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Optimizing Cost-Risk-Environmental Performance and Policy Guidance in Urban Hazardous Waste-Management Systems

Liping Zhan[1], Rui Zhao[2*], Yang Yu[2], Yuxin Yu[2]

[1]School of Urban Construction and Design, Urban Vocational College of Sichuan, Chengdu 610110, China
[2]School of Environmental Science and Engineering, Southwest Jiaotong University, Chengdu 611756, China

*Correspondence e-mail: ruizhaoswjtu@hotmail.com

Abstract

This study addresses the challenges of imbalanced upstream-downstream waste matching and insufficient coordination among stakeholders in urban hazardous waste management. A bi-level optimization model for management systems is developed by integrating multi-objective optimization and game theory. Then, the city of Chengdu, China, is analysed as a case study. An upper-level model is designed to formulate an optimal hazardous waste matching scheme by weighing economic costs against social risks and environmental impact. The lower-level model, meanwhile, uses evolutionary game theory to examine strategy interactions among core stakeholders. The results indicate that the optimization scheme facilitates the local disposal of hazardous waste, resulting in a 36.85% reduction in the total cost of the management system. Notably, the transportation segment achieves the most significant reduction, dropping by about 50% compared with pre-optimization levels. The evolutionary game results show that for a given matching scheme, district-level governments and waste-generating enterprises in 90.91% of Chengdu's regions adopt the proactive strategy of "supervision and implementation." The volume of waste generation significantly influences the strategies of waste- generating enterprises, which can be guided by the government through adjustments to subsidy and penalty policies. Compared with subsidies, penalties can more effectively steer the system toward ideal equilibrium. This study presents a "scheme optimization-behaviour guidance" framework for pollution control and carbon reduction in urban hazardous waste. Furthermore, the findings can provide a valuable reference for hazardous waste-management policy in megacities.

Keywords: hazardous waste management, bi-level optimization, evolutionary game, reward and punishment

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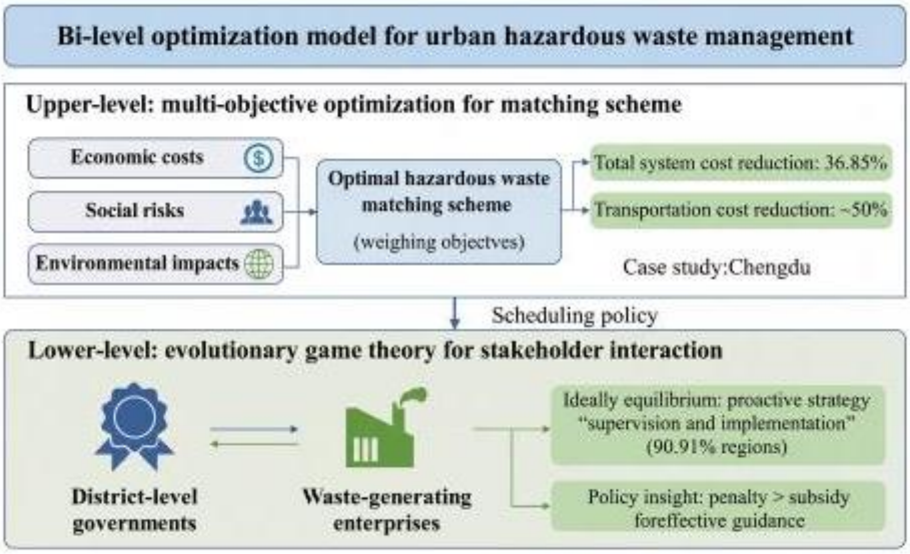
Graphical abstract



1. Introduction

With rapid socioeconomic development and rising consumption, large amounts of hazardous waste—including organic solvent waste, acid waste, incineration residues, and mineral oil waste—are generated from product manufacturing, healthcare services, and domestic activities (Zhan *et al.*, 2022). In 2023, China's annual hazardous waste generation exceeded 103 million tons, of which more than 50% contained toxic substances such as heavy metals and persistent organic pollutants. If improperly managed, the migration of these toxic components poses a severe threat to soil and aquatic ecosystems (Fazzo *et al.*, 2017; Xu *et al.*, 2022). Concurrently, disruptions in the resource utilization and disposal chain have resulted in year-on-year increases in illegal transfers, thus escalating the risk of secondary pollution (Jiao *et al.*, 2024). Furthermore, waste metabolism is a significant source of greenhouse gas emissions, accounting for about 3.2% of the global total and thus exacerbating climate change (Zhao *et al.*, 2025). This underscores the need to establish a control system for hazardous waste management that adheres to environmental standards and achieves synergistic benefits in pollution control and carbon mitigation.

Many studies have adopted a life-cycle perspective on hazardous waste metabolism, focusing on distinct objectives at specific control nodes (Barros *et al.*, 2008; Morero *et al.*, 2022). Studies have investigated improving production processes at the source to reduce hazardous waste generation and toxicity (Qiao *et al.*, 2010; Kong and Li, 2021), enhancing resource utilization rates to mitigate potential environmental impacts (Wu *et al.*, 2014; Matsubae *et al.*, 2015), strategically selecting disposal facility locations to minimize human exposure risk (Stemn and Kumi-Boateng, 2019), and optimizing collection and transportation routes to control investment costs (Paredes-Belmar *et al.*, 2017). Nevertheless, hazardous waste management is a complex, multifaceted system that encompasses multiple nodes, such as generation, collection, transportation, recycling, treatment, and final disposal (Samanlioglu, 2013; Roudneshin and Azadeh, 2019; Homayouni and Pishvaee, 2020). These nodes are interconnected, and their control objectives are interdependent and reciprocally influential. Focusing solely on individual components can hinder system-wide optimization. Therefore, formulating an optimal plan that harmonizes environmental, economic, and social benefits requires integrating all metabolic processes in the hazardous waste-management system.

Goal-programming methods have been used to design and optimize hazardous waste-management systems and balance trade-offs among conflicting control objectives (Mantzaras and Voudrias, 2017; Yu *et al.*, 2020). Early approaches to optimizing regional hazardous waste-management systems mainly focused on controlling costs and risks. Such studies used multi-objective optimization models to address issues such as facility siting and the integration of waste allocation with collection route planning (Xie *et al.*, 2012; Samanlioglu, 2013; Ardjmand *et al.*, 2015; Zhao *et al.*, 2016). With the refinement of the quantitative representation of objective functions, factors such as accident probability (Farrokhi-Asl *et al.*, 2020), equity (Rabbani *et al.*, 2021), and economic benefits (Saeidi, 2024) have been incorporated into optimization models as objectives or constraints. Zhao *et al.* (2017) integrated carbon emissions into a waste system optimization model, spurring research interest in the environmental impact of greenhouse gas emissions during hazardous waste metabolism. Aiming to minimize cost, risk, and environmental impact, Ziaei *et al.* (2021)

constructed an optimization model for a hazardous waste-management system designed to formulate a coordinated location-routing decision-making solution that covers waste-generation sources, treatment centres, and disposal centres.

To address the challenge of decision-making coordination among various stakeholders, evolutionary game theory has been widely applied in waste management due to its effectiveness in modeling the dynamic decision-making processes of boundedly rational agents (Su, 2020; He and Sun, 2022). For instance, Wang *et al.* (2020) constructed an evolutionary game model involving the government, recycling enterprises, and consumers, demonstrating the government's dominant role in promoting the sustainable development of the electronic waste recycling market. Chen *et al.* (2019) used evolutionary game theory to analyse the decision-making behaviours of waste-generating enterprises and government departments, revealing that government agencies can curb illegal dumping through strengthened supervision and fines. Ma and Zhang (2020) developed an evolutionary game model involving waste-generating and recycling enterprises to investigate the effect of government incentives on their cooperation. It was found that subsidizing waste-generating enterprises was more conducive to the sustainable development of the construction waste recycling industry. Drawing on evolutionary game theory, Li *et al.* (2022) investigated the behavioural strategies of governments, communities, and residents regarding the implementation of household waste sorting. It was found that a dynamic penalty-subsidy mechanism could better facilitate the system's convergence toward optimal stable equilibrium.

While existing studies provide valuable insights for enhancing the efficiency of hazardous waste management, the following limitations remain: First, extant multi-objective or bi-level optimization models predominantly follow a "top-down" imperative planning logic, presupposing that participants will strictly implement the prescribed optimal solutions. Consequently, these models overlook the behavioral heterogeneity of stakeholders driven by individual rationality. Secondly, extant evolutionary game-theoretic studies on hazardous waste management rely heavily on abstract parameter assumptions, often becoming detached from real-world geospatial constraints and the specific characteristics of waste generation scales. Therefore, how to integrate behavioral decision-making into the optimization process to achieve a closed-loop synergy between "solution generation" and "behavioral guidance" remains a critical issue that current research must urgently address.

To this end, this study develops a bi-level "scheme optimization-behavioral guidance" model. Its core contributions are manifested as follows: The upper-layer model generates an optimal matching scheme between hazardous waste generation sources and disposal facilities by integrating environmental, economic, and risk objectives. At the lower level, evolutionary game analysis is conducted to reveal the response strategies and interaction mechanisms of various stakeholders concerning the proposed scheme. This study contends that the integration of spatial matching results based on real-world geographic information with behavioral evolutionary mechanisms is not a mere superposition of two methodologies; rather, it represents a deep synergy of "scheme generation and strategy response": Specifically, the optimization model provides cost-benefit benchmarks grounded in real-world scenarios for game-theoretic analysis, while the game model offers a dynamic basis for policy regulation to ensure the effective implementation of the optimized solutions.

Next, section 2 presents the problem to be studied and its mathematical formulation. Section 3 introduces the case study area and the model's parameter settings. Section 4 presents the results and discussion, while section 5 makes policy recommendations. The final section concludes with directions for future research.

2. Materials and methods

2.1. Problem description

The hazardous waste-management system examined in this study is delineated by municipal administrative boundaries and encompasses the entire life cycle, from generation to final disposal. The primary stakeholders include municipal government departments, district-level government departments, and hazardous waste-generating enterprises. Figure 1 depicts the hierarchical structure and interactive relationships among these three entities. As the top-level decision-making body, the municipal government formulates an optimal matching scheme based on the conditions of hazardous waste generation and disposal in each district, balancing economic, social, and environmental benefits to plan the reverse logistics of hazardous waste across administrative districts. The established matching scheme applies to both district-level governments and the waste-generating enterprises in their jurisdictions. As the primary executors of the scheme, these enterprises are, in principle, required to report their implementation status to their respective district governments, which in turn exercise regulatory oversight in accordance with regulations.

Waste-generating enterprises and governmental decision-making bodies are both influenced by multiple factors and face a degree of uncertainty when determining the implementation methods of the scheme and the supervisory mechanism for non-compliance. For waste-generating enterprises, their behavioural strategies are not independent: They are influenced not only by the strategic choices of government departments but also by the strategic actions of other enterprises. For government departments, strategy formulation must be based on analyses of the strategies of waste-generating enterprises. The game between the two parties constitutes a dynamic process of observation, learning, and adjustment. This can be analysed using evolutionary game theory to understand the decision-making behaviours of waste-generating enterprises and government departments in different scenarios (Chen *et al.*, 2023).

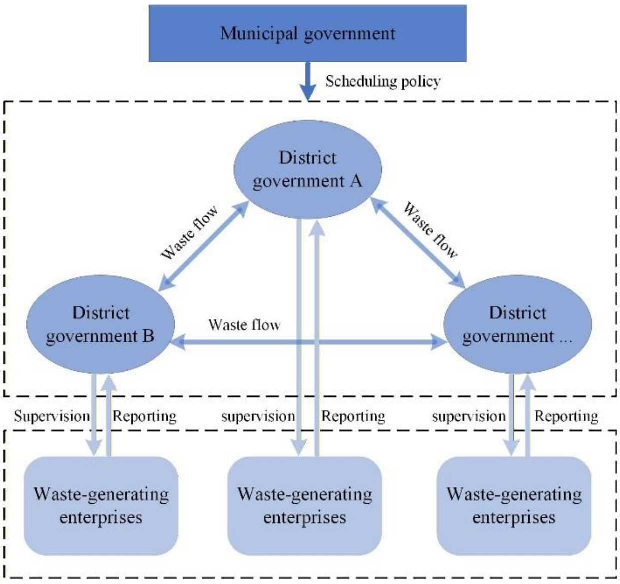


Figure 1. Hierarchical structure of the hazardous waste-management system

2.2. Mathematical model

This study constructs an optimization model that considers economic costs, social risks, and environmental impacts. The goal is to formulate a hazardous waste matching scheme among district-level administrative units for the safe, efficient disposal of such waste in a municipality. On that basis, an evolutionary game model involving district-level governments and waste-generating enterprises is constructed to investigate coordination among stakeholders under the optimal matching scheme. The symbols and definitions used in the mathematical formulations are introduced below, with the corresponding indices given as follows.

Sets:

G: Administrative units outsourcing hazardous waste

R: Administrative units receiving hazardous waste

Parameters:

Q_g: Quantity of hazardous waste outsourced by the administrative unit g, g∈G (ton)

Q_r: Quantity of hazardous waste received by administrative unit r, r∈R (ton)

$Q_{g,r}$: Quantity of hazardous waste transferred from administrative unit g to administrative unit r, g∈G, r∈R (ton)

$D_{g,r}$: Distance between administrative unit g and r, g∈G, r∈R (km)

V_r^1: Direct economic losses and personnel casualties caused by accidents during the hazardous waste treatment process (yuan)

V_r^2: Environmental losses caused by accidents during the hazardous waste treatment process (yuan)

V_s^1: Direct economic losses and personnel casualties caused by accidents during the hazardous waste storage process (yuan)

V_s^2: Environmental losses caused by accidents during the hazardous waste storage process (yuan)

$V_{g,r}^1$: Direct economic losses and personnel casualties caused by accidents during the hazardous waste transportation process (yuan)

$V_{g,r}^2$: Environmental losses caused by accidents during the hazardous waste transportation process (yuan)

P_r: Probability of hazardous accidents during the hazardous waste treatment process

P_s: Probability of hazardous accidents during the hazardous waste storage process

$P_{g,r}$: Probability of hazardous accidents during the hazardous waste transportation process

W_r: Carbon dioxide emission factor for the treatment process ($tonCO_2$/ton)

$W_{g,r}$: Carbon dioxide emission factor for the transportation process ($tonCO_2$/ton·km)

C_0: Unit regulatory cost for the government on enterprises (yuan/ton)

C_1: Unit cost of hazardous waste treatment, yuan/ton

C_2: Subsidies to enterprises for compliant hazardous waste treatment (yuan/ton)

C_3: Fines payable by enterprises for non-compliant hazardous waste treatment (yuan/ton)

C_4: Tax per unit of carbon emissions (yuan/ton)

C_5: Unit cost of hazardous waste transportation (yuan/ton·km)

C_6: Unit cost of hazardous waste storage (yuan/ton)

K_r: Hazardous waste treatment capacity of administrative unit r, r∈R (ton)

2.2.1. Construction of upper-level optimization model

The optimization model aims to minimize the total cost of the hazardous waste-management system, which encompasses the direct economic costs, environmental damage costs, and social risk costs associated with the treatment and transportation of hazardous waste. The model assumptions are as follows:

1) The quantity of generated hazardous waste remains constant and stable over a specific period.

2) The safety ratings of roads and vehicles comply with the requirements for hazardous waste transportation, presenting no capacity constraints.

3) All hazardous waste-receiving enterprises use identical treatment technologies.

4) The unit costs of hazardous waste transportation and treatment remain constant over a specific period.

The objective function of minimizing the total system cost is expressed as follows:

$$OBJ = \min\left(DC + EC + RC\right) \quad (1)$$

Where

$$DC = \sum_{r\in R} Q_r \cdot C_1 + \sum_{g\in G}\sum_{r\in R} Q_{g,r} \cdot D_{g,r} \cdot C_5 \quad (2)$$

$$EC = \sum_{r\in R} Q_r \cdot W_r \cdot C_4 + \sum_{g\in G}\sum_{r\in R} Q_{g,r} \cdot D_{g,r} \cdot W_{g,r} \cdot C_4 \quad (3)$$

$$RC = \sum_{r\in R} P_r \cdot \left(V_r^1 + V_r^2\right) + \sum_{g\in G}\sum_{r\in R} P_{g,r} \cdot \left(V_{g,r}^1 + V_{g,r}^2\right) \quad (4)$$

Where DC represents the direct economic cost of the hazardous waste treatment and transportation process, defined as the product of the unit cost and the quantity of hazardous waste. EC is the environmental cost induced by carbon emissions during this process, calculated as the product of the unit carbon tax and the volume of carbon dioxide emissions. RC denotes the risk cost resulting from potential accidents, which is the product of the accident probability and its consequences.

Subject to:

$$\sum_{r\in R} Q_{g,r} = Q_g \quad (5)$$

$$\sum_{g\in G} Q_{g,r} = Q_r \quad (6)$$

$$Q_r \le K_r \quad (7)$$

Where Equations (5) and (6) represent the hazardous waste flow conservation constraints. Equation (7) represents the capacity constraint for hazardous waste treatment at the receiving facilities.

2.2.2. Construction of lower-level evolutionary game model

Solving the upper-level optimization model enables the municipal government to formulate a hazardous waste matching scheme among districts. Implementing the plan requires collaboration between district-level government departments and waste-generating enterprises. However, as agents with bounded rationality, both parties tend to make strategic choices aimed at maximizing their own short-term benefits. Specifically, the district-level government (district-level government) has two available behavioural strategies: supervision and non-supervision. Similarly, waste-generating enterprises have two behavioural strategies: implementation and non-implementation. This study posits the following basic assumptions in the framework of the evolutionary game model.

Hypothesis 1: When district-level governments adopt lax supervision while waste-generating enterprises implement the optimization scheme, information asymmetry prevents higher-level governments from accurately assessing the actual performance of local authorities. Consequently, it becomes challenging to hold district-level governments accountable for inaction or misconduct.

Hypothesis 2: To ensure the efficient operation of the hazardous waste-management system, the district-level government adopts strict supervision, incurring a cost denoted as C.

Hypothesis 3: Waste-generating enterprises incur direct costs associated with hazardous waste management. If the proposed scheme is implemented, the associated treatment cost is denoted as G, and a carbon tax, T, is incurred during the transportation and treatment stages. If treatment is not conducted in accordance with the prescribed scheme, resulting in the on-site storage of all hazardous waste, the corresponding storage cost is denoted S.

Hypothesis 4: The non-compliant treatment of hazardous waste poses significant safety risks, which can potentially trigger accidents at any stage of the life cycle, resulting in potential associated costs. If the waste-generating enterprise adheres to the prescribed scheme, the direct economic losses and casualty-related losses resulting from hazardous accidents are denoted as M_1, and environmental damage losses are denoted as M_2. If the waste-generating enterprise fails to adhere to the prescribed scheme, the direct economic losses and casualty-related losses resulting from hazardous accidents are denoted as K_1, and environmental damage losses are denoted as K_2.

Hypothesis 5: The district-level government implements an incentive and penalty mechanism to supervise the behaviour of waste-generating enterprises. When the waste-generating enterprise treats hazardous waste in accordance with the prescribed scheme and completes the relevant procedures, such as reporting and registration, it receives a subsidy F, while the district-level government collects carbon tax revenue. If the waste-generating enterprise fails to dispose of hazardous waste in accordance with the scheme, it is subject to a penalty, denoted as I, upon detection of the violation by the district-level government.

Hypothesis 6: If the district-level government implements supervision of the waste-generating enterprise and a hazardous incident occurs, the enterprise is fully liable for all resulting direct economic losses, casualties, and environmental damage. If the district-level government forgoes supervision and a hazardous incident occurs, the waste-generating enterprise is liable for direct economic losses and casualties, while the district-level government assumes liability for the resulting environmental damage owing to its dereliction of regulatory duty.

Hypothesis 7: The probabilities of the district-level government choosing to supervise or not supervise are x and $1-x$, respectively, while the probabilities of the waste-generating enterprise choosing to implement or not implement are y and $1-y$, respectively, where $x, y \in [0,1]$.

Based on the above assumptions, the payoff matrix for the district-level government and the waste-generating enterprise is constructed, as shown in Table 1.

Table 1. Payment matrix for government and waste-generating enterprise.

Game player		Waste-generating enterprise	
		Implementation y	Non-implementation 1−y
district-level government	Supervision x	$-C+T-F$ $-C+T-F$; $-G-T-M_1-M_2+F$	$-C+I$; $-S-K_1-K_2-I$
	Non-supervision $1-x$	$T-F-M_2$; $-G-T-M_1+F$	$-K_2$; $-S-K_1$

The payoff functions are formulated using the corresponding parameters, as follows:

$$C = Q_g^{'} \cdot C_0 \quad (8)$$

$$S = Q_g^{'} \cdot C_6 \quad (9)$$

$$F = Q_g^{'} \cdot C_2 \quad (10)$$

$$I = Q_g^{'} \cdot C_3 \quad (11)$$

$$K_1 = P_s \cdot V_s^1 \quad (12)$$

$$K_2 = P_s \cdot V_s^2 \quad (13)$$

$$M_1 = P_r \cdot V_r^1 + P_{g,r} \cdot V_{g,r}^1 \quad (14)$$

$$M_2 = P_r \cdot V_r^2 + P_{g,r} \cdot V_{g,r}^2 \quad (15)$$

$$G = Q_g^{'} \cdot C_1 + Q_{g,r}^{'} \cdot D_{g,r}^{'} \cdot C_5 \quad (16)$$

$$T = Q_g^{'} \cdot W_r \cdot C_4 + Q_{g,r}^{'} \cdot D_{g,r}^{'} \cdot W_{g,r} \cdot C_4 \quad (17)$$

The above payoff functions are calculated based on the fixed allocation scheme determined by the upper-level optimization model. Where $Q_g^{'}$ represents the quantity of hazardous waste outsourced by the administrative unit after optimization (ton). $Q_{g,r}^{'}$ denotes the hazardous waste transfer volume between administrative units after optimization (ton). $D_{g,r}^{'}$ is the transportation distance between administrative units after optimization (km). All other parameters remain consistent with those prior to optimization.

3. Case study: Chengdu

To validate the model, this study selects the megacity of Chengdu in Southwest China as a case study. Situated in the western Sichuan Basin and the heartland of the Chengdu Plain, Chengdu is known as the “Land of Abundance”. As of the end of 2022, Chengdu’s permanent population was 21.268 million, and its regional GDP was 2,081.75 billion yuan, ranking it among the leading “new first-tier” cities in China. Accompanied by rapid economic development, Chengdu’s hazardous waste generation has remained persistently high, surpassing 500,000 tons in 2022 and accounting for about 10% of the provincial total (Zhan *et al.*, 2025). Owing to significant environmental risks and high pollution control costs, hazardous waste is highly prone to triggering conflicts of interest among stakeholders (Zhan *et al.*, 2022). Accordingly, this study selects the top six categories of hazardous waste by total generation in Chengdu from 2019 to 2022 (HW06, HW08, HW12, HW17, HW34, and HW49), aiming to provide transferable experience for hazardous waste management in other megacities.

With 2022 as the base year, district-level administrative divisions are taken as the primary statistical units to compile data on the generation, consigned disposal, and treatment capacity of hazardous waste-management enterprises in these jurisdictions. All data are sourced from the Chengdu Municipal Solid Waste Management Department. Based on the names of hazardous waste-generating and disposal companies in the statistical data, Python web scraping is used to retrieve business information from the Qichacha database (https://www.qcc.com/), including data on spatial location and operational status. Then, by integrating the location data of the enterprises with their established disposal partnerships and applying the principle of shortest travel time, hazardous waste transportation routes are determined using Gaode Map (https://lbs.amap.com/) to calculate transport distances.

The unit costs for transportation and treatment, environmental damage costs, and direct economic losses and casualties resulting from accidents are quantified based on prior research (Zhao *et al.*, 2017). The cost of on-site storage for hazardous waste-generating enterprises is based on the values determined by Zhao and Ke (2017). The remaining parameter data are obtained from the China Solid Waste Network (http://www.gufeichuli.com/). **Table 2** provides details on the values of all variables.

Table 2. Parameter information.

Parameter	Value	Unit
C_0	216	yuan/ton
C_1	100	yuan/ton
C_2	100	yuan/ton
C_3	500	yuan/ton
C_4	42	yuan/ton
C_5	10	yuan/ton·km
C_6	60	yuan/ton
P_r	5×10^{-5}	—
P_s	1×10^{-4}	—
$P_{g,r}$	$0.4\times(10^{-6}/km)\times0.9\times$	
$D_{g,r}$ (km)	—	
W_r	0.24	$tonCO_2$/ton
$W_{g,r}$	0.14×10^{-3}	$tonCO_2$/ton·km
V_r^1	1×10^9	yuan
V_r^2	9×10^9	yuan
V_s^1	10×10^9	yuan
V_s^2	0.55×10^9	yuan
$V_{g,r}^1$	1.5×10^9	yuan
$V_{g,r}^2$	0.6×10^9	yuan

4. Results and discussion

4.1. Optimization results

In this study, the optimization model is solved using the simplex method, implemented via the linprog function of the SciPy library in a Python 3.9 environment. The convergence tolerance is set to the default value of 1×10^{-6} to ensure numerical stability and precision. Additionally, all decision variables are subject to non-negative bounds, with specific upper and lower limits applied according to the practical constraints defined in the model. Furthermore, the pre-optimization system cost is calculated based on the original hazardous waste flow patterns and volumes. Table 3 presents the cost composition of the hazardous waste-management system before and after optimization. As shown in the table, the total system cost prior to optimization is 4.09×10^7 yuan, with the transportation sector accounting for about 80%. Following optimization, the total system cost decreases to 2.58×10^7 yuan, representing a reduction of 36.85%. The cost of the disposal stage remains unchanged, as the existing local disposal capacity is sufficient to meet disposal demand, and the number of required facilities remains constant before and after optimization. However, the cost of the transportation stage decreases from 3.26×10^7 yuan before optimization to 1.75×10^7 yuan, representing a reduction of about 50%. After optimization, the transportation stage accounts for less than 70% of the total system cost.

Table 3. Composition of system costs before and after optimization.

	Transportation cost ($\times 10^7$ yuan)	Treatment cost ($\times 10^7$ yuan)	Total cost ($\times 10^7$ yuan)	Number of waste facilities
Before optimization	3.26	0.83	4.09	11
After optimization	1.75	0.83	2.58	11

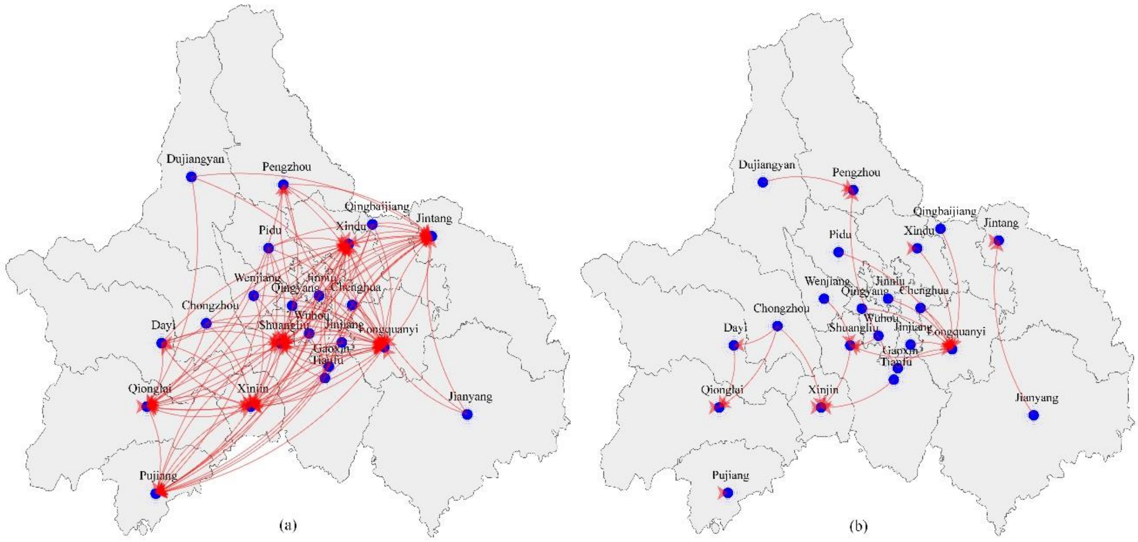


Figure 2. Spatial distribution of hazardous waste matching paths before and after optimization. (a) Before optimization; (b) After optimization.

Figure 2 further illustrates the spatial distribution of the hazardous waste matching paths before and after optimization. As shown in Figure 2(a), the hazardous waste matching paths are widely dispersed across various administrative districts before optimization. This is likely because waste-generating enterprises, owing to their small output and insufficient bargaining power, are often rejected by disposal units on grounds such as "licensed capacity is full" when outsourcing disposal, thereby compelling them to seek cooperation with multiple disposal facilities (Jia *et al.*, 2022). This decentralized matching pattern leads to longer total transportation distances, representing the primary reason for the high transportation costs before optimization. This also reveals the indiscriminate manner in which waste-generating enterprises select disposal units to ensure the safe disposal of their hazardous waste. As shown in Figure 2(b), after optimization, the number of transportation routes for hazardous waste awaiting disposal in each district decreases from 5–9 to 1–3, and waste flows become concentrated in adjacent areas. This concentration is the primary reason for the significant reduction in transportation costs post-optimization. In summary, granting district-level governments unified authority over hazardous waste management and holistically planning waste flows and volumes in the municipality can curb disorderly cross-regional transportation.

4.2. Evolutionary game results

This study first analyses the equilibrium solutions of the game model and discusses the stability conditions of the corresponding solutions across the four development stages of the hazardous waste-management industry. On this basis, the optimized matching plan is incorporated into the evolutionary game model to analyse the evolutionary dynamics of the decision-making behaviours of district-level governments and waste-generating enterprises under this plan. The effects of factors such as hazardous waste generation, subsidies, and penalties on both parties' strategies are also investigated.

4.2.1. Analysis of evolutionary game model

According to evolutionary game theory, in the game process, participants dynamically adjust their strategic choices in response to their environment; the analysis mainly relies on the replicator dynamics equation (Su *et al.*, 2020). Based on Friedman's (1991) definition, as well as the payoff matrix for district-level governments and waste-generating enterprises presented in section 2.2.2, the replicator dynamics equations for both parties are derived as follows:

$$F(x)=x(1-x)\left[I+K_2-C-y(I-M_2+K_2)\right] \tag{18}$$

$$F(y)=y(1-y)\left[S+K_1+F-G-T-M_1-x(M_2-K_2-I)\right] \tag{19}$$

In the evolutionary game process, as participants' understanding of the game rules and information about the other party continuously deepen, their strategic choices eventually stabilize and converge to an equilibrium point. Based on the necessary conditions for equilibrium, setting $F(x)$ =0 and $F(y)$ =0 yields four pure-strategy equilibria—(0,0), (1,0), (1,1), and (0,1)—as well as one mixed strategy equilibrium, (x*,y*), where $x^*=\frac{S+K_1+F-G-T-M_1}{M_2-K_2-I}$ and $y^*=\frac{I+K_2-C}{I-M_2+K_2}$. Building on this, the study analyses the local stability of the system using the Jacobian matrix (Friedman, 1991). The Jacobian matrix J corresponding to the local equilibrium points of the system is given by

$$J=\begin{pmatrix}\frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y}\\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y}\end{pmatrix}=\begin{pmatrix}a_{11} & a_{12}\\ a_{21} & a_{22}\end{pmatrix} \tag{20}$$

According to the stability theory of differential equations, the stability of an equilibrium point is determined by the determinant $\det(J)$ and the trace $tr(J)$ of the Jacobian matrix, where , $\det(J)=a_{11}a_{22}-a_{12}a_{21}$, and $tr(J)=a_{11}+a_{22}$. If $\det(J)>0$ and $tr(J)<0$, the equilibrium point is termed as the convergence (ESS). If $\det(J)>0$ and $tr(J)>0$, the equilibrium point is unstable. The remaining equilibrium points are classified as saddle points.

The calculations indicate that the mixed strategy is not an ESS. Consequently, this study analyses the stability of the four pure-strategy equilibrium points. Substituting the four-pure strategy equilibrium points into Equation (20) yields the corresponding $\det(J)$ and $tr(J)$ values. Table 4 presents the results, from which the conditions for each equilibrium point to be an ESS can be determined.

Table 4. The det(J) and tr(J) of the four equilibrium points.

Equilibrium points	$\det(J)$	$tr(J)$	ESS conditions
E_1 (0,0)	$(I+K_2-C)(S+K_1+F-G-T-M_1)$	$I+K_2-C+S+K_1+F-G-T-M_1$	$\det(J)>0$
E_2 (1,0)	$-(I+K_2-C)(S+K_1+F-G-T-M_1-M_2+K_2+I)$	$C+S+K_1+F-G-T-M_1-M_2$	
E_3 (1,1)	$-(C-M_2)(S+K_1+F-G-T-M_1-M_2+K_2+I)$	$C-S-K_1-F+G+T+M_1-K_2-I$	$tr(J)<0$
E_4 (0,1)	$(C-M_2)(S+K_1+F-G-T-M_1)$	$-(C+S+K_1+F-G-T-M_1-M_2)$	

Drawing on the life-cycle classification of the waste-management industry by Wang *et al.* (2020), this study divides the development process of the hazardous waste-management system into the following four stages: the initial stage, the early development stage, the mid-term development stage, and the mature stage. Furthermore, the stability conditions of the equilibrium points are analysed in the context of the characteristics of the various development stages.

In the initial stage, waste-generating enterprises, driven by behavioural inertia, tend to adhere to their original matching paths and thus do not adopt the proposed optimization plan. At the same time, taking into account factors such as regulatory costs, district-level governments are inclined to forgo supervision. This stage corresponds to equilibrium point E_1(0,0). As shown in Table 4, the stability condition for E_1(0,0) is $I+K_2<C$. This implies that when the loss incurred by the district-level government owing to non-supervision is less than the cost of supervision, the government will opt to forgo supervision. Meanwhile, the inequality $G+T+M_1-F>S+K_1$ indicates that the cost for the waste-generating enterprise to implement the optimization scheme exceeds the cost of non-implementation. Consequently, the enterprise does not adopt the established matching scheme.

During the initial phase of development, driven by environmental impacts and public pressure, district-level governments are compelled to intensify regulatory measures, such as increasing reward incentives. At this stage, since the loss incurred from forgoing supervision exceeds the cost of supervision ($I+K_2>C$), the district-level government opts to implement supervision. However, for the waste-generating enterprise, despite increased government reward incentives, the cost of implementing the optimization scheme still exceeds the expenditure associated with non-implementation

$(G+T+M_1+M_2-F>S+K_1+K_2+I)$. Consequently, the enterprise still decides not to dispose of hazardous waste under the optimization scheme. At this point, the system stabilizes at equilibrium $E_2(1,0)$.

In the intermediate stage of development, the government continues to refine regulatory measures (e.g. by increasing the severity of penalties). At this stage, given that the loss incurred from forgoing supervision exceeds the cost of supervision ($M_2>C$), the district-level government continues to supervise the enterprise. When the cost of implementing the optimization scheme is less than the expenditure associated with non-implementation $(G+T+M_1+M_2-F<S+K_1+K_2+I)$, the enterprise is inclined to adopt the optimization scheme. At this point, the system stabilizes at $E_3(1,1)$.

In the mature stage, waste-generating enterprises have established long-term cooperative relationships with downstream disposal firms and, driven by market mechanisms, will continue to implement the optimization scheme. At this stage, continued intervention by the district-level government would incur unnecessary fiscal expenditures; consequently, the government gradually withdraws its intervention, corresponding to equilibrium point $E_4(0,1)$. The condition for a stable equilibrium point is $M_2<C$, indicating that the loss resulting from the district-level government's lack of supervision is less than the cost of supervision. $G+T+M_1-F<S+K_1$, indicating that the cost for waste-generating enterprises to implement the optimization scheme is less than the expenditure associated with non-implementation.

4.2.2. Numerical simulation analysis

To intuitively illustrate the dynamic evolutionary process of strategy selection by district-level governments and waste-generating enterprises across various districts, and to clarify the developmental stage of hazardous waste management in each district, this study conducts a simulation analysis based on field survey data. The results indicate that, among the 22 districts in Chengdu, 9.09% exhibit the (1,0) stable strategy, while 90.91% exhibit the (1,1) stable strategy. This suggests that hazardous waste management in the vast majority of districts in the study area is at the intermediate stage of development. During this stage, as the hazardous waste-management industry achieves a substantial scale and establishes a relatively complete industrial chain, district-level government interventions will be gradually phased out. However, an analysis of the payoff matrix reveals that the returns for both district-level governments and waste-generating enterprises are influenced by the quantity of hazardous waste associated with different strategies. Ma and Zhang (2020) likewise found that although participants' costs and benefits were closely correlated with the volume of waste operations, the effect of waste quantity on the equilibrium state of the game system remained to be clarified. With the advancement of the "waste-free city" initiative, the innovation and widespread implementation of clean production and waste-recycling technologies are expected to reduce hazardous waste generation (Meng and Wang, 2022). Consequently, this study investigates the influence of changes in hazardous waste generation on the strategic choices of district-level governments and waste-generating enterprises during the intermediate stage.

Assume that hazardous waste generation in a district is reduced by a proportion $\alpha(\alpha\varepsilon[0,1])$ from its initial level. Specifically, hazardous waste generation is progressively reduced from its initial level in 10% increments, up to a maximum reduction of 50%. At the same time, the volume of hazardous waste transported along the corresponding routes is reduced by the same proportion. Consequently, six evolutionary scenarios are constructed (Figure 3). In all scenarios, the initial regulatory probability for district-level governments (x_0) and the initial compliance probability for waste-generating enterprises (y_0) are set to 0.5. The values of the remaining parameters are shown in Table 2. As shown in Figure 3, the change in hazardous waste generation does not affect the district-level government's regulatory willingness, whereas the behavioural strategies of waste-generating enterprises change significantly. When α=0.2, the behavioral strategies of waste-generating enterprises undergo a significant reversal, and the system evolves from the (1,1) equilibrium to the (1,0) state. The underlying cause of this phenomenon lies in the non-linear characteristics of the impact exerted by the reward-penalty mechanism on enterprises' psychological perceptions and behavioral decisions across different production scales. First, in terms of compliance costs and incentive structures, the implementation of optimization schemes by enterprises typically entails fixed management and equipment investments, which exhibit significant economies of scale. When the production reduction reaches 20%, the output-based proportional subsidies shrink concurrently, causing their capacity to amortize fixed costs to fall below the "incentive threshold" of the enterprise, which leads to a significant decline in the marginal utility of compliant production. Secondly, from the perspective of psychological and behavioral effects, the reduction in output significantly attenuates the enterprises' risk perception of the penalty mechanism. In socioeconomic reality, enterprises often develop a "concealment mentality", believing that small-scale non-implementation is more clandestine, thereby lowering their subjective assessment of the probability of regulatory capture. This diminished perception of oversight causes the expected cost of non-implementation to fall significantly below the nominal penalty amounts, leading enterprises to exhibit a heightened risk appetite at this critical threshold. At this juncture, the enterprise's decision-making logic shifts from the pursuit of long-term compliance gains toward short-term cost minimization, as the opportunity gains of non-implementation outweigh the potential risks. Consequently, even if district-level governments maintain their initial regulatory intent, the enterprises' motivation for compliance is rendered ineffective by the erosion of psychological barriers and the imbalance of the cost-benefit structure, ultimately leading the system to deviate from the ideal equilibrium state.

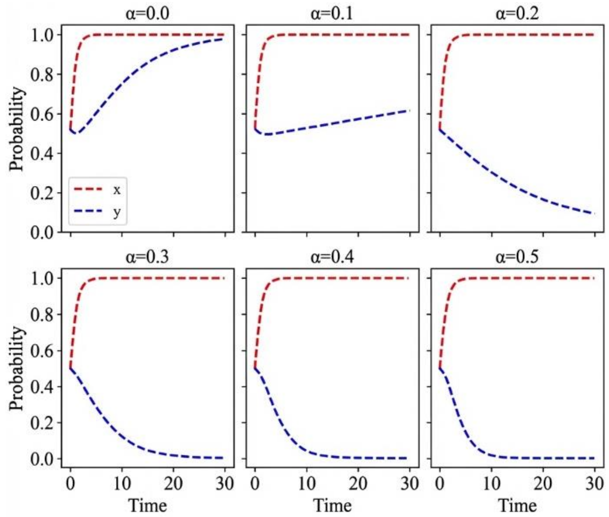


Figure 3. Effects of hazardous waste amount on the behavioural strategies of both players in the game.

When the game stabilizes at (1,0) equilibrium, how to transition the players' behavioural strategies toward (1,1) becomes a core issue. Studies indicate that moderate adjustments to subsidies and penalties can steer the decision-making behaviour of both parties toward the optimal solution (Wang *et al.*, 2020). Accordingly, the effect of government incentives on the game system is examined here to provide theoretical guidance for the evolution of the hazardous waste-management industry from the initial to the intermediate stage. Specifically, based on Equations (10) and (11), this study adjusts the key parameters for subsidy F and fine I—subsidy intensity (C_2) and penalty intensity (C_3)—by ±20%, thereby generating nine combined scenarios. In each scenario, the initial supervision probability for the district-level government and the initial compliance probability for waste-generating enterprises are both set to 0.5. Table 2 details the values of the remaining parameters.

Figure 4 illustrates the dynamic evolution of the probability of the district-level government choosing the "supervision" strategy (x) and the waste-generating enterprise choosing the "implementation" strategy (y) over time, under different combinations of subsidy and penalty intensities. The district-level government's willingness to supervise exhibits a strong tendency to approach 1 in most scenarios. This indicates that, under the game model's current parameter settings, the district-level government has strong internal incentive for continuous supervision. Similarly, Su (2020) found that adjusting subsidies and penalties for firms during the initial stage did not influence the government's willingness to supervise.

In contrast, the waste-generating enterprise's compliance willingness exhibits significant sensitivity to changes in parameters C_2 and C_3. In the low-fine scenario (C_3=400, Figure 4(a, d, g)), the waste-generating enterprise's probability of compliance rapidly declines to 0, regardless of the subsidy level. This shows that even if the district-level government provides varying levels of subsidies, waste-generating enterprises will overwhelmingly choose not to implement the optimization plan if the penalty intensity is insufficient. This implies that in a low-penalty environment, subsidies are neither sufficient to offset the potential economic gains from non-compliance nor adequate to cover compliance costs, thereby causing the enterprise to deviate completely from the optimization plan. In the medium-penalty scenario (C_3=500, Figure 4(b, e, h)), enterprise compliance behaviour begins to diverge. Specifically, under low (C_2=80, Figure 4(b)) and medium (C_2=100, Figure 4(e)) subsidy conditions, the enterprise's compliance probability still converges to 0, albeit at a slower rate. However, when the subsidy is further increased to C_2=120 (Figure 4(h)), the enterprise's compliance probability does not converge to zero but instead stabilizes at an intermediate level of 0.55. This suggests the possibility of a mixed-strategy equilibrium, in that some enterprises may choose to comply while others do not, or an individual enterprise may choose between compliance and non-compliance with a certain probability. This state represents a deviation from the ideal (1,1) stable equilibrium, indicating that at this penalty level, increasing subsidies alone is insufficient to achieve full compliance. In the high-penalty scenario (C_3=600, Figure 4(c, f, i)), the compliance probability of waste-generating enterprises rapidly increases and stabilizes at 1, regardless of the subsidy level (C_2=80, 100, 120). This indicates that the system eventually converges to stable equilibrium (1,1), where the government maintains continuous supervision and enterprises fully implement the optimization plan. This provides evidence that adequate punitive intensity is the most critical driver for ensuring compliance by waste-generating enterprises, an effect that, to some extent, outweighs that of subsidies.

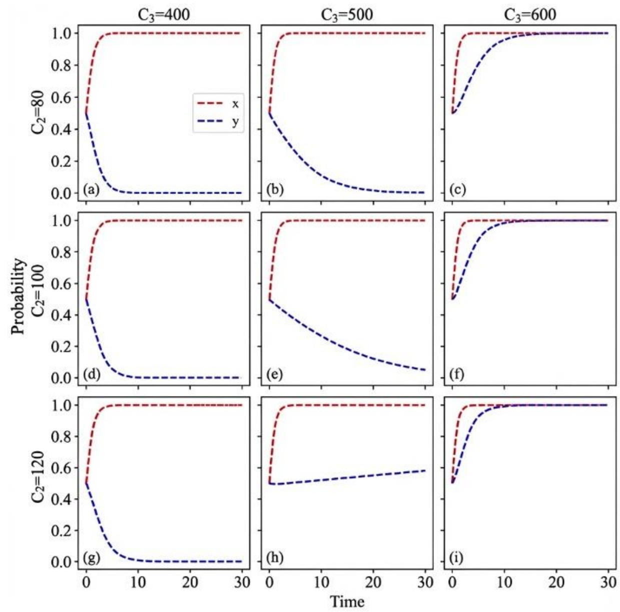


Figure 4. Influence of penalties and subsidies on the strategy evolution of the two participants.

5. Managerial implications

Given the potential for system cost reduction revealed by the optimization results, the stability of the district-level government's supervisory willingness, and the significant disparity in the sensitivity of waste-generating enterprises to subsidies versus penalties, this study makes the following policy recommendations. The aim is to construct a more resilient hazardous waste-management system under the "Zero-Waste City" initiative, capable of guiding stakeholders toward collaborative participation.

First, a quantitative incentive and penalty mechanism centered on "high-deterrence sanctions" should be established. Simulation results indicate that the severity of penalties is the key driver of corporate compliance. When the penalty intensity is increased to 600 yuan/ton (a 20% increase relative to the baseline), the system evolves toward the ideal stable state. Conversely, relying solely on increasing subsidies (e.g., a subsidy intensity of 120 yuan/ton) fails to ensure full compliance within a low-penalty environment. Therefore, local governments should establish dynamic penalty benchmarks to ensure that the cost of non-compliance is significantly higher than the cost of compliance.

Second, the government should exercise its coordination and management functions, guiding and encouraging small-scale waste-generating enterprises to engage in collaborative management and centralized hazardous waste disposal. Regional temporary storage or transfer centres can be constructed, or a hazardous waste information-sharing platform established, to promote the consolidated transport and disposal of hazardous waste, thereby achieving economies of scale and reducing disposal costs for individual enterprises. However, this initiative imposes high demands on the government's institutional coordination capacity, necessitating cross-functional collaboration among environmental, planning, and fiscal departments to dismantle administrative barriers in site selection and operational oversight. Meanwhile, as initial infrastructure construction involves significant fiscal outlays, local governments can alleviate fiscal pressure and ensure long-term operational sustainability by leveraging private capital. Furthermore, waste-generating enterprises should be encouraged to establish stable, long-term partnerships with downstream disposal companies to ensure reliable hazardous waste disposal channels and enhance their bargaining power, thereby avoiding disposal disruptions caused by issues such as exhausted permitted capacity.

Third, policymakers should increase base fines for the illegal storage, transfer, and disposal of hazardous waste. Particularly for violations involving small quantities of hazardous waste, a higher per unit fine coefficient should be established to curb the complacent "small quantity, low risk" mindset among small-scale generators, thereby increasing the economic cost of non-compliance. The implementation of this policy is predicated on the allocation of administrative resources for regular market research and cost assessments to ensure that the penalties are both scientifically grounded and sufficiently deterrent.

Furthermore, district-level governments should leverage modern technologies—such as full-chain traceability systems for electronic hazardous waste, Internet of Things sensors, satellite remote sensing, and AI-enabled video surveillance—to enable the real-time, precise monitoring of the entire hazardous waste life cycle, including generation, storage, transfer, and disposal. A higher likelihood of detection increases the expected fine. This serves as a powerful deterrent, compelling enterprises to recognize through cost-benefit analysis that the expected risks and costs of arbitrary, unregulated practices outweigh the cost of compliant disposal. While advanced technological measures can significantly enhance the probability of detection and reduce long-term labor costs for inspections, they entail substantial upfront expenditures for equipment procurement and system integration.

6. Limitation

This study has several limitations that provide avenues for future research. First, the empirical analysis in this study is exclusively based on data from Chengdu, which limits the generalizability of the findings to some extent. Due to significant variations in economic development, industrial structures, and geographical environments across different regions, the underlying logic of hazardous waste management may shift depending on the context. As demonstrated by Demirarslan and Çelik (2018) in their study of the eastern Black Sea region, regional heterogeneity directly influences waste characterization and the required management infrastructure. Consequently, while the integrated "spatial optimization-evolutionary game" framework proposed in this study is logically adaptable, its application to other geographical or institutional contexts (e.g., coastal regions or cross-border management) necessitates recalibrating parameters to reflect local waste generation characteristics, logistics costs, and specific regulatory environments.

Second, although the integration of Python-based data collection and spatial analysis ensures data reliability, the optimization model remains inherently static. Specifically, the model does not account for the temporal variations of parameters or the effects of uncertainty. The temporal fluctuations in hazardous waste generation were not incorporated into the model, which, to some extent, constrained its capacity to forecast long-term trends. Furthermore, key parameters such as risk coefficients, unit costs, and carbon emission factors were assumed to be constant, overlooking the impact of uncertainties arising from the external environment, such as policy shifts or market fluctuations. Future research should therefore transition toward dynamic optimization under uncertainty, potentially employing stochastic programming or robust optimization to address time-matching issues between waste generation and downstream capacity, as well as the impact of evolving service prices on disposal demand. Such advancements will lead to more adaptive and forward-looking regional hazardous waste management strategies with enhanced predictive reliability.

Besides, the evolutionary game model developed in this study only involves two stakeholders. Consequently, given that the hazardous waste-management system is complex and involves numerous stakeholders and multiple factors in its operation, future research should expand system boundaries to incorporate additional key stakeholders and factors. Accordingly, more comprehensive policy recommendations should be proposed for hazardous waste-management systems.

7. Conclusion

This study integrates multi-objective optimization with evolutionary game methods, spanning from the municipal government's (upper-level) formulation of control plans to the implementation willingness of district governments and enterprises (lower level). By considering the behavioural strategies of both administrators and executors, this study aims to promote the implementation of urban hazardous waste-management strategies. First, this study constructs an optimization model that integrates the economic, environmental, and social risk-benefit objectives of various stakeholders in the hazardous waste-management system. Through this optimization analysis, the study aims to formulate a city-wide hazardous waste matching plan. Second, accounting for the bounded rationality of key stakeholders, an evolutionary game model is established between district and county governments and waste-generating enterprises to analyse their decision-making behaviours under the optimal matching plan. Additionally, the effects of key variables (e.g. hazardous waste generation, subsidies, penalties) on the behavioural evolution of both parties are investigated to provide a theoretical basis for stable collaboration among the system's stakeholders.

The main conclusions are as follows. Prior to optimization, the total system cost is 4.09×10^7 yuan, of which about 80% is attributed to transportation. Following optimization, the total cost of the hazardous waste-management system is reduced to 2.58×10^7 yuan, representing a decrease of 36.85%. Specifically, the disposal cost remains unchanged, while the transportation cost decreases from 3.26×10^7 yuan prior to optimization to 1.75×10^7 yuan, representing a reduction of about 50%. (2) Regarding the game-theoretic interactions between district-level governments and waste-generating enterprises under the optimal solution, 90.91% of the 22 districts in Chengdu stabilize at the "supervision and implementation" strategy. However, when hazardous waste generation decreases by about 20%, the game no longer sustains "supervision and implementation" equilibrium and instead evolves to "supervision and non-implementation" equilibrium. (3) When the game stabilizes at "supervision and non-implementation" equilibrium, the system can be induced to evolve toward the optimal "supervision and implementation" solution by appropriately increasing government subsidies and penalties for waste-generating enterprises.

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