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Multi-objective optimization algorithm and its remediation path design in soil pollution control

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Abstract Soil pollution control is a key area in environmental protection, and with the acceleration of urbanization, the demand for remediation of polluted land is increasing. This paper investigates multi-objective optimization algorithms in soil pollution control and proposes a hybrid multi-objective genetic algorithm combined with local search for remediation path design. The method includes a global search using NSGAII algorithm combined with HCS local search strategy to improve the quality of search efficiency and remediation. The study constructed a multi-objective optimization function for economic and environmental benefits based on different land types and restoration technologies, and optimized the decision-making by simulating the restoration costs and land benefits under different scenarios. The results show that during the restoration process, the unit land benefit increases and the restoration cost decreases gradually with the increase of volume ratio. The unit restoration cost when maximizing the land benefit is 0.05 million yuan/m², while the unit land benefit can reach 18,200 yuan/m² when minimizing the restoration cost. The optimized scheme significantly improved the economic benefits and effectively reduced the environmental impacts, providing a scientific basis for the remediation and redevelopment of contaminated soil.

Index Terms Multi-objective optimization, NSGAII algorithm, remediation path design, land benefit, remediation cost, environmental benefit

I. Introduction

With the rapid development of urbanization, industrialization, and agricultural intensification in China, the intensity of soil development is increasing, and a large number of pollutants are being transferred to the soil, and the problem of soil pollution is becoming increasingly serious [1], [2]. Soil pollution is a process in which when the content, rate and toxicity of pollutants entering the soil exceed the soil's tolerance capacity, the soil itself is unable to eliminate the effects of these pollutants, causing deterioration of soil quality, which in turn acts as a hindrance to the growth of plants, and may jeopardize human health through its products [3]-[6]. Soil pollution affects the physical, chemical and biological properties of soil, thus affecting the growth of plants and the quality of agricultural products, destroying the quality of surface water and groundwater, and at the same time leading to atmospheric pollution, ecosystem degradation and other secondary ecological and environmental problems, which seriously threaten the health of human beings, and therefore the prevention and control of soil pollution is of vital importance [7]-[10].

Soil pollution prevention and control is an activity to prevent soil from being polluted and to improve and treat the already polluted soil [11]. Soil protection should be based on prevention, and the focus of prevention should be on controlling the concentration and total amount of emissions from various pollution sources [12], [13]. Regular monitoring and supervision of agricultural water use should be carried out so that it meets the water quality standards for farmland irrigation. Reasonable application of chemical fertilizers and pesticides, careful use of sewage sludge, river mud, pond mud. The use of urban sewage for irrigation must be purified and treated [14]-[16]. Promote biological control and integrated control of pests and weeds, as well as remediation of mines to prevent mineral toxic pollution, etc. And with the development of artificial intelligence, multi-objective optimization algorithms play an important role in soil pollution prevention and control, it is important for soil control, sustainable development and utilization by constructing prediction models and evaluating soil pollution, so as to design soil remediation paths [17]-[20].

In this study, a multi-objective optimization framework is proposed by combining the NSGAII genetic algorithm with the HCS local search method, and the framework is used for the design of remediation paths. The study firstly, establishes a mathematical model of restoration cost and land benefit, and evaluates the restoration effect by combining different restoration techniques; secondly, global optimization is carried out by hybrid multi-objective genetic algorithm, which takes into account multiple factors such as restoration cost, land benefit and environmental impact; finally, the global optimization results are finely tuned by using local search algorithms, in order to obtain a more accurate restoration path. The study also evaluated the practical effects of the optimization strategy under different conditions by simulating different land development scenarios.

II. Hybrid multi-objective genetic algorithm

II. A.Fast non-dominated genetic algorithm

NSGAII is a non-dominated multi-objective genetic algorithm that can perform Pareto sorting quickly, and the advantages of this algorithm mainly include the following three aspects: (i) proposing a fast non-dominated sorting method to reduce the complexity of the algorithm; (ii) proposing the crowding degree and crowding degree comparison operator, replacing the fitness-sharing strategy that needs to specify the sharing radius, and taking the crowding degree as a winning criterion for the individuals in the same level of sorting, which maintains the diversity of the population; (iii) introduces the elite strategy, which is conducive to preserving the good individuals in the process of population evolution and accelerates the convergence of the population [21]. The above advantages make NSGAII a widely used multi-objective intelligent optimization algorithm and serve as a benchmark for comparison with other improved algorithms.

II. B.Local Search Algorithm

HCS is an iterative local search method based on the optimal search direction. Since the groundwater pollution remediation management model is a complex nonlinear planning problem, the gradient information of the objective function cannot be calculated accurately, so this paper adopts the local search method without gradient calculation.

In order to elaborate the specific search process of HCS, HCS can be coupled with NSGAII as an independent algorithm that locally searches the Pareto solution evolved by the genetic algorithm and then outputs the local optimal solution. In order to decide the direction of the local search, it is necessary to use the neighborhood solution within a given neighborhood radius of the initial solution. The definition of a neighborhood solution i.e:

$$S(X_0, r) = \{X_n \in R^n \mid X_n \in H, (x_{0i} - r \le x_i \le x_{0i} + r \forall i = 1, \cdots, m)\} \tag{1}$$

where $X_0 = (x_{01}, x_{02}, \cdots, x_{0m}); X_n = (x_{n1}, x_{n2}, \cdots, x_{nm})$. X_0 is the vector form of the initial solution policy variables; X_n is the vector form of the neighborhood solution policy variables; m is the number of decision variables; x_{0i} is the i th decision variable of the initial solution; and H is the reference set of solutions from which the neighborhood solutions are selected during the optimization process, with the set of the parent and the set of the offspring solutions in the evolutionary process as the reference solution set and select the neighborhood solution that meets the requirements from it, which can reduce the evaluation of the objective function required for generating the neighborhood solution and increase the efficiency of the algorithm; r is the radius of the neighborhood. If the neighborhood solution Pareto dominates the initial solution and is denoted by $X_n < X_0$, it can be described as:

$$\begin{cases} f_i(X_n) \le f_i(X_0), \forall i \in \{1, 2, \cdots, k\} \\ f_i(X_n) < f_i(X_0), \forall i \in \{1, 2, \cdots, k\} \end{cases} \tag{2}$$

where $f_i(X)$ denotes the i th objective function and k denotes the number of objectives.

II. C.Methods of combinatorial optimization

Two important problems of hybrid multi-objective algorithms are how to select individuals as initial solutions for local search and how to balance the relationship between global and local search [22]. The search of genetic algorithms is characterized by the global search ability in the early stage that can quickly find individuals close to the optimal solution, but the convergence to the optimal solution slows down in the later stages [23]. Therefore, when implementing the local search, the optimal individual obtained from the current generation evolution should be selected as the initial solution. The balanced relationship between global search and local search can be regulated by the current probability of selecting an individual as the initial solution. If the selection probability is large in the early stage of evolution, the searched solution is prone to fall into the trap of local optimality.

III. Multi-objective planning for soil pollution prevention and remediation

III. A. Accounting for unit restoration costs

This study used an empirical modeling approach to calculate the cost of remediation of contaminated plots. The calculation of the model is mainly based on the average cost of the selected remediation technology and the level of contamination risk of the site. The average cost, i.e., unit remediation cost, required to remove the target contaminants from a contaminated site within the scope of the site investigation is used as an input indicator for remediation. The unit remediation cost can be calculated during the evaluation process by multiplying the remediation volume of each pollutant with the unit price of the corresponding remediation technology and dividing it by the area of the pollution survey. The formula is as follows:

$$ULRC = \frac{RP_{x1} \cdot \sum_{i}^{n} RA_i \cdot Dep_i + RP_{x2} \cdot \sum_{j}^{m} RA_j \cdot Dep_j + ...RP_{xk} \cdot \sum_{k}^{n} RA_k \cdot Dep_k}{TLRA} \quad (3)$$

where, $RPx_1, RPx_2 \cdots, RPx_k$ are the average market prices of remediation technologies for remediation of the target pollutants $x_1, x_2, ..., x_k$ the average market price of remediation technologies; RA is the site area to be remediated, m²; different remediation units (i, j) are divided according to the depth of contamination; Dep is the depth of remediation of remediation units, m; $ULRC$ is the cost of remediation of land parcel units, million yuan/m²; $TLRA$ is the area of contamination investigation.

III. B. Accounting for unit land revenue

Currently, the accounting methods for unit land revenue mainly include the simulated market method, the conditional value method and the hedonic value method, etc. The simulated market method treats land projects as a market transaction. The simulated market method treats the land project as a market transaction, and through analyzing and simulating the market data, it can predict the economic benefits of the land project more accurately, and it has the advantages of strong predictability, sufficient flexibility and high accuracy, so this method is chosen for the calculation of land revenue per unit in this paper.

Redevelopment revenue is calculated by the simulated market method, which comes from developing the land into commercial houses or stores for sale, and the remaining profit after deducting the relevant costs such as land transaction fees, construction and installation, and ancillary facilities, etc. is the land revenue. The parameters of this return mainly include the type of land redevelopment (Class I site, Class II site), the area of redevelopment, the residential plot ratio specification, and the relevant ancillary facilities. The calculation formula is as follows:

$$ULI = \frac{\sum_{i=R2,R1} LA_i (PCH_i \cdot FAR_i + PCUS_i - LSP - CP_i \cdot FAR_i) - \sum_{j}^{n} LA_j (PLSP_j + CP_j \cdot FAR_j)}{TLA} \quad (4)$$

where, LA_i is the area of the i th piece of land gained (B1 indicates commercial land, R2 indicates residential land); LA_j is the area of the land for ancillary facilities of the j th piece of land; FAR denotes the plot ratio; PCH denotes the unit price of the sale of commercial houses, 10,000 yuan/m²; $PCUS$ denotes the unit price of the sale of commercial houses on the ground floor sales unit price; $LSP, PLSP$ den.otes the land transaction price of commercial and residential land and the land transaction price of land for ancillary facilities, 10,000 yuan/m²; CP denotes the average unit price required for construction and installation works, 10,000 yuan/m²; ULI denotes the unit land revenue of the redevelopment plot, 10,000 yuan/m²; and TLA denotes the site area of the redevelopment plot, m².

III. C. Fixing and redeveloping the multi-objective optimization function

Economic objective function: the accounting method is the difference between the unit land revenue and the unit remediation cost, based on the remediation cost-land revenue analysis, i.e., the economic objective f_1, adding the remediation efficiency objective f_2 and the environmental objective f_3 constitutes the multi-objective optimization function for the redevelopment of contaminated plots:

$$Maxf1 = \max(ULI) - \min(ULRC) \quad (5)$$

$$Maxf2 = \max(REi) \quad (6)$$

$$Maxf3 = \min(RIi) \quad (7)$$

where, REi represents the efficiency indicator of the restoration technology; RIi represents the environmental impact of the restoration technology (secondary environmental impact)

The formula for calculating ULRC and ULI is linked through the three indicators of planning land area, planning population and volume ratio, where,

$$ULI_x = \frac{(Pop \cdot 30 / FAR + x) \cdot ULI_R + (LAR_B - x) \cdot ULI_B}{TLA} \quad (8)$$

$$ULRG = \frac{(Pop \cdot 30 / FAR + x) \cdot ULRG + ULRC_n \cdot TLRA_n}{TLRA} \quad (9)$$

Meanwhile, the constraints of the economic objective function are determined based on stakeholder analysis:

$$FAR < x_2 \tag{10}$$

$$LAR_B \le \frac{30 \times Pop \times 20\%}{FAR} \tag{11}$$

where, Pop denotes the redevelopment planning population; LAR_B is the commercial land area; and ULI_R, ULI_B denotes the unit land yield of residential land and the unit land yield of commercial land; x is the size of the residential land area in excess of demand; $ULRC_f, ULRC_m$ are the unit rehabilitation costs required for the first and second site types, respectively; TLA denotes redevelopment parcel footprint; 30 denotes residential square footage per capita; and 20% denotes the maximum percentage of commercial land use to residential land use, as specified by the individual Natural Resources and Planning Agencies.

In order to get the maximum net profit of restoration $Maxf_1$, firstly, combine the three variables of redevelopment site area land, redevelopment planning population, and site volume ratio, use formula (4) to calculate the unit land revenue of residential and commercial land, respectively, and then bring the results into formula (8) and calculate the unit land revenue through redevelopment site area land, redevelopment planning population, and site volume ratio. Relationship. The amount of pollution remediation calculated based on different remediation standards identified in the site plan is then brought into Equation (3) to calculate the unit remediation cost for different site types. Finally, the unit remediation cost relationship is expressed in Equation (9) by redevelopment site area, redevelopment planning population, and site volume ratio.

The calculation of the unit land revenue of the site to be rehabilitated involves multiple stakeholders such as the land developer and the government, so the unit land revenue should be calculated based on the actual market situation.

IV. Analysis of soil pollution prevention and remediation

IV. A. Rehabilitation Costs and Land Benefits for Different Planned Land Types

Based on the various types of land identified in the planning program, the planning population and the amount of restoration corresponding to different volume ratios and restoration objectives were analyzed according to the criteria of planning volume ratio of 1.5~2.8, restoration objective of natural background, risk screening value and risk control value, as shown in Table 1. The results show that when the volume ratio of residential land is 1.5, only 19,300 people can be planned in this area, while only about 0.35 million m³ of BaP need to be restored if the GB36600-2018 control value is used for restoration. When the residential floor area ratio goes to 2.8, the area can be planned for 32,500 people, and the remediation volume reaches 1,025,000 m³ when using the natural background or the lowest detection value. The amount of remediation that reduces remediation goals increases exponentially relative to the planning population raised by increasing volumetric rates. Reasonable remediation treatment standards and planning volumetric targets greatly influence the benefit-cost relationship of redeveloping contaminated parcels.

Table 1: The land FAR and remediation target value for different land redevelopment patterns

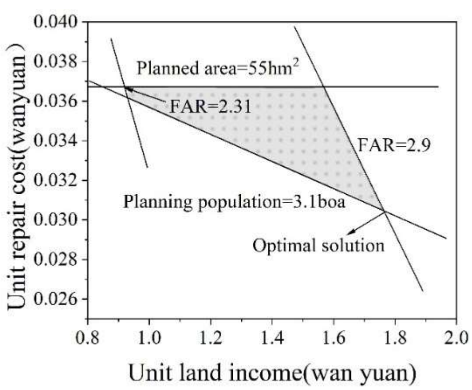
Land development strength	Volume ratio		As(mg/kg)		BaP(mg/kg)		Planning population (boa)	Recovery (wan m³)
	Residential land	Commercial land	First type of land	Second type of land	First type of land	Second type of land		
1**	1.5	2.6	130	150	6.2	17	1.93	0.35
2	1.6	2.7	110	130	6	13	2.04	0.60
3	1.7	2.8	90	100	5	11	2.15	0.95
4	1.8	2.9	70	90	4	8	2.30	2.05
5	1.9	3.0	60	80	3	7	2.35	3.55
6	2	3.2	50	70	2	6	2.41	14.74
7	2.2	3.5	40	60	1	5	2.55	28.25
8**	2.4	3.7	30	40	0.8	3	2.90	39.21
9	2.6	3.8	20	30	0.60	2	3.01	53.22
10	2.7	4.0	10	20	0.5	1	3.11	70.35
11**	2.8	4.1	10	15	0.4	0.5	3.25	100.25

Note: *Based on local requirements, the plot ratio of residential land is controlled at 1.5~2.8, commercial land is not higher than 4.0, and the proportion of commercial land does not exceed 20% of residential land. **1 and 8 are the As and BaP risk screening and control values determined by GB36600-2018, respectively; 11 is the minimum detection value of As and BaP sampling points.

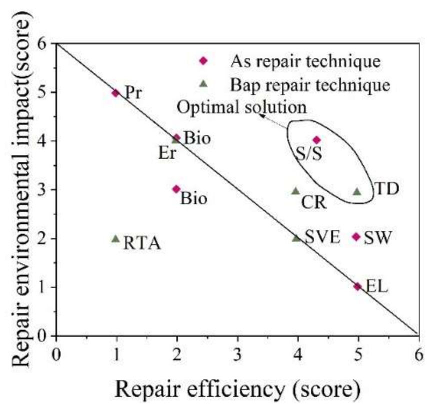
IV. B. Multi-objective optimization decision-making for remediation and redevelopment of contaminated sites

On the basis of the cost and benefit accounting results of restoration of different land types, the functions of economic objective f_1 and environmental objective f_2 are constructed under the planning constraints, as shown in Fig. 1. Figure 1(a) According to the constraints of planning area 52hm², plot ratio ≤2.8, and planning population ≥30,000 people, the variation interval of unit land revenue is 157~17,800 yuan/m². The maximum unit land revenue is achieved when the residential population is 31,000 and the residential plot ratio is 2.9 (Maxf1=1.79). Since the non-sensitive commercial land use can reduce the overall restoration amount, the minimum restoration cost is achieved at a planned population of 31,000 people (Min(ULRC)=0.05). According to the indicator of 28m² per capita of residential land use, the area of the residential land use is 29,987.84m², and the area of the commercial land use is 75,232.04m² when the land gain is maximized.

Figure 1(b) Assessment of remediation technologies shows that solidification-stabilization (S/S) has high remediation efficiency and low environmental impacts among As remediation technologies, whereas phytoremediation (Pr) has low remediation environmental impacts but low remediation efficiencies, and excavation-landfill has high efficiencies but high environmental impacts.Thermal desorption (TD) has high remediation efficiencies but some environmental impacts among BaP remediation, while chemical oxidation (CR) remediation has the same environmental impact as TD but low remediation efficiency, and room temperature analysis (RTA) remediation has low environmental impact but low remediation efficiency, and is suitable for remediation of plots that are not exploited for the time being. Combining the planning constraints and MCA assessment, Maxf2 = Min(ULRC) + Max(S/S,TD/RTA), i.e., the lowest unit remediation cost of 0.03 million yuan/m², the remediation technologies combining solidification stabilization, thermal desorption, chemical oxidation, and ambient temperature analysis were adopted, respectively.



(a) Land planning strategy



(b) Repair management strategy

Figure 1: The optimized results of the brownfield remediation and redevelopment strategies

Figures EL Excavation-Landfill; S/S Curing/Stabilization; SW Soil Drenching; Er Electro-Remediation; Bio Microbial Remediation; Pr Phytoremediation; RTA Ambient Resolutions; TD Thermal Desorption; CR Chemical Reduction by Oxidation; SVE Vapor Phase Extraction.

IV. C. Evaluation of Multi-Objective Optimization Scenarios for Redevelopment of Contaminated Sites

According to the constructed multi-objective optimization decision results, the combination of site adjustment and restoration techniques significantly increased the economic return of the land and reduced the restoration environmental impacts. The three planning site adjustment scenarios are shown in Table 2.For the three site redevelopment scenarios, the planning population is 33,500 and 31,000 people, the floor area ratio is 2.9, and the area of commercial land is 5.83 and 7.96 hm², respectively.The S2 and S3 scenarios reduce the planning population by 0.25 million people compared with the S1 planning population, and the area of commercial land is increased by 2.13 hm², and the revenue of the unit of land compared with the S1 scenario is increased from 14,100 yuan/m² to 18,200 yuan/m². The unit restoration cost of S1 was reduced from 0.13 million yuan/m² in S1 to 0.09 million yuan/m² through the adjustment of the land use planning scheme, and the unit restoration cost of S3 scenario was further reduced to 0.05 million yuan/m² through the optimization of restoration technology.

Table 2: Three scenarios of land use adjustment and their remediation volumes

Scene	Land area(hm²)		Planning population (thousands of people)	Individual land income(wan yuan/m²)	Repair amount (10,000 m²)		Repair technology*		Unit repair cost (10,000 yuan /m²)
	Inhabit	Business			AS	BaP	AS	BaP	
S1	32.78	5.83	3.35	1.41	13.84	35.83	S/S	TD	0.13
S2	29.61	7.96	3.1	1.82	6.17	28.71	S/S	TD	0.09
S3	29.61	7.96	3.1	1.82	6.17	6.17	S/S	TD	0.05
						5.32		CR	
						14.2		RTA	

Note: *S/S curing/stabilization; TD thermal desorption; CR chemical redox; RTA room temperature resolution.

IV. D. Decision-making preference analysis

Decision preference refers to the tendency of a decision maker to choose one of the options or alternatives when faced with several options or alternatives. Different decision-making judgments may lead to changes in the results of the study case, but also can use different decision-making means to achieve different goals set by the decision maker, so it has a non-negligible role in the land planning method of site reuse. The decision maker of the site can take into account the actual situation, combined with the set objectives, in the fuzzy interval of the objective function to take the value of the weekly integer value and thus obtain the benefits of different decision-making preferences.

Let $\omega_1 \in$ [0,1], $d_{f1} = f_{1\max} - f_{1\min}$, define the feasible domain for the decision maker's choice as $[f_{1\min} + \omega.d_{f1}, f_{1\max}]$, while $f_2 \in f_{2\min}, f_{2\max}]$. At this point, with $\omega_1 \to 1$, the decision maker's preference for economic benefits increases, and the calculated value converges to the maximum value of economic benefits; on the contrary, if the preference is for environmental benefits, adjust the fuzzy interval of the objective function of the environmental benefits $[f_{2\min} + \omega.d_{f2}, f_{2\max}](\omega_2 \in [0,1], d_{ff2} = f_{2\max} - f_{2\min})$, $f_1 \in [f_{1\min} - f_{1max})$. At this point the target value of environmental benefits will change accordingly as the decision maker adjusts oz. Take ① ω_1 =1, ω_2 =0; ω_1 =0.8, ω_2 =0; ω_1 =0.6, ω_2 =0; ω_1 =0.4,o2=0; ω_1 =02, ω_2 =0; ② ω_1 =0, ω_2 =0; ③ ω_1 =0, ω_2 =0.2; ω_1 =0, ω_2 =0.4; ω_1 =0, ω_2 =0.6; ω_1 =0, ω_2 =0.8; ω_1 =0, ω_z =1. The optimization results for the combined 11 scenarios enable the software origin 2018 to plot the model change curves as shown in Figure 2.

Combining the curves in the figure, the parameter combinations in ① correspond sequentially to scenarios 1-5 in the figure, when the decision maker has a greater preference for economic benefits, where ω_1 =1 and ω_z =0 when the decision maker focuses only on the economic benefits and ignores the bad environment benefits; The parameter combinations in ② indicate that the decision maker has no preference, and at this time the economic and environmental benefits are considered equally important; the parameter combinations in ③ correspond to the scenarios in Figs. 7~11 in turn, and at this time the decision maker has a greater preference for the environmental benefits, in which ω_1 =0, and ω_z =1 the decision maker focuses on the environmental benefits only and ignores the economic benefits. ignore the economic benefits. Throughout the change of the curve, with the decrease of the preference degree of the decision maker for economic benefits and the increase of the preference degree of bad environment benefits, the area of public land has been increasing, the area of commercial land has been decreasing, and the area of residential land has been increasing first (1~4) and then decreasing (4~7) and then increasing (7~9) and finally leveling off (9~11).

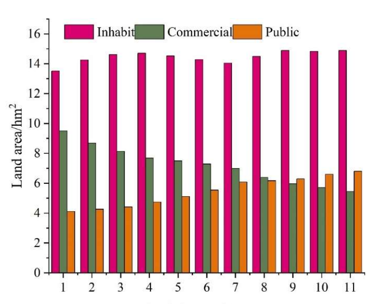


Figure 2: Optimal area of the three land use pattems under diferent decision preferences

Based on the same parameter combinations as in Figure 2, the total economic benefits and total environmental benefits under different decision preference scenarios are plotted and analyzed as shown in Figure 3. The total economic benefit gradually decreases and the total environmental benefit gradually increases as the decision maker's preference for bad environment benefits increases. This figure can serve as a guide for decision-making preferences under the focus on total benefits.

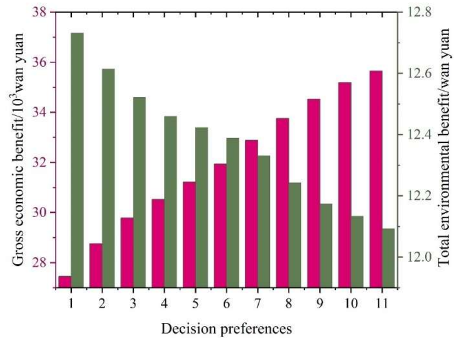


Figure 3: The change of total economic and total environmental benefits of the site

The three site reuse planning scenarios in this paper are substituted into the model to find their corresponding economic and bad environment benefits, which are graphically displayed on the Benefit Decision Preference Scenario Map, as shown in Figure 4. The three groups of circular dots from right to left represent the economic and environmental benefits under Scenario 1 (purple), Scenario 2 (blue), and Scenario 3 (green), respectively. Scenario 3 has the highest economic benefits and the lowest environmental benefits; Scenario 2 has the highest environmental benefits and the lowest economic benefits; and Scenario 3 balances economic and environmental benefits. It can be seen that the calculation results of the multi-objective decision mirror model are basically consistent with the prediction under the actual planning and design, which can be used to analyze and judge the economic and environmental benefits of the contaminated site and the land use planning situation.

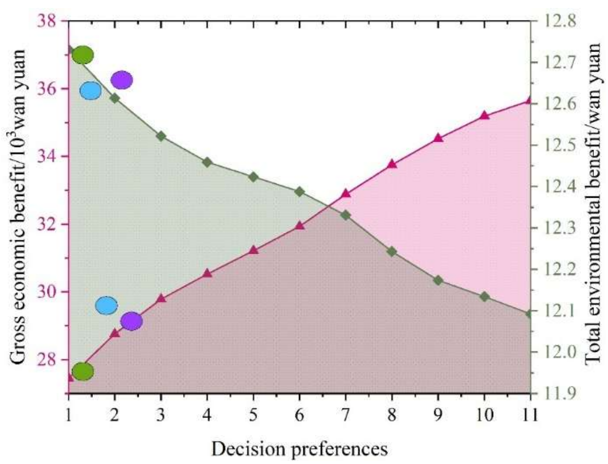


Figure 4: Changes in total economic and environmental benefits of site reuse

V. Conclusion

By adopting a hybrid multi-objective optimization algorithm, the remediation path design method proposed in this paper is able to significantly improve the soil remediation efficiency and reduce the cost under the comprehensive optimization of multiple objectives. The optimization results show that in the remediation process, the increase of volume ratio directly affects the unit land revenue and remediation cost. When maximizing the land benefit, the remediation cost is minimized, and the unit remediation cost is 0.05 million yuan/m². In this case, the economic benefits of land redevelopment are substantially increased, while the environmental impact is effectively reduced.

In addition, through the analysis of decision-making preferences, it was found that different decision-making preferences have a significant impact on land use and restoration effects. When the priority of environmental benefits is elevated, the economic benefits will decrease, and vice versa. Therefore, decision makers should flexibly adjust the decision preferences according to the actual needs and planning objectives in order to obtain an optimized restoration scheme.

In summary, the multi-objective optimization method proposed in this paper not only provides a feasible path for the remediation of contaminated soil, but also provides a scientific decision-making basis for land redevelopment, which has important practical application value.

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