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Two-Level Programming Model Based on Cooperative Operation Study of Stakeholders in Hazardous Chemical Storage

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Abstract: Due to the uncertainty of risk occurrence and the severity of accident consequences in the process of hazardous chemical storage, there are many stakeholders involved in the management and supervision of hazardous chemical storage, and their interest appeals are different. On the basis of ensuring storage safety, in order to balance the interests of stakeholders and achieve cooperative operation, a two-level programming model considering the maximization of social welfare and the interests of warehousing enterprises was proposed. First, the upper model mainly refers to the regulatory department represented by the government, including the daily supervision cost, risk loss cost, risk compensation cost, and penalty coefficient formulated by combining various indicators. In the lower model, the comprehensive risk level of the warehouse is determined by the warehouse enterprise. Based on this, the supervision coefficient is determined. Combined with the punishment coefficient, the warehousing operation cost, warehousing supervision cost, and the punishment cost when the accident occurs under different risk levels are determined. The relevant case analysis shows that, compared with the evolutionary game model, the social supervision cost of the upper level and the enterprise cost of the lower level can be reduced by 0.49% and 30.43% respectively. Compared with the traditional improved particle swarm optimization algorithm, the proposed algorithm can reduce the supervision cost of the upper society and the lower enterprise by 0.11% and 7.05%, respectively, thus achieving a better supervision effect at a relatively low cost.

Keywords: hazardous chemical warehousing; two-level programming model; stakeholder; cooperative operation; penalty coefficient; improved adaptive particle algorithm

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1. Introduction

Due to the special physical and chemical properties of hazardous chemicals, special protective measures must be taken in the process of storage, transportation, production, and waste disposal. Otherwise, once an accident occurs, it will not only cause property loss, casualties, and environmental pollution, but also cause serious negative social impact. It is precisely because of the danger of hazardous chemicals that there are many stakeholders involved in the construction, operation, and supervision of hazardous chemicals storage facilities. Additionally, their interests are different, so there are multiple cooperative game problems. On the other hand, because the two-level programming model has the characteristics of hierarchy, independence, priority, and autonomy, it can effectively balance the interests of multiple stakeholders. Thus, the stakeholders can achieve the goal of cooperative operation under the premise of equality and mutual benefit of multiple stakeholders. This is also a kind of operation model that guarantees the normal operation of the main enterprises' rights and obligations.

Regarding the research on the risk of hazardous chemicals, scholars have adopted different research methods according to the characteristics of the subject. Tu Yuanyuan et al. used the cause theory of trajectory cross accidents to build a quantitative risk assessment index system in which the improved risk grading index method can more objectively reflect the risk of hazardous chemicals [1]. Zhang Le and Tong Xing analyzed the serious hazardous chemical accidents of 29 cranes in 2010–2019 so as to find a solution to promote safety production management [2]. Yue Baoqiang et al. established a power system risk assessment model for hazardous chemical explosion accidents in specific scenarios [3]. Yang Li et al. used electrostatic discharge to optimize the support vector machine so as to improve the dynamic risk assessment performance of the support vector machine model [4]. Ning Zhou et al. used the fuzzy comprehensive evaluation method to build a secondary evaluation index group of fire resource demand according to different storage methods of hazardous chemicals, which scientifically and effectively improved the fire fighting rate of hazardous chemicals [5]. Xiangcui Liu et al. designed a risk assessment and decision support system for hazardous chemicals transportation, mainly based on the needs of hazardous chemicals transportation risk assessment, path planning, and emergency rescue [6]. Wei Jiang et al., on the other hand, used the HFACS model to study the human–causal relationship of hazardous chemical storage accidents. It was concluded that the divergent claims of different interests in hazardous chemical storage are important causes of accidents [7].

Regarding the research on solving the divergent claims of interest subjects in hazardous chemical storage mostly adopts a game theory approach. Firstly, Wang Wei and Wang Xiaonan built a three-way evolutionary game model to study the impact of changes in fines, regulatory costs, and regulatory success rates on the evolutionary equilibrium, puting forward more targeted policy recommendations for multi-department cooperation [8]. Under the condition of asymmetric information, Xiao Maocai built a tripartite game model of regional government, local government, and hazardous chemical logistics enterprises in hazardous chemical logistics supervision to analyze the relationship of interests of the three in the process of hazardous chemical supervision [9]. Liu Jiaguo et al. introduced the incidence of safety accidents and studied the impact of port logistics enterprises and government regulatory authorities' strategy choices on the accident results [10]. Secondly, when the number of p-levels increases, the game strategy will change. Yingzuo Zhao et al. discussed the national supervision of hazardous chemical inspection institutions through evolutionary game on the basis of third-party chemical inspection [11]. Wang Wei et al. introduced public supervision into the supervision of hazardous chemical transport industry, proving that the degree of public participation is the decisive factor affecting the strategic choice of hazardous chemical transport enterprises [12]. It can be seen from the above literature that previous studies mostly affected the government's regulatory strategy through the formulation of game strategies by all parties, reducing regulatory costs and accident incidence. However, there is not an eternal zero-sum game relationship between the stakeholders, and the stakeholders can also coordinate the interests of all parties through a cooperative relationship.

Regarding the research on the promotion of collaborative stakeholder operating models, a review of the existing literature shows that two-level programming model is more widely used. Since the decision behaviors between the upper and lower layers in the two-level programming model are not completely constrained by each other, but they are adjusted in time according to the changes of the other side, one can finally making the model optimal as a whole, which may be applicable to the optimization of such problems. There are many studies on the two-level programming model to seek cooperation when the main objectives are different. For example, Mingtao Ma et al. used the two-level programming model to maximize the benefits of stakeholders sharing energy storage and reduce the operating costs of the hybrid system [13]. Long Yong et al. proposed a two-level programming model for the cooperative operation of relevant stakeholders of the micro grid, which can not only reduce carbon emissions, but also increase the profits of operators [14]. Zhou Ziyu and Jiang Huiyuan established a two-level programming model for cold chain logistics distribution location and path optimization, providing a theoretical basis for multi-objective optimization of the cold chain logistics network [15]. Zheng Bin et al. based on the characteristics of the post-earthquake disaster relief network, established a two-level programming dynamic model with the goal of maximizing the satisfaction of material delivery time at the upper level and maximizing the fairness of material distribution at the lower level [16]. Jianfeng Lu et al. established a two-level programming model for distribution and scheduling of emergency materials in hazardous chemicals storage to reduce the risk of hazardous chemicals storage in the emergency network [17]. Zhou Haixia et al. built a two-level programming model with the goal of minimizing the logistics cost at the upper level and the logistics time at the lower level so as to quickly and accurately transport emergency supplies to the demand point [18].

Therefore, the main contribution of this paper are as follows:

(1) This study focuses on the regulatory cooperation among the government, third-party regulatory agencies, the public, and hazardous chemical warehousing enterprises. It also analyzes the interest demands of each stakeholder.
(2) This study proposes a two-level planning economy model to balance the interest demands of all parties as much as possible.
(3) The model in this paper reduces social cost and enterprise cost to the greatest extent.

In general, game theory is generally used for interactive decision-making, where players choose strategies that benefit them. However, game theory is mostly non-cooperative games, and the two-level programming model makes up for it. Based on the above analysis, the social cost minimization pursued by the government, third-party regulatory agencies, and the public is combined with the overall cost minimization pursued by the hazardous chemicals warehousing enterprises. A two-level programming model, which is a linear programming problem, is established, and risk is introduced into the model in the form of cost [19]. The idea of the paper is divided into three steps as follows:

(1) Firstly, the government in the upper model formulates the relevant penalty coefficient, and the hazardous chemicals warehousing enterprises in the lower model formulates the supervision cost coefficient.
(2) Secondly, the hazardous chemicals warehousing enterprises in the lower-level model determine the comprehensive risk level of goods warehousing status according to relevant standards and estimate the probability of risk occurrence.
(3) Then, the penalty coefficient formulated by the upper-level government will affect the penalty cost of the lower-level enterprises. Through the formulation of the penalty coefficient, the lower-level warehousing enterprises are urged to meet the safety standards in daily supervision.

Based on the above analysis, the specific model structure is shown in Figure 1. Among them, in the upper level planning model, the following can be seen:

Daily supervision cost refers to the expenses incurred by the government and third-party regulatory agencies for the daily supervision of enterprises, which is to fulfill their own supervision responsibilities.

Risk loss cost refers to the cost that the government has to spend and the expected reduction of economic benefits, which is because of the existence of risks.

Risk compensation cost is the monetary compensation for the people who may bear the risk and suffer the injury around the hazardous chemical storage enterprise.

In the lower level planning model, it can be seen:

Warehousing cost refers to the sum of the input of various factors in the warehousing business activities of an enterprise and is expressed in the form of currency.

Warehousing supervision cost refers to the additional supervision cost invested according to the comprehensive risk level of different warehouses on the basis of daily supervision.

Estimated penalty cost is the penalty that the government imposes on the company after the accident according to the risk level of the accident.

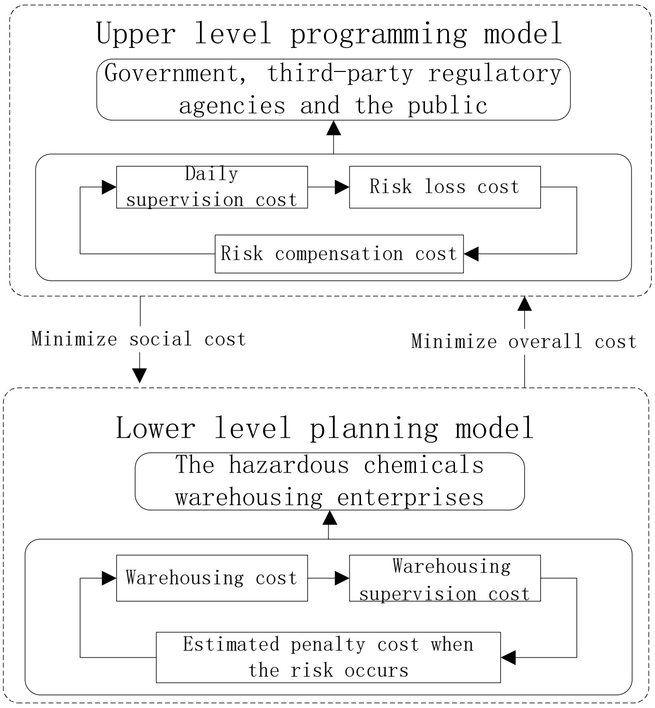

Figure 1. Model Structure of two-level programming model for stakeholders in hazardous chemicals storage.

2. Method and Model

This paper is divided into an upper and lower-level model. Relevant symbols are explained in Table 1. The penalty coefficient, α_{ri}, formulated by the government and the supervision cost coefficient, β_{ri}, formulated by the enterprise for different comprehensive risk levels of warehousing enterprises are taken as the decision variables to urge warehousing enterprises to reach safety standards in their daily management activities [20].

Table 1. Relevant symbols.

Symbols	Meanings	Ranges
α_{ri}	Penalty coefficient	$\alpha_{ri} > 0$
β_{ri}	Supervision cost coefficient	$\beta_{ri} > 0$
O_r	Risk compensation coefficient in warehouse r	$O_r > 0$
W_r	Storage of goods in warehouse r or not	$W_r = \begin{cases} 1, & \text{Storage of goods} \\ 0, & \text{No storage of goods} \end{cases}$
d_r	Comprehensive risk level	$\begin{cases} \textit{slight risk level}, & 0 < d_r \leq HD_r \\ \textit{medium risk level}, & HD_r < d_r \leq JD_r \\ \textit{serious risk level}, & d_r > JD_r \end{cases}$
R	Warehouses set	$R \in N+, r \in R$
Z_r	Daily supervision costs per unit area in warehouse r	$Z_r > 0, r \in R$
X_r	Storage area of goods in warehouse r	$X_r > 0, r \in R$

Table 1. *Cont.*

Symbols	Meanings	Ranges
U_r	Average risk loss in warehouse r	$U_r > 0, r \in R$
G_r	Risk compensation cost in warehouse r	$G_r > 0, r \in R$
U_{r1}	Loss when the estimated risk occurs in warehouse r	$U_{r1} > 0, r \in R$
U_{r2}	Fixed cost invested to deal with the risk in warehouse r	$U_{r2} > 0, r \in R$
E_r	Additional loss when the estimated risk occurs in warehouse r	$E_r > 0, r \in R$
F_r	Unit fixed cost invested in warehouse r to prevent the risk from occurring	$F_r > 0, r \in R$
ℓ_r	Additional unit loss incurred when the risk occurs in warehouse r	$\ell_r > 0, r \in R$
q_r	Estimated risk occurrence probability in warehouse r	$q_r \in [0,1], r \in R$
N_r	Number of exposed populations within a radius of three kilometers	$N_r \in N+, r \in R$
b	Compensation for each person	$b \geq 0, r \in R$
t_r	Estimated risk value of warehouse r	$t_r \geq 0, r \in R$
$\bar{t}$	Average estimated risk value of warehousing enterprise	$\bar{t} \geq 0$
C_r	Unit storage cost of goods in warehouse r	$C_r > 0, r \in R$
P_r	Storage supervision cost in warehouse r	$P_r > 0, r \in R$
M_r	Estimated penalty cost when risk occurs in warehouse r	$M_r > 0, r \in R$
Y_r	Unit warehousing supervision cost in warehouse r	$Y_r > 0, r \in R$
L_r	Unit compensation cost	$L_r > 0, r \in R$
B_r	Maximum capacity of warehouse r	$B_r > 0, r \in R$
QL	Quantitative value of risk level	
D	Degree of risk impact	
Q	Probability of risk occurrence	$Q \geq 0$
RL_r	Comprehensive risk level in warehouse r	
ql_r	A quantitative value of risk level of a risk factor	
A_r	Risk weight value for a risk factor	

In view of the complexity of the research problem, the following assumptions are made for the model establishment:

(1) Considering the complexity of enterprise cost, this paper only studies the cost of enterprise storage, so as to replace the overall cost of the enterprise;
(2) The government involved in this paper is the general name of all government departments;
(3) This paper only considers one warehousing enterprise;
(4) In order to simplify the calculation, the classification of people is not considered in risk compensation;
(5) Assume that each costing is based on the unit area of hazardous chemical storage.

2.1. Construction of the Upper Level Model

The upper-level model mainly analyzes the daily supervision cost, risk loss cost, and risk compensation cost of the government, the third-party regulatory agencies, and the public in the process of participating in the supervision. The government estimates the risk value according to the comprehensive risk level so as to change the formulation of the penalty coefficient, as well as to affect the penalty cost of the lower level warehousing enterprises when the risk occurs. This is performed to ultimately reduce the probability of the final risk occurrence and, at the same time, minimize the social cost [21]. Specifically:

This is the upper social cost minimization objective function:

$$\min F = \sum_{r \in R} (Z_r X_r W_r + U_r + G_r) \tag{1}$$

where: Z_r is daily supervision costs per unit area of goods in warehouse, r, from the value of the government and the third-party regulatory agency; X_r is storage area of goods in warehouse, r; W_r is whether to store goods in warehouse, r; U_r is the average risk loss in warehouse, r, and G_r is the risk compensation cost in warehouse, r.

U_r is calculated as follows:

$$U_{r1} = E_r + F_r X_r W_r \tag{2}$$

$$E_r = \begin{cases} \alpha_{r1} \ell_r X_r W_r, & 0 < d_r \leq HD_r \\ \alpha_{r2} \ell_r X_r W_r, & HD_r < d_r \leq JD_r \\ \alpha_{r3} \ell_r X_r W_r, & d_r > JD_r \end{cases} \tag{3}$$

$$U_{r2} = F_r X_r W_r \tag{4}$$

$$U_r = q_r U_{r1} + (1 - q_r) U_{r2} \tag{5}$$

where, U_{r1} represents the loss when the estimated risk occurs in warehouse, r, E_r represents the additional loss when the estimated risk occurs in warehouse, r; F_r is the unit fixed cost invested in warehouse, r, to prevent the risk from occurring; $\alpha_{r1}, \alpha_{r2}, \alpha_{r3}$ is the penalty coefficients corresponding to the slight risk level $(0, HD_r]$, the medium risk level $(HD_r, JD_r]$, and the serious risk level (JD_r, ∞), which are the decision variables of the upper level model [22]. Among them, it is impossible to have a risk of 0 in the actual production activities. Therefore, the case of the comprehensive risk level $d_r = 0$ does not exist. ℓ_r indicates the additional unit loss incurred when the risk occurs in warehouse, r; U_{r2} represents the fixed cost invested to deal with the risk in warehouse, r; and q_r is used to describe the estimated risk occurrence probability in warehouse, r.

G_r is calculated as follows:

$$G_r = O_r N_r b \tag{6}$$

$$O_r = \left| t_r - \bar{t} \right| / \bar{t} \tag{7}$$

where O_r is the risk compensation coefficient in warehouse, r; t_r is the estimated risk value of the warehouse, r; $\bar{t}$ is the average estimated risk value of the warehousing enterprise;

N_r is the number of exposed population within a radius of three kilometers around the warehousing enterprises, and the number of surrounding population is obtained through GIS software; and b is the compensation for each person [23].

Constraint conditions:

$$W_r = \begin{cases} 1, & \text{Storage of goods in the warehouse } r \\ 0, & \text{No storage of goods in the warehouse } r \end{cases} \tag{8}$$

$$q_r \in [0, 1] \tag{9}$$

$$\alpha_{ri} > 0, i = 1, 2, 3 \tag{10}$$

Equation (8) indicates the satisfaction state of the condition; Equation (9) indicates the probability range of risk occurrence; and Equation (10) indicates the value range of penalty coefficient.

2.2. Construction of the Lower Level Model

The lower-level model needs to ensure that the sum of storage cost, storage supervision cost, and penalty cost when the estimated risk occurs is minimized, that is, to minimize the overall cost of the hazardous chemicals warehousing enterprises. The objective function is as follows:

$$\min f = \sum_{r \in R} (C_r X_r W_r + P_r + q_r M_r) \tag{11}$$

where: C_r is unit storage cost of goods in warehouse, r; P_r is storage supervision cost in warehouse, r; M_r is the estimated penalty cost when the risk occurs in warehouse, r. P_r is determined according to the comprehensive risk level, d_r, and the enterprise supervision cost coefficient, β_{ri}; M_r is determined according to the comprehensive risk level, d_r, and the penalty coefficient α_{ri} of the corresponding level.

The storage supervision costs P_r is calculated as follows:

$$P_r = \begin{cases} \beta_{r1} Y_r X_r W_r, & 0 < d_r \le HD_r \\ \beta_{r2} Y_r X_r W_r, & HD_r < d_r \le JD_r \\ \beta_{r3} Y_r X_r W_r, & d_r > JD_r \end{cases} \tag{12}$$

where Y_r is the unit warehousing supervision cost in warehouse, r, and β_{r1}, β_{r2}, β_{r3} correspond to the enterprise supervision coefficients of slight, medium, and serious levels, respectively.

M_r is defined as (13):

$$M_r = \begin{cases} 0, & d_r = 0 \\ \alpha_{r1} L_r X_r W_r, & 0 < d_r \le HD_r \\ \alpha_{r2} L_r X_r W_r, & HD_r < d_r \le LD_r \\ \alpha_{r3} L_r X_r W_r, & d_r > LD_r \end{cases} \tag{13}$$

Among them, L_r is the unit compensation cost that the warehousing enterprise needs to pay when the estimated risk occurs in warehouse, r.

Constraint conditions:

$$\beta_{ri} > 0, i = 1, 2, 3 \tag{14}$$

$$W_r X_r \le B_r \tag{15}$$

Equation (14) indicates the value range of supervision coefficient; and Equation (15) indicates that the quantity of hazardous chemicals stored in a warehouse cannot exceed the maximum capacity of the warehouse, B_r.

3. Model Solving and Case Analysis

3.1. The Solution Method of Two-Level Programming Model

Based on the analysis of some existing excellent algorithm ideas [24], this study proposes to use the improved adaptive particle swarm optimization algorithm to solve the two-level programming problem. The parameters of the model were set as follows: population size $n = 50$, dimension $D = 2$, learning factor $c_1 = c_2 = 2$, and ωMax and ωMin are, respectively, 0.9 and 0.4. The termination condition of the algorithm is the maximum number of iterations, $iterMax = 50$, and the convergence accuracy $\lambda_\alpha \leq 10^{-10}$, $\lambda_\beta \leq 10^{-10}$, where the convergence accuracy is solved as in Equations (16) and (17).

$$\lambda_\alpha = \frac{|\alpha_{i+1} - \alpha_i|}{|\alpha_i|} \tag{16}$$

$$\lambda_\beta = \frac{|\beta_{i+1} - \beta_i|}{|\beta_i|} \tag{17}$$

Considering the randomness of the initial setting, the program was run independently for 30 times, and the best solution was taken as the approximate optimal solution. Additionally, the main improvement strategies of the algorithm are as follows:

(1) The disturbance factor is added to the velocity update formula to expand the population search range [25];
(2) The adaptive weight method is used to balance the global search ability and local improvement ability of PSO;
(3) Mutation operation is carried out on the global best solution, that is, random disturbance is added to the global optimum to improve the ability of PSO to jump out of the local best solution [26]. Assuming that random variable η follows the standard normal distribution, and its values are greater than 0 and less than 1, and the improved optimal position of particles is:

$$P_g^* = P_g(1 + \eta) \tag{18}$$

First of all, the upper-level decision maker formulates an appropriate accident penalty coefficient according to the comprehensive risk level of the warehouse storage state. The lower level takes this decision variable as a parameter, substitutes the result into the formulation of supervision cost, obtains the approximate optimal solution within the possible range, and feeds back the approximate optimal solution to the upper level. This cycle is repeated for many times, and the upper and lower levels of the two-level programming are optimized synchronously, and the approximate global optimal solution of the two-level programming model is finally obtained. The specific model solving process is shown in Figure 2 [27].

3.2. Case Analysis

This paper takes Shanghai Beifang Storage and Transportation Group as an example, uses the improved adaptive particle swarm optimization algorithm to solve, and gives the government's penalty coefficient α_i and the enterprise's supervision coefficient β_i for different risk levels in order to minimize the upper and lower objective functions, and then it analyzes the results.

3.2.1. Case Data Survey

Two warehouses of Beifang Group are selected as the research objects, namely, the dust sodium chlorate warehouse (warehouse 1) and the liquid hydrogen peroxide warehouse (warehouse 2), to find a relatively reasonable penalty coefficient and regulatory coefficient to minimize the social cost and the overall cost of the enterprise.

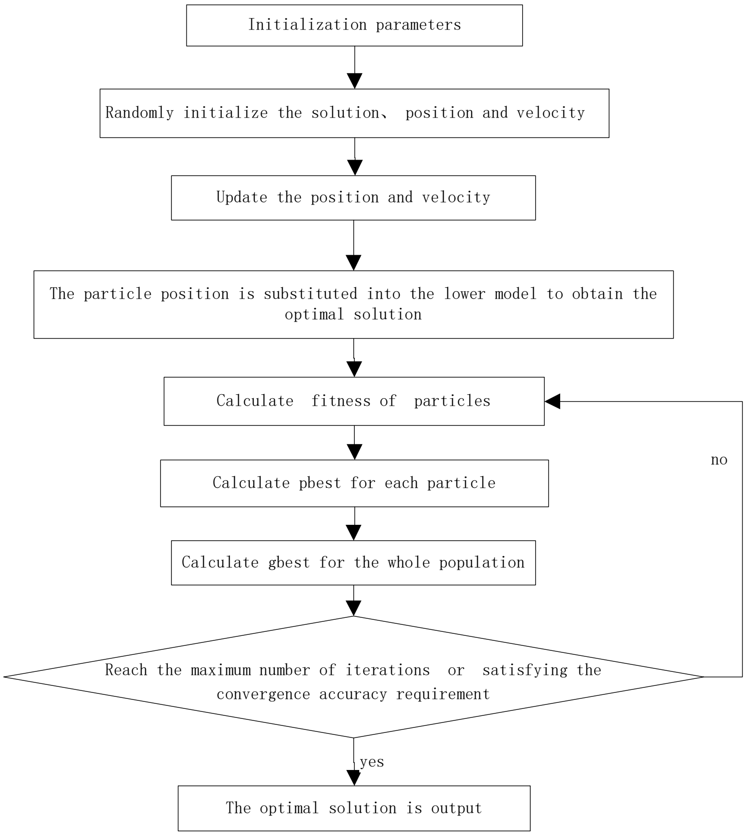

Figure 2. Solution process of two-level programming model.

In order to make the risk assessment results accurate and credible, expert survey method and the literature review were used to collect data and information. First, the quantified values of risk impact levels and the related criteria of risk impact degree were determined, as shown in Table 2. Then, based on the probability of risk occurrence and risk impact level, the risk level classification criteria and the level quantification interval were determined, as shown in Tables 3 and 4. From the relevant criteria in Tables 2–4, the quantitative value of risk level of each risk factor of hazardous chemical storage is calculated by using Equation (19).

Table 2. Risk occurrence probability and risk impact level table.

Risk Probability Level	Probability of Occurrence Q_1, Q_2	Influence Degree	Quantization Value of Influence Level D_1, D_2	Risk Impact Level
A	(0, 40]	Slight	(0, 4]	1
B	(40, 60]	Moderate	(4, 6]	2
C	(60, 100]	serious	(6, 10]	3

Table 3. Risk classification standard table.

Risk Probability Level	Risk Level		
	1	2	3
A	I	I	II
B	I	II	III
C	II	III	III

Table 4. Risk level quantification interval table.

Risk Level	Quantitative Range	Explain
I	(0, 1]	The risk is small and appropriate action is required
II	(1, 2]	The risks are high and prompt action is needed
III	(2, 3]	The risks are enormous and require immediate action

Among them, seven risk indicators affecting the safety of hazardous chemical storage were selected in a generalized manner by interviewing the relevant personnel of Beifang Group and combining with the General Rules for Storage of Commonly Used Chemical Hazardous Materials. Finally, the risk weights were calculated by applying the AHP rule to each risk factor in turn to determine the comprehensive risk level of each warehouse and complete Tables 5 and 6 [28].

Among them, since the quantization interval of the level is not a specific quantization value of the risk level, linear interpolation method is used for division, as shown in Equation (19):

$$QL = QL_1 + (QL_2 - QL_1)\frac{(D - D_1)(Q - Q_1)}{(D_2 - D_1)(Q_2 - Q_1)} \tag{19}$$

where: QL is the quantitative value of risk level, and QL_1, QL_2 are the value range of its quantization interval; D is the degree of risk impact, and D_1, D_2 are the value range of its quantitative value; Q is the probability of risk occurrence; and Q_1, Q_2 are the value range of its occurrence probability.

Table 5. Risk matrix table for warehouse 1.

Risk Factors	Probability of Risk Occurrence	Risk Impact		Risk Level		Risk Weighting A_r	Comprehensive Risk Level RL_1
		Quantitative Values	Level	Quantitative Values ql_1	Level		
Storage location is not reasonable	50	8	Serious	2.25	III	0.1429	II
Improper temperature and humidity control	90	9	Serious	2.57	III	0.2173	
Product deterioration	50	7	Serious	2.125	III	0.1825	
Mixed storage of chemicals of different properties	10	9	Serious	1.25	II	0.2021	
Lax control of ignition source	50	7	Medium	2.125	III	0.1002	
Lack of awareness of personnel management	40	7	Medium	1.25	II	0.1223	
Improper operation	30	3	Slight	0.57	I	0.0327	

In addition, the estimated risk occurrence probability of each warehouse can be determined by calculating the weighted average of each risk factor, and the calculation model is shown in Equation (20):

$$RL_r = ql_r A_r \tag{20}$$

where: RL_r is the comprehensive risk level in warehouse r; ql_r is a quantitative value of the risk level of a risk factor; and A_r is the risk weight value for a risk factor. Other relevant parameters in the investigation case are shown in Table 7, and the solution idea is shown in Figure 3.

Table 6. Risk matrix table for warehouse 2.

Risk Factors	Probability of Risk Occurrence	Risk Impact		Risk Level		Risk Weighting A_r	Comprehensive Risk Level RL_2
		Quantitative Values	Level	Quantitative Values ql_2	Level		
Storage location is not reasonable	20	1	Slight	0.125	I	0.0901	I
Improper temperature and humidity control	55	5	Medium	1.38	II	0.1437	
Product deterioration	50	5	Medium	1.25	II	0.1638	
Mixed storage of chemicals of different properties	10	9	Serious	1.25	II	0.2527	
Lax control of ignition source	30	3	Slight	1.57	II	0.0797	
Lack of awareness of personnel management	40	5	Medium	0.5	I	0.1522	
Improper operation	30	3	Slight	0.57	I	0.1187	

Table 7. Value of parameters.

Parameter	Symbol	Value	Unit
Daily supervision cost per unit of cargo	Z_r	12	RMB/ton
Storage capacity of hazardous chemicals in warehouse r	X_r	55 (Warehouse 1) 60 (Warehouse 2)	Ton
The additional unit loss incurred when the risk occurs	ℓ_r	120	RMB/ton
The fixed cost of dealing with the occurrence of a risk	F_r	50	RMB/ton
Compensation per person	b	1000	RMB
Unit storage cost of holding goods in warehouse r	C_r	10 (Warehouse 1) 9 (Warehouse 2)	RMB/ton
Unit storage supervision cost	Y_r	18	RMB/ton
The unit compensation to be paid when the risk is estimated to occur	L_r	300	RMB/ton

On the basis of Tables 5 and 6, the estimated risk probability of warehouse 1 is 48.73% and that of warehouse 2 is 32.43% by calculating the weighted average of all factors affecting warehouse risk. According to Equation (18), the estimated risk value of warehouse 1 is 1.904 and that of warehouse 2 is 0.998. Assuming that the average estimated risk value of warehouse 1 and warehouse 2 is taken as $\bar{t}$, the value is 1.451. Meanwhile, according to GIS, the number of exposed people within the radius of three kilometers of Beifang Logistics Company is 562. Ignoring the distance between warehouse 1 and warehouse 2, the risk compensation coefficient of warehouse 1 is 0.904, and that of warehouse 2 is 0.312.

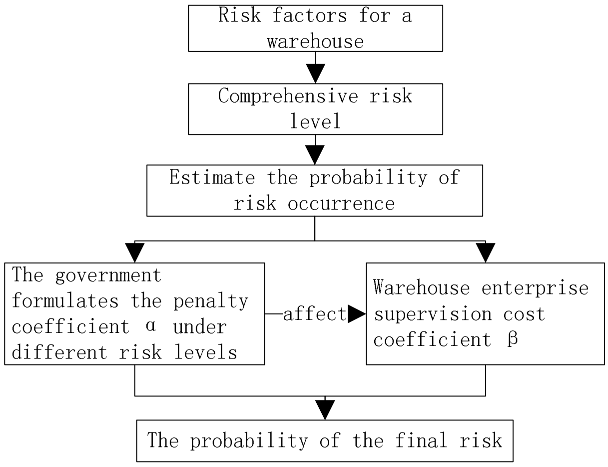

Figure 3. Case model solution ideas.

In addition, it is particularly emphasized that when the accident level is judged as serious, the enterprise itself is immediately rectified. Therefore, the case when the accident level is serious is not considered.

3.2.2. Case Result Analysis

MATLAB was used to program and solve the adaptive particle swarm optimization algorithm in Section 3. Considering the randomness of the initial setup, the program is run 30 times independently, and the best solution is taken as the approximate global optimal solution.

In addition, to further verify the effectiveness of the bilevel programming model for solving the cooperative operation research of the stakeholders of the hazardous chemical warehouse. Improved particle swarm optimization algorithm and classical evolutionary game method [29] are, respectively, used to compare the behaviors of regulatory entities represented by the government and warehousing enterprises in this paper. The specific numerical results are shown in Table 8, and the comparative analysis is shown in Figure 4. It can be seen that the optimal solutions of the adaptive particle swarm optimization algorithm in this paper are better than other solution methods. Not only the convergence performance of this algorithm is significantly improved, but also the standard deviation of the algorithm is 0 for 30 runs, and the results are very stable.

It can be seen that, in the case of a small degree of social cost optimization, the overall cost of the enterprise can still be significantly reduced. In addition, the method of this research can reduce the government's penalty coefficient for slight risk level to a large extent while ensuring the reduction of social costs and overall enterprise costs. However, it also increases the penalty for medium risk level. This is because an excessively high penalty factor may not produce a better supervision effect when the risk level is slight. On the contrary, it will bring great pressure to the enterprise operation and lead to unnecessary cost increases. However, when the risk level exceeds a certain range, a low penalty coefficient may also weaken the incentive for enterprises to supervise themselves, which increases the likelihood of risk occurrence. Therefore, a relatively better value should be obtained according to the actual situation so as to achieve the approximate optimal system configuration.

In addition, we can also see that in terms of enterprise supervision coefficient, the method in this paper can make enterprises strengthen their own supervision coefficient and fundamentally reduce the probability of accidents, no matter whether the risk level is slight or medium. At the same time, with the increase in risk level, the regulatory coefficient is also increasing. In conclusion, the results obtained by the cooperative operation model of the stakeholders of hazardous chemical warehousing based on two-level programming are more practical.

Table 8. Optimization results of model in this paper, evolutionary game model, and traditional particle swarm algorithm.

Plan	Social Cost/RMB	Overall Enterprise Cost /RMB	Slight Risk Level Government Penalty Coefficient (Warehouse 2)	Medium Risk Level Government Penalty Coefficient (Warehouse 1)	Slight Risk Level Enterprise Supervision Coefficient of (Warehouse 2)	Medium Risk Level Enterprise Supervision Coefficient of (Warehouse 1)
Evolutionary game model	698,073.7	28,756.8	2.2	1.47	1.49	1.41
Improper temperature and humidity control	55	5	Medium	1.38	II	0.1437
Traditional improved particle swarm optimization algorithm	695,398.9	21,524.1	1.05	1.47	0.76	1.66
Mixed storage of chemicals of different properties	10	9	Serious	1.25	II	0.2527
adaptive particle swarm optimization algorithm	694,612.9	20,006.7	0.24	1.82	1.31	1.51
Lack of awareness of personnel management	40	5	Medium	0.5	I	0.1522
Improper operation	30	3	Slight	0.57	I	0.1187

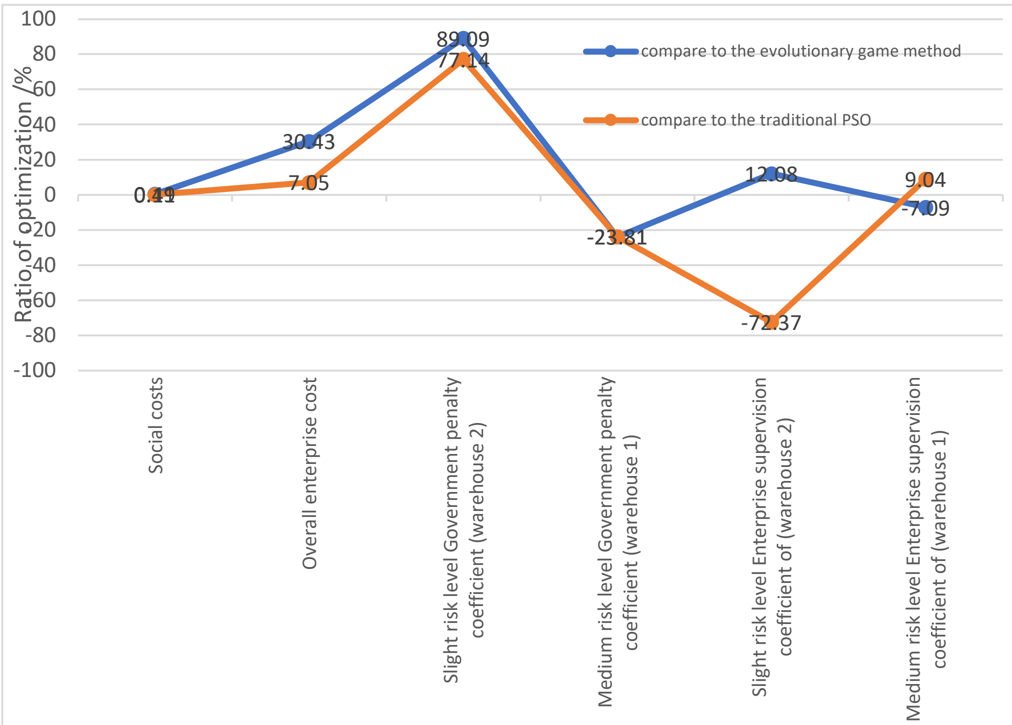

Figure 4. Comparison analysis of models among this paper, evolutionary game method, and traditional particle swarm algorithm.

4. Conclusions

Once an accident occurs in the hazardous chemical storage link, it will often cause catastrophic consequences. Moreover, there are many stakeholders, and it is difficult to balance the interests of each subject. Therefore, it is of great significance to study the way of cooperative operation among stakeholders. On the basis of summarizing the existing research results, this study analyses the cost composition of the government, third-party regulatory agencies, the public, and the hazardous chemicals warehousing enterprises in the process of production and operation under the premise that the hazardous chemicals warehousing enterprises may have an impact on society. This involves including the daily supervision cost and risk loss represented by the government and the warehousing operation cost, warehousing supervision cost, and the punishment cost when the risk occurs. A two-level programming model is established in which the upper level minimizes the social cost and the lower level minimizes the overall cost of the warehousing enterprise. Then, the improved adaptive particle swarm optimization algorithm is used to solve the model. Finally, the effectiveness of the model is verified by an example. The relevant case analysis shows that, compared with the evolutionary game model, the social supervision cost of the upper level and the enterprise cost of the lower level can be reduced by 0.49% and 30.43%, respectively. Compared with the traditional improved particle swarm optimization algorithm, the proposed algorithm can reduce the supervision cost of the upper society and the lower enterprise by 0.11% and 7.05%, respectively, thus achieving a better supervision effect at a relatively low cost.

However, only one company's data were validated by the model, so the validation of the same type of companies needs further improvement. Moreover, the relevant cost differences caused by hazardous chemicals with different chemical properties need to be discussed in the subsequent study. This can be performed by adjusting the composition of the cost parameters in the model and the costs incurred in the actual situation. Substituting these into the formula to solve realistic problems can improve the generalizability of the model. Additionally, through the model, government penalty coefficient and enterprise supervision coefficient for practitioners in the government or the enterprise were solved to develop a reasonable regulatory strategy to ensure the safety of hazardous chemical storage. Finally, about the proposed model in this paper, since two-level programming is an NP-hard problem, it needs to design a specific algorithm for the problem studied, so it does not have wide applicability.

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