq X_i\cdot RES_i, \forall i \in I \tag{10}$$

$$Y_{is} \leq X_i, \forall i \in I, \forall s \in S \tag{11}$$

$$X_i \in \{0,1\}, Y_{is} \in \{0,1\}, \forall i \in I, \forall s \in S \quad (12)$$

The objective function Equation (7) represents the sum of the risk values covered by the maximized fire stations. The objective function Equation (8) represents minimizing the total cost of building fire stations. Equations (9)–(12) are constraints, where Equation (9) indicates that the emergency resource requirements of each potential accident area must be met; Equation (10) indicates that the amount of emergency resources provided by each fire station cannot exceed its capacity limit; Equation (11) indicates that emergency services can be performed only after the fire station is confirmed to have been constructed; and Equation (12) indicates the range of values of decision variables.

3.3. Methods and Steps for Solving the Mathematical Model

The location model for fire stations in CIPs proposed in this study is a mixed integer linear optimization model with bi-objectives. In this model, the cost is measured in monetary terms (RMB) and the risk is quantified in terms of the probability of human fatalities due to accidents at hazard installations for hazardous chemicals in the demand point. The model used an improved risk model and a modeling network different from the traditional location model, thus providing novel ideas and solutions to deal with emergency management and emergency response in CIPs. Based on the characteristics and solution requirements of the model, this study used the augmented ε-constraint method to solve the model and generate feasible solution sets. The augmented ε-constraint method is a multi-objective problem-solving algorithm that is both theoretically and computationally attractive, and it has been widely used in multi-objective optimization problems in logistics and transportation and location selection planning [26]. Finally, the feasible solution is preferred by the TOPSIS method to arrive at the optimal solution [27]. Decision-making and risk management based on prioritized ranking results is a common tool in fire risk assessment and control [28]. A detailed description of the method and steps is shown in Algorithm 1.

Algorithm 1. Methodology and detailed steps for solving the optimal solution of fire station location model

Augmentedε-Constraint Method to Find the Pareto Solutions—TOPSIS Method to Optimize the Pareto Solutions

Step 1 Input data and relevant parameters.
Step 2 The optimal and inferior values of the objective functions Z_1 and Z_2 are solved with lexicographic optimization [29]:
  2.1 $MinZ_1(X)$, s.t. Equations (9)–(12), output $x_1 = (z_1^*, z_2)$
  2.2 $MaxZ_2(X)$, s.t. Equations (9)–(12), output $x_2 = (z_1^*, z_2^*)$
  2.3 Perform step 2.1 for $Z_2(X)$
  2.4 Obtain the optimal and inferior values of the objective functions Z_1 and Z_2
Step 3 Make $\eta = 0$ and set the value of λ
Step 4 Execute the following loop to generate the Pareto solution of the model.
  4.1 When $\eta \leq \lambda$,
    Execute:
    $MinZ_2 - \frac{\rho \cdot \mu_1}{\nu_1}$
    s.t. Equations (9)–(12) and
    $Z_1 + \mu_1 = Z_1^{Max} - \frac{\eta \cdot \nu_1}{\lambda}$
    $\mu_1 \geq 0$
    $\eta = \eta + 1$
    End
  4.2 Output all Pareto solutions
Step 5 The Pareto solutions derived from step 4 are preferred using the TOPSIS method.
Step 6 The preferred solution is output according to the ranking result of TOPSIS, i.e., the best fire stations locating solution.

In the complex context of emergency management and planning in CIPs, this study solved the fire station location model by transforming the objective of minimizing the total cost into a constraint to optimize the objective of total risk. The advantage of this is that if the decision makers have a requirement for the future risk level of the chemical industry park, the location options for fire stations at different risk level requirements could be obtained more easily by adjusting the range of the objective function of the total cost (i.e., the decision makers adjust the total cost budget).

4. Analysis of the Case

4.1. Information about the Case

To prove the effectiveness of the proposed method in this study, the information and data about hazardous chemical storage tank regions in a green chemical industry park in the literature [10] were used as the case, and the arithmetic data were supplemented based on the proposed method above, including the gridded coordinates of each storage tank region, the emergency disposal area, the demand for emergency resources, and the identification coefficients of major hazard installations for hazardous chemicals. Detailed information on storage tank regions is shown in Table 2. The gridded layout of storage tank regions and candidate fire stations is shown in Figure 2, where the black squares represent the storage tank regions for hazardous chemicals and the diagonal shaded triangles represent the candidate fire stations.

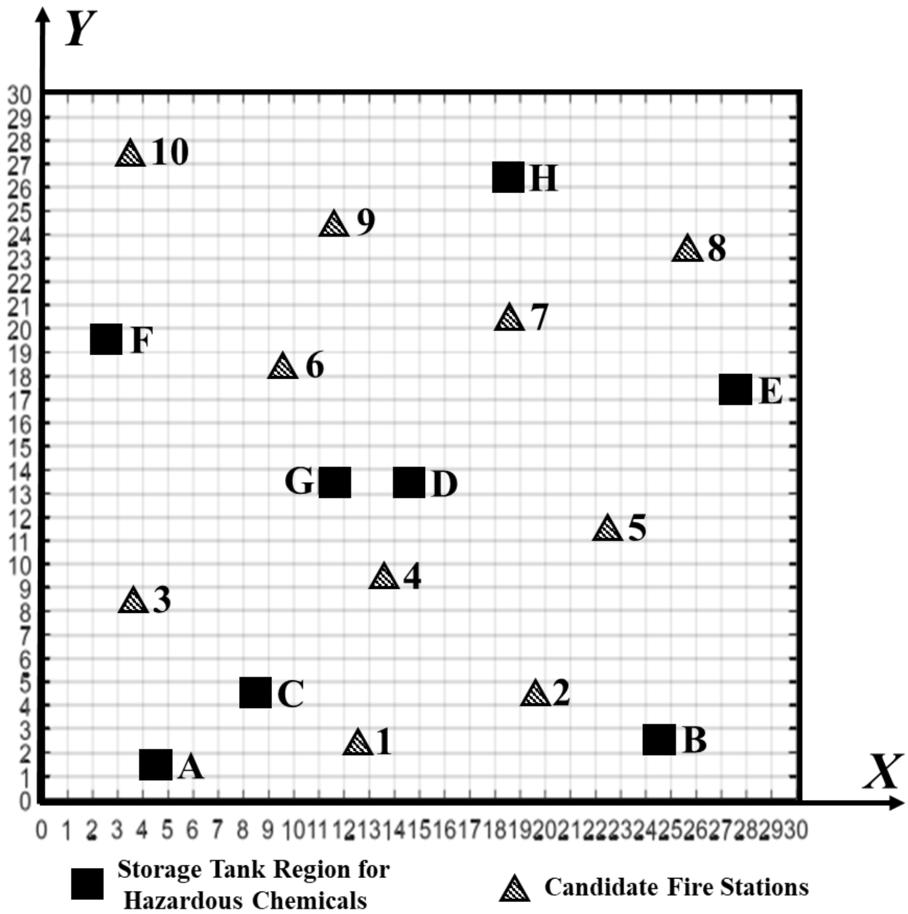

Figure 2. Demand points and candidate fire stations layout. The number in this figure indicates the code of the candidate fire station, and the letter indicates the code of the storage tank region for hazardous chemicals.

Table 2. Case information—Storage tank regions for hazardous chemicals.

No.	Substances	Types of Accidents	Reserves (ton)	Types of Storage Tanks	ϕ_m	Gridding Coordinates	A (m^2)	R_s (m^3)
A	LNG	UVCE	175	Atmospheric	3	(5, 2)	452	5
B	Liquid ammonia	UVCE	170	Pressure	4	(25, 3)	314	3
C	Chlormethane	UVCE	160	Atmospheric	2	(9, 5)	200	2
D	Ethane	UVCE	265	Atmospheric	2	(15, 14)	615	6
E	Oxirane	BLEVE	130	Atmospheric	3	(28, 18)	200	2
F	HFO	BLEVE	135	Atmospheric	1	(3, 20)	200	2
G	Methylal	BLEVE	170	Pressure	3	(12, 14)	379	4
H	LPG	BLEVE	235	Atmospheric	3	(19, 27)	452	5

Due to the volatility of the construction cost of fire stations and the sensitivity of the actual construction engineering data, the parameters related to fire stations in this study were obtained by making assumptions based on actual data and generating them randomly. Detailed information on each candidate fire station is presented in Table 3.

Table 3. Case information—candidate fire stations.

No.	Construction Cost ($\times 10^4$RMB)	Maximum Capacity of Emergency Resources	Gridding Coordinates
1	950	9	(13, 3)
2	900	8	(20, 5)
3	900	8	(4, 9)
4	950	9	(14, 10)
5	900	8	(23, 12)
6	950	9	(10, 19)
7	900	8	(19, 21)
8	1000	10	(26, 24)
9	1000	10	(12, 25)
10	900	8	(26, 24)

4.2. Results of the Risk Assessment and Its Analysis

According to the risk assessment method based on the domino effect and the identification of major hazard installations for hazardous chemicals proposed above, the risk assessment of the case was carried out. The grid division of the case was 30×30, the grid distance step was 200 m, and the number of iterations of the Monte Carlo simulation was set to 10^6. The level of the domino effect was set to 2. The accident frequency values for both UVCE and BLEVE were based on previous studies [30]; they were: 3×10^{-6} and 3.74×10^{-5}, respectively. The calculation platform used was Matlab R2021a. The calculation results are shown in Figure 3.

Figure 3a,b shows the results of the three-dimensional distribution of risk assessment corresponding to the risk models R' and R, respectively. It could be seen that, in the overall distribution of risk results, the high-risk region and the storage tank region are consistent, with the risk distribution from the center of the storage tank region outward gradually decreasing. The risk model R' derived from the peak risk of the storage tank regions was higher than the risk model R, which is due to the domino effect resulting in a higher accident probability and the common effect of the major hazard installations for hazardous chemicals identification coefficient. The risk peak in the center of the case was the highest because of the proximity of the storage tank regions D and G, which produce the most significant risk superposition effect. It is worth noting that after considering the domino effect and the major hazard installations for hazardous chemicals identification coefficient, the risk distribution and peak value of each storage tank region change, among which the more prominent is the area where the storage tank regions B and F are located, especially the storage tank region B. The reason for this is that the major hazard installations for hazardous chemicals identification coefficient corresponding to this storage tank region is 4. However, compared with the other storage tank regions, the risk gain brought about by its major hazard installations for the hazardous chemicals identification coefficient is greater. The risk gain is greater than in other storage tank regions, but it is less affected by the domino effect compared with the other storage tank regions. While the major hazard classification factor for the storage tank region F is smaller, its regional risk peak under the influence of the domino effect is still higher than that without considering the domino effect.

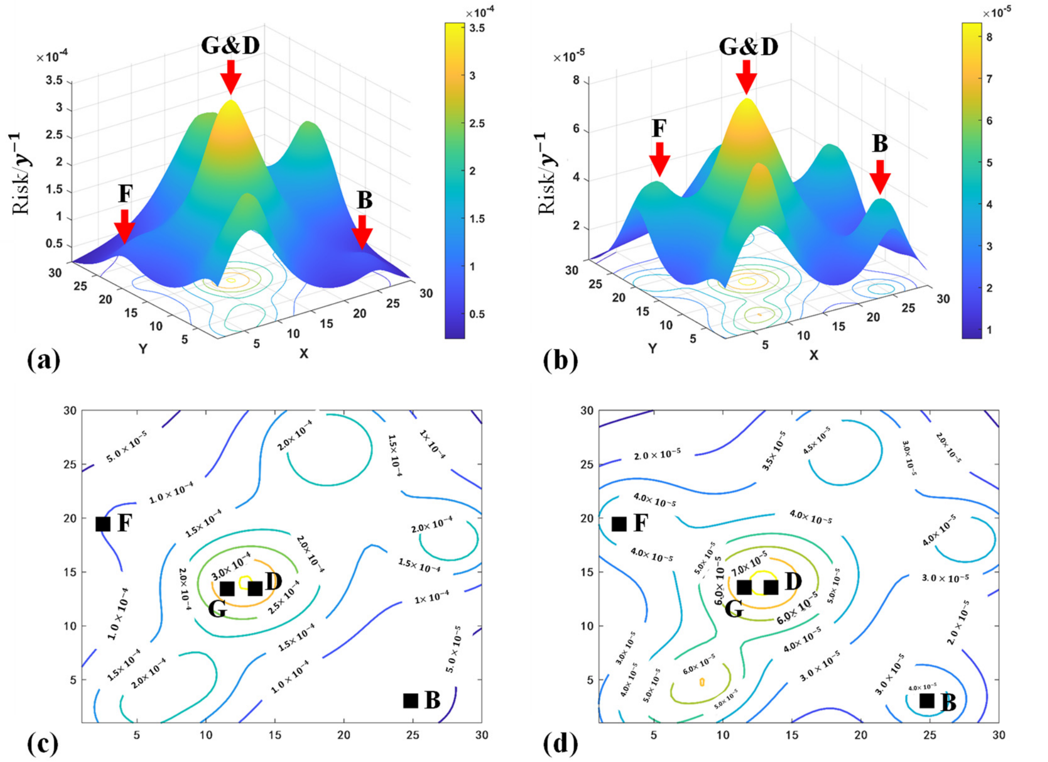

Figure 3. Results of the risk assessment. (**a**,**c**) show the 3D view and 2D contour plot of the results of the risk model R', respectively. (**b**,**d**) then show the corresponding result plots for the risk model R, respectively. The black squares represent hazardous storage tank region for hazardous chemicals, and the letters are their codes.

Figure 3c,d shows the results of the two-dimensional contour distribution of the risk assessment results corresponding to the risk models R' and R, respectively. From them, it could be seen that after considering the domino effect and the major hazard installations for hazardous chemicals identification coefficient, the difference in the overall risk distribution of the region was further increased, and the risk values of the whole region were larger than those of the risk model R, which further illustrated the gain effect of the domino effect and the major hazard installations for hazardous chemicals identification coefficient. Based on the ALARP principle, the acceptable risk criterion for the region with a lower population density is 3×10^{-5}. Obviously, the acceptable risk criterion line of risk models R' was shifted back relative to the risk model R, which indicated an increase in the range of unacceptable risk. In addition, in each storage tank region of the case, the risk results obtained from the improved risk model of this study showed significant differences in risk level and risk distribution compared to the calculated results of the risk model of the previous study (Figure 9a,b of the literature [10]).

4.3. Results and Analyses of the Location Model for Fire Stations

According to the proposed model-solving method and steps, the fire station location model was solved. The solution parameters were set as follows: the sensitivity factors k and γ for the decay function were 0.5 and 2, respectively. The values of λ and ρ for the augmented ε-constraint method were 5 and 10^{-4} [26]. The value of λ set to 5 represents the number of solutions finally solved by the augmented ε-constraint method. The value of λ is not fixed and could be customized by the decision maker according to the actual decision needs. In order to compare the impact of the difference in risk assessment results between the risk models R' and R on the locating decision of the fire stations, the location models under the above two risk models were solved separately. The results arere summarized in Table 4.

Table 4. Results of the cases solution.

Risk Models	TOPSIS Rank	Total Covered Risk	Total Cost	Optimal Solution
$R' = \sum_m p_{\Omega,death,m} \cdot p_{domino,accident,m} \cdot \phi_m$	5	0.0122	9350	1, 2, 3, 4, 6, 7, 8, 9
	4	0.0113	8400	
	1	0.0096	7550	
	3	0.0101	7450	
	2	0.0086	7350	
$R = \sum_m p_{\Omega,death,m} \cdot p_{accident,m} \cdot \varphi_\Omega$	5	0.0038	9350	1, 2, 3, 4, 5, 6, 7, 10
	4	0.0035	8400	
	3	0.0032	7500	
	2	0.0031	7400	
	1	0.0028	7350	

In the results obtained using the TOPSIS method, the higher the overall score of the solution, the higher it is ranked. The two solutions from the TOPSIS result ranked 1 were the optimal location selection solutions for risk models R' and R. In terms of the objective function results, the optimal location solution for the risk model R' covered approximately 3.4 times the total risk value of that of the risk model R, with a change rate of 242.86%, while the total cost only increased by 2.7%. The optimal location option of the risk model R' focused more on the high-risk regions in the center of the case, while the optimal location option of the risk model R was more evenly distributed, notably for the fire stations numbered 5 and 10, which did not appear in the optimal location options for the risk model R. This was because the fire stations numbered 5 and 10 were located closer to the storage tank regions B and F. From the regional risk assessment results above, it could be seen that after taking into account the domino effect and the major hazard installations for hazardous chemicals identification coefficient, the risks in the regions where the storage tank regions B and F were located were more variable, and they were relatively weaker compared to the regional center. Therefore, under the risk assessment results of the risk model R', the fire stations numbered 5 and 10 were not included in the corresponding location selection plan. Accordingly, the fire station numbered 9 was included in the location selection option due to its proximity to the high-risk regional center. Figure 4a shows the optimal location plan for the fire stations from the previous study [10], where the green square (with red boxes) is the location of the facilities. In that location plan, the higher risk regions were not built with fire stations, especially in the middle of the region. Moreover, Figure 4b shows the best location plan for the fire stations in this study. At the level of focusing on the impact of risk outcomes on locating decisions, the optimal location option of this study focused more on emergency planning in high-risk regions compared to the literature, and the distribution of fire station locations is more reasonable compared to that.

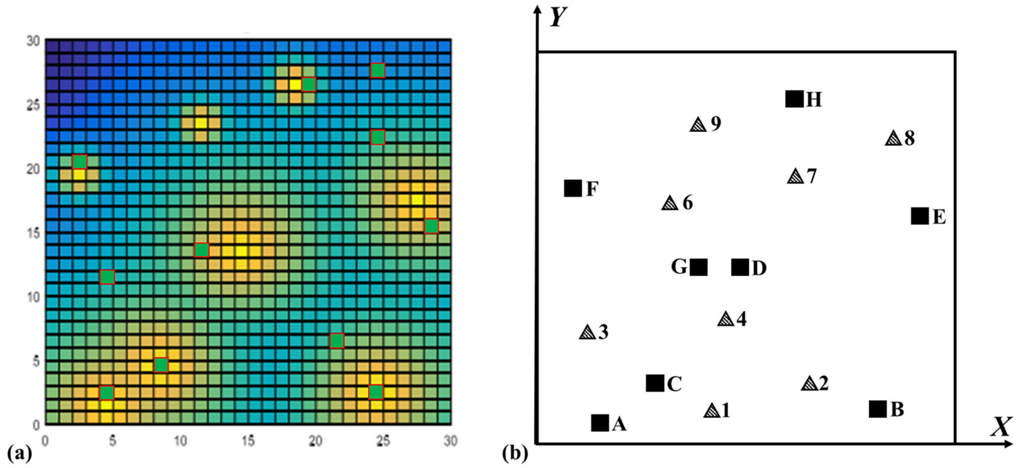

Figure 4. Comparison of the best location options for fire stations. (**a**) showed the optimal location plan derived from the literature [10], where the green squares (with red boxes) are the fire stations in this scheme. (**b**) showed the optimal location plan derived from this study. In Figure 4a, the yellow color indicates the area with high risk, and its darker color represents the deeper risk. And this risk decreases from the center to the surrounding.

5. Conclusions

A bi-objective fire station location optimization model based on an improved risk calculation model is established in this study for the emergency planning of major hazard installations for hazardous chemicals in CIPs. A case study of a green chemical industry park is conducted to demonstrate the location optimization model. The major findings of this study include the following:

1. In the location problem of fire stations, the domino effect and the classification of major hazard installations for hazardous chemicals could have a comprehensive impact on the location decision of fire stations.
2. The improved risk calculation model that integrates the domino effect and the classification of the major hazard installations for hazardous chemicals could highlight the differences in risk levels and their distribution in the regions with different hazard installations.
3. At the level of focusing on the impact of the risk results on locating decisions, the location optimization model developed in this study could make the location results of fire stations pay more attention to high-risk regions. In the results of the case study, an increase of only 2.7% in total cost resulted in a 242.86% increase in total risk covered.

Author Contributions: Conceptualization, J.J. and S.H.; Methodology, J.J. and X.Z. (Xiaochun Zhang); Formal analysis, X.Z. (Xiaolei Zhang) and R.W.; Investigation, J.J., S.H. and X.Z. (Xiaochun Zhang); Resources, X.Z. (Xiaochun Zhang) and S.H.; Writing—original draft preparation, J.J. and X.Z. (Xiaochun Zhang); Visualization, X.Z. (Xiaolei Zhang) and R.W.; Data curation, J.J. and X.Z. (Xiaochun Zhang); Project administration, X.Z. (Xiaochun Zhang) and S.H.; Software, J.J.; Supervision, X.Z. (Xiaochun Zhang) and S.H.; Funding acquisition, X.Z. (Xiaochun Zhang) and S.H.; Writing—review and editing, J.J. All authors have read and agreed to the published version of the manuscript.

Funding: This study is supported by National Natural Science Foundation of China (Grant No. 52276108), Key-Area Research and Development Program of Guangdong Province (Grant No. 2019B111102003), Science and Technology Program of Guangzhou (Grant No. 202201010555) and Scientific Research Startup Fund for Shenzhen High-Caliber Personnel of SZPT (6023330004K).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sets generated during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Zhou, Y.; Liu, M. Risk Assessment of Major Hazards and Its Application in Urban Planning: A Case Study: Risk Assessment of Major Hazards. *Risk Anal.* **2012**, *32*, 566–577. [CrossRef] [PubMed]
2. Yang, M. Integrating Safety and Security Management to Protect Chemical Industrial Areas from Domino Effects. *Reliab. Eng. Syst. Saf.* **2022**, *191*, 106470.
3. Kourniotis, S.P.; Kiranoudis, C.T.; Markatos, N.C. Statistical Analysis of Domino Chemical Accidents. *J. Hazard. Mater.* **2000**, *71*, 239–252. [CrossRef] [PubMed]
4. Zhang, N.; Shen, S.; Zhou, A.; Chen, J. A Brief Report on the March 21, 2019 Explosions at a Chemical Factory in Xiangshui, China. *Proc. Saf. Prog.* **2019**, *38*, e12060. [CrossRef]
5. Zhang, J.-H.; Sun, X.-Q.; Zhu, R.; Li, M.; Miao, W. Solving an Emergenc-y Rescue Materials Problem under the Joint Reserves Mode of Government and Framework Agreement Suppliers. *PLoS ONE* **2017**, *12*, e0186747. [CrossRef]
6. Zhao, M.; Chen, Q. Risk-Based Optimization of Emergency Rescue Facilities Locations for Large-Scale Environmental Accidents to Improve Urban Public Safety. *Nat. Hazards* **2015**, *75*, 163–189. [CrossRef]
7. Wang, J. Discussion on Fire Prevention Code for Petrochemical Enterprise Design (GB 50160). *Pet. Refin. Eng.* **2005**, *35*, 59.
8. Cozzani, V.; Reniers, G. *Dynamic Risk Assessment and Management of Domino Effects and Cascading Events in the Process Industry*; Elsevier: Amsterdam, The Netherlands, 2021.
9. de Lira-Flores, J.A.; Gutiérrez-Antonio, C.; Vázquez-Román, R. A MILP Approach for Optimal Storage Vessels Layout Based on the Quantitative Risk Analysis Methodology. *Process Saf. Environ. Prot.* **2018**, *120*, 1–13. [CrossRef]
10. Men, J.; Jiang, P.; Zheng, S.; Kong, Y.; Zhao, Y.; Sheng, G.; Su, N.; Zheng, S. A Multi-Objective Emergency Rescue Facilities Location Model for Catastrophic Interlocking Chemical Accidents in Chemical Parks. *IEEE Trans. Intell. Transport. Syst.* **2020**, *21*, 4749–4761. [CrossRef]
11. Du, Y.; Xiao, H.; Sun, J.; Duan, Q.; Qi, K.; Chai, H.; Liew, K.M. Hierarchical Pre-Positioning of Emergency Resources for a Chemical Industrial Parks Concentrated Area. *J. Loss Prev. Process Ind.* **2020**, *66*, 104130. [CrossRef]
12. Zhao, J.; Ke, G.Y. Optimizing Emergency Logistics for the Offsite Hazardous Waste Management. *J. Syst. Sci. Syst. Eng.* **2019**, *28*, 747–765. [CrossRef]
13. Zahiri, B.; Suresh, N.C. Hub Network Design for Hazardous-Materials Transportation under Uncertainty. *Transp. Res. Part E Logist. Transp. Rev.* **2021**, *152*, 102424. [CrossRef]
14. Freeman, R.A. CCPS Guidelines for Chemical Process Quantitative Risk Analysis. *Plant Oper. Prog.* **1990**, *9*, 231–235. [CrossRef]
15. Lees, F. *Lees' Loss Prevention in the Process Industries: Hazard Identification, Assessment and Control*; Butterworth-Heinemann: Oxford, UK, 2012.
16. Rui, W.; Mingguang, Z.; Yinting, C.; Chengjiang, Q. Study on Safety Capacity of Chemical Industrial Park in Operation Stage. *Procedia Eng.* **2014**, *84*, 213–222. [CrossRef]
17. Cong, L.; Ke, X.; Qian, L.; Yunsheng, Z. Discrimination of Relevant Concepts of Safety Risk Classification Control. *China Saf. Sci. J.* **2019**, *29*, 43.
18. Basheer, A.; Tauseef, S.M.; Abbasi, T.; Abbasi, S.A. A Template for Quantitative Risk Assessment of Facilities Storing Hazardous Chemicals. *Int. J. Syst. Assur. Eng. Manag.* **2019**, *10*, 1158–1172. [CrossRef]
19. Pak, S.; Kang, C. Increased Risk to People around Major Hazardous Installations and the Necessity of Land Use Planning in South Korea. *Process Saf. Environ. Prot.* **2021**, *149*, 325–333. [CrossRef]
20. Sebos, I.; Progiou, A.; Symeonidis, P.; Ziomas, I. Land-Use Planning in the Vicinity of Major Accident Hazard Installations in Greece. *J. Hazard. Mater.* **2010**, *179*, 901–910. [CrossRef]
21. Xu, X.; Zhu, H. Fire Station Planning Method Based on Identification of Major Hazards in Chemical Parks. In Proceedings of the Annual Scientific and Technical Conference of the China Fire Protection Association, 2020, Beijing, China, 23 September 2020. (In Chinese)
22. Abdolhamidzadeh, B.; Abbasi, T.; Rashtchian, D.; Abbasi, S.A. A New Method for Assessing Domino Effect in Chemical Process Industry. *J. Hazard. Mater.* **2010**, *182*, 416–426. [CrossRef]
23. Vose, D. *Risk Analysis: A Quantitative Guide*; John Wiley & Sons: Hoboken, NJ, USA, 2008.
24. Kai, K.; Tao, C.; Hongyong, Y. Cooperative Scheduling Model for Multi-Level Emergency Response Teams. *J. Tsinghua Univ. (Sci. Technol.)* **2016**, *56*, 830–835.
25. Berman, O.; Krass, D. The Generalized Maximal Covering Location Problem. *Comput. Oper. Res.* **2002**, *29*, 563–581. [CrossRef]
26. Zhao, J.; Wu, B.; Ke, G.Y. A Bi-Objective Robust Optimization Approach for the Management of Infectious Wastes with Demand Uncertainty during a Pandemic. *J. Clean. Prod.* **2021**, *314*, 127922. [CrossRef] [PubMed]

27. Li, X.; Wang, K.; Liu, L.; Xin, J.; Yang, H.; Gao, C. Application of the Entropy Weight and TOPSIS Method in Safety Evaluation of Coal Mines. *Procedia Eng.* **2011**, *26*, 2085–2091. [CrossRef]
28. Nan, S.; Li, K.; Li, P.; Tang, F.; Baolati, J.; Zou, Y.; Tu, J.; Jin, Y. A Novel Method for Priority Assessment of Electrical Fire Risk in Typical Underwater Equipment Cabins in China. *Fire Technol.* **2022**, *58*, 2441–2462. [CrossRef]
29. Mavrotas, G. Effective Implementation of the ε-Constraint Method in Multi-Objective Mathematical Programming Problems. *Appl. Math. Comput.* **2009**, *213*, 455–465. [CrossRef]
30. He, Z.; Weng, W. A Dynamic and Simulation-Based Method for Quantitative Risk Assessment of the Domino Accident in Chemical Industry. *Process Saf. Environ. Prot.* **2020**, *144*, 79–92. [CrossRef]