The Impact of Dual Objective Optimization Model Combining Non-Dominated Genetic Algorithm on Rural Industrial Ecological Economy

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***Abstract*—Due to the development of industrial economy, it has caused serious damage to the ecological environment. Based on the industrial structure and production scale, rural industrial economic parks are planned to analyze the quantity and weight of pollutants emitted from the original industries. The results showed that the quantity and weight of hydrogen sulfide in the coking industry were 10kg/t and 94, respectively. The weight of smoke and carbon monoxide in the steelmaking industry was relatively high, with 54 and 34, respectively. Non-dominated sorting genetic algorithm and multi-objective programming model are used to optimize the comprehensive benefits and industrial structure of rural industrial ecological economy. According to the experimental results, when the scale of the coking industry was 135600 tons, the steelmaking industry was 314900 tons, the ironmaking industry was 148100 tons, and the underground coal gasification industry was 424.76 million Nm3. The comprehensive economic benefits of the industry reached the optimal level of 0.6415. The environmental and comprehensive benefits generated by the increased power generation industry were 64.98 and 40.87, respectively. Therefore, it indicates that the dual objective programming model combining non-dominated sorting genetic algorithm can improve the rural industrial ecological economy.**

***Keywords*—Industrial chain production mode; ecological economy; environmental benefits; non-dominated sorting genetic algorithm; dual objective programming model**

I. INTRODUCTION

With the acceleration of urbanization, rural industrial development has become an important force in promoting rural economic development. The rural industrial economy not only increases the sources of income for farmers and improves their income, but also optimizes the rural industrial structure and promotes diversified economic development [1-3]. But industrial development needs to consider the balance of rural ecological environment. When developing rural industrial economy, it is also necessary to adapt to local conditions, prioritize ecological protection, and form a rural ecological economic system. Guided by the ecological civilization development, rural ecological economy combines ecological and industrial economic development, reasonably utilizes ecological resources and industrial chain models, comprehensively considers economic and environmental benefits, and promotes the development of rural ecological industrial parks and their economy [4-6]. The development of ecological industrial parks is led by the government and responded by enterprises to establish different parks, connect with industrial industries, and create sustainable green industrial parks with a circular economy as the main focus. Guided by the green development concept, especially for the extensive heavy industrial economy, the emissions of this economic model do not belong to the green economy, causing serious damage to the environment [7]. Based on this, the study analyzes the industrial structure of rural industrial economy and constructs a dual objective programming model to analyze the production mode of industries. In order to comprehensively consider the coordinated development and resource utilization of the industrial chain in industrial parks, an innovative multi-objective genetic algorithm, namely, Non dominated Sorting Genetic Algorithms (NSGA-II), was used to analyze the comprehensive benefits of industries and reasonably consider the green environmental benefits, in order to promote the sustainable development of rural industrial ecological economy. Compared with the indicator model analysis of existing research, the combination of industrial structure and benefit planning not only focuses on the growth of economic benefits, but also effectively combines the needs of environmental benefits, and maximizes the recycling of resources in the industrial chain. Based on the analysis of environmental benefits indicators, it has been proven that the dual objective programming model combined with NSGA-II algorithm is superior and feasible for rural industrial ecological economy.

The study is conducted in five parts. The first part is to elaborate on the current research progress. The second part is to analyze the industrial structure to construct a dual objective planning industrial chain model. The third part is to analyze the industrial production mode using environmental benefit indicators and NSGA-II. The fourth part is a discussion of the research results. The last part is a summary of the entire study.

II. RELATED WORKS

With the deepening of the green development concept, people are not only pursuing high-speed economic development, but also paying more attention to the coordination between ecological environment and economic development [8]. The main focus is on ecological transformation of the existing economic system, namely ecological economy, which mainly includes production modes, resource utilization, etc. While pursuing high profits, it also takes into account environmental benefits, thereby driving new economic growth and providing model exploration for the development of ecological economy. In recent years, domestic and foreign scholars have conducted different explorations on the ecological transformation of industrial economy. Regarding the green economic development models, Zhiguang Zhang used sustainable development theory, super cycle theory, etc. to extract and classify green economic models. Combined with the theoretical model, the theoretical basis was provided for green economic models [9]. Regarding the ecological and economic issues in the Yangtze River Delta, Wang et al. combined energy theory to construct evaluation indicators for sustainable development of green economy. The ecological and economic system was analyzed to propose sustainable development recommendations [10]. Regarding the industrial economic transformation, Shukla et al. proposed to test the soil in polluted areas and analyze its metal concentration, thereby providing theoretical reference for the development of industrial economy [11]. Regarding the development model of industrial economy, Haowei et al. used digital economy to improve industrial ecological efficiency and promote regional ecological economic development [12]. FAN Weiguang et al. proposed a coupled coordination measurement model that combined balance attributes and performance evaluation to address the green economic development in Northeast China, providing reference for achieving sustainable development goals in the region [13]. The green economy and sustainable development goals are important directions for current economic development. Therefore, in different regions and industrial economies, the development indicators of green ecological economy are used. Regarding the ecological and economic issues related to the tourism industry structure, Yang et al. used correlation analysis and multi-objective programming models to optimize the industry structure, improving the low-carbon development of the tourism economy [14]. Chen combined the digital economy to analyze and transform the industrial structure reasonably, thereby promoting the development of carbon reduction economy [15]. Junjie et al. used digital economy and model construction to analyze the changes and effects of industrial structure upgrading, improving industrial structure and ecological economic development [16]. Weicheng et al. conducted heterogeneity analysis on industrial structure optimization and upgrading using information technology and substitution effects, to promote industrial structure optimization and upgrading [17]. Agarwal et al. Used the Analytic Hierarchy Process (AHP) to manage the circular supply chain of Jinning County's traditional industrial economy, promoting the sustainable development goals of the industry [18]. To achieve green ecological economic development and sustainable development, industrial structure is the primary direction of transformation. Therefore, the optimization of industrial structure varies in different regions.

In summary, although domestic and foreign scholars have proposed many models and methods for green ecological economy and industrial structure changes, there is a lack of in-depth research on the integration of rural and industrial economy in industrial transformation. Therefore, the dual objective programming model combining NSGA-II is feasible for the development of rural industrial ecological economy.

III. Planning of Rural Industrial Ecological Economy and Environmental Benefits

The rise of rural industry promotes the further development of rural economy. Ecological protection has become the main goal of rural economic development. While pursuing economic benefits, rural ecological environment protection needs to be taken into account. This study analyzes the development of industrial structure in industrial parks. Combined with the dual objective optimization model, the economic model of rural industrial ecological parks is further improved.

A. Construction of Industrial Chain Model for Rural Industrial Ecological Parks

Ecological industrial park is a enterprise community mainly engaged in manufacturing and service industries. Various enterprises jointly manage economic affairs and environmental maintenance, thereby promoting the comprehensive development of economic, social, and environmental benefits [19]. The construction of rural ecological industrial parks needs to follow the principles of circularity, diversity, regionalism, and evolution. The main enterprises were analyzed for their current situation and industrial chain formation. The development model of the traditional industrial chain focuses on pursuing profits. It inputs and outputs various materials, resources, and waste treatment, as shown in Fig. 1.

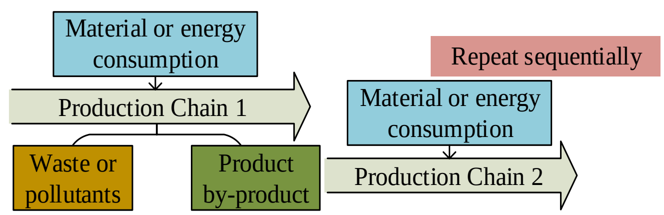


Fig. 1. Schematic diagram of the production process in the industrial chain

In Fig. 1, each production chain starts with material or energy consumption. Through the complete production process, products or by-products are formed, while also generating waste or pollutants. The generated products will also be put into the next industrial chain as one of the consumables, repeating the consumption and production of resources, input and output in sequence. Therefore, industrial production models need to maximize the utilization of existing resources and waste, and treat pollutants. Thus, the role of each link in the production chain can be leveraged to complete the production circular economy model. Enterprises within the industrial park coexist for mutual benefit. The mutually beneficial relationship between enterprise production chain and environmental resources is coordinated. The pressure index caused by enterprises ignoring environmental resources and establishing industrial chains on the environment is shown in equation (1).

$$\text{Environmental Pressure Index} = \sum_{n=1}^{N} \frac{a_{bn}}{j_{bn}} + \sum_{k=1}^{K} \frac{P_{bk} \times \theta_{bk}}{AC_{bk}} \tag{1}$$

In equation (1), b represents the enterprise. n is material, resource, or energy. k is a pollutant. a_{bn} represents the amount of material or energy consumed by an industry in the production process. j_{bn} represents the amount of resources that can be provided by the industrial region. P_{bk} represents the amount of pollutants emitted in industrial production. AC_{bk} is the maximum capacity of the enterprise's location for pollutant emissions. θ_{bk} is the pollution concentration emitted. To consider mutual benefit and symbiosis among industries, resource consumption and pollution emissions between industries are calculated, as shown in equation (2).

$$Multualism = J - K - L \tag{2}$$

In equation (2), $Multualism$ represents the degree of mutual benefit and symbiosis between two enterprises. J is the quantity of industrial waste collection and input production collection. K is the number of identical elements in the set. L is the number of identical elements in the output set. Finally, based on the construction relationship of multiple enterprise industrial chains, the resource utilization and conversion between multiple enterprises will be carried out for the operation of industrial parks, thereby strengthening the mutually beneficial and symbiotic relationship between industries. The degree of mutual benefit and symbiosis among multiple industries is shown in equation (3).

$$\text{Pressure Index}(S) = \sum_{b=1}^{B}\left\{\sum_{n=1}^{N}\frac{a_{bn}-a_{bn}^{*}}{j_{bn}} + \sum_{k=1}^{K}\frac{\left(P_{bk}-P_{bk}^{*}\right)\times\theta_{bk}^{*}}{AC_{bk}}\right\} \tag{3}$$

In equation (3), $\text{Pressure Index}(S)$ represents the pressure index of the industrial chain S of multiple enterprises on the environment, which is the degree of mutual benefit and symbiosis. a_{bn}^{*} is the amount of resources that the industry converts into waste from other industries during production. P_{bk}^{*} represents the amount of waste generated by the industry that is converted into input for other industrial resources. B represents the number of enterprises in the industrial chain S. The industrial chain within the park connects multiple enterprises. The conversion and utilization of resources, waste or energy between enterprises provides a better production mode for the environmental benefits of the region, as shown in Fig. 2.

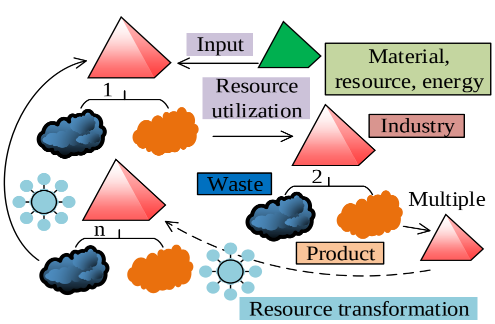


Fig. 2. Schematic diagram of industrial chain production model for multiple enterprises

In Fig. 2, the products of the first industry are converted into material inputs for the second industry through resource conversion, thereby completing the production chain of the second industry. Multiple enterprises participate in this process, which allows for the recycling of some of the waste produced by the industry, strengthening the internal connections between industries. Therefore, the exchange of material resources between any two industries promotes the exchange of material energy in the overall industrial chain, thereby achieving the overall environmental symbiosis of the ecological park. The waste in the production chain can be reused through the production process, but the generated pollutants cannot be put into production again. Therefore, pollutants and their weights are treated separately to reduce their harm to the environment. When constructing industries in ecological industrial parks, the maximum benefit evaluation of the environment is carried out. The indicator is used as the objective function of environmental benefit single objective planning, as shown in equation (4).

$$\text{Environmental benefit} = \sum_{b=1}^{B}\left(\alpha RCU_b + \beta WOU_b\right) \tag{4}$$

In equation (4), RCU_b represents the energy consumption per unit output value of the industry. WOU_b represents the discharge of three types of industrial waste. The consumption of industrial unit output value is shown in equation (5).

$$\begin{cases} RCU_b = \dfrac{E_b}{\sum_{m=1}^{M} i_{bm}V_{bm}} \\ WOU_b = \dfrac{\sum_{k=1}^{K} P_{bk}}{\sum_{m=1}^{M} i_{bm}V_{bm}} \end{cases} \tag{5}$$

In equation (5), α and β represent the energy consumption per unit of industrial output and the weight of three types of waste emissions, respectively. The total annual energy consumption of a company is E_b. The quantity and emission quantity of the b-th product are i_{bm} and P_{bk}, respectively. V_{bm} represents the unit output value of enterprise product production. In addition, the total value of energy consumption is shown in equation (6).

$$E_b = \sum_{m=1}^{M}\left(U_{bm}^{E} i_{bm}\right) \tag{6}$$

In equation (6), U_{bm}^{E} is the production energy consumption coefficient of the industry per unit product. The total value of waste emissions from industrial output is shown in equation (7).

$$P_{bk} = \sum_{m=1}^{M}\left(U_{bm_k}^{P} i_{bm}\right) \tag{7}$$

In equation (7), $U_{bm_k}^{P}$ is the waste coefficient discharged by the enterprise during production. $B, b = 1, 2, ..., B$ represents the number of industries in the industrial chain of the ecological industrial park. $M, m = 1, 2, ..M$ and

$K, k=1,2,...,K$ represent the quantity of product types and the quantity of waste types. To achieve maximum environmental benefits, energy consumption, product and waste emissions should be minimized, and resources within the entire ecological park should be allocated reasonably. According to the calculation standards for environmental benefits, energy consumption, and waste emissions, environmental constraints are set for resource types, mainly including water sources, coal, and electricity. The relationship between the total consumption of resources by enterprises in the overall industrial chain and the total available resources is shown in equation (8).

$$\sum_{b=1}^{B} \varphi_{bm_n} i_{bm} \le Rr_{n_{\max}} \tag{8}$$

In equation (8), φ_{bm_n} is the resource coefficient consumed by the industry in producing a certain unit of product. $Rr_{n_{\max}}$ represents the total amount of available resources in the location of the park. $N, n=1,2,...,N$ represents the type and quantity of resources invested in the ecological industry chain. The energy usage relationship within the ecological industrial park is shown in equation (9).

$$\sum_{b=1}^{B} E_b \le E_{\max} \tag{9}$$

In equation (9), E_b represents the total energy consumption of the industry's annual production. $E_{\max}$ represents the total value of energy available. The environmental constraints for the overall ecological industrial park are shown in equation (10).

$$\sum_{b=1}^{B} U_{bm_k}^{P} i_{bm} \le Er_{k_{\max}} \tag{10}$$

In equation (10), $Er_{k_{\max}}$ represents the maximum pollutant emission of the ecological industrial park, which is the prescribed standard. In addition, the construction of the ecological industry chain also needs to consider factors such as the minimum emission standards and production scale of the region to meet the maximum environmental benefits.

B. Industrial Development and Construction based on Dual Objective Programming Model

The planning based on a single objective of environmental benefits is the main factor considered in the ecological industrial economy, but the essence of enterprises is still to pursue benefits. Therefore, economic and environmental benefits are comprehensively considered. Then a dual objective programming model is constructed. The economic and environmental benefits of ecological industrial economy are used as comprehensive evaluation indicators. The variables of other technologies or industries remain unchanged within 10 years. The economic benefit objective function is shown in equation (11).

$$\text{Economic benefits}=\max\left\{\sum_{b=1}^{B}\left[\sum_{m=1}^{M_b} V_{bm}^{*} i_{bm} - \sum_{n=1}^{N_b} V_{bn}^{a} a_{bn}^{*} - \sum_{l=1}^{B}\sum_{k=1}^{K_l} V_{l-b_k}^{p} P_{l-b_k}\right]\right\} \tag{11}$$

In equation (11), V_{bm}^{*} represents the industrial added value per unit of product produced by the enterprise before the construction of the industrial chain. V_{bn}^{a} is the unit value of resources invested during production. $V_{l-b_k}^{p}$ and P_{l-b_k} represent the unit cost and quantity of waste conversion resources invested by enterprise l in enterprise b. The amount of resources input by other enterprises is expressed as a_{bn}^{*}. The objective function of environmental benefits is shown in equation (12).

$$IENB(\max)=\left\{\frac{\sum_{b=1}^{B}\sum_{k=1}^{K_b} P_{bk}^{*}}{\sum_{b=1}^{B}\sum_{k=1}^{K_b} P_{bk}}\right\}_{\max} \tag{12}$$

In equation (12), K_b represents the environmental benefit indicator of the industrial chain. B represents the total value of pollutant types exported by the industry. The total amount of pollutants produced without considering inter industry recycling is P_{bk}. The quantity of pollutants produced in the industrial chain and converted into resources is P_{bk}^{*}. In addition, the specific constraints on resource consumption are shown in equation (13).

$$\sum_{b=1}^{B} \varphi_{bm_n} i_{bm} \le Rr_{n_{\max}} \tag{13}$$

In equation (13), φ_{bm_n} represents the resource consumption coefficient per unit product produced by the enterprise. $N, n=1,2,...,N$ is the number of types of resources invested in the industrial chain. The maximum total amount of resources that can be utilized in ecological industrial parks is $Rr_{n_{\max}}$. The constraint on energy in the industrial chain is shown in equation (14).

$$\sum_{b=1}^{B} E_b \le E_{\max} \tag{14}$$

In equation (14), $E_{\max}$ represents the maximum total amount of energy that can be provided by the area where the ecological industrial park is located. The constraint condition for pollutants in environmental benefits is shown in equation (15).

$$\sum_{b=1}^{B} U_{bm_k}^{P} i_{bm} \le Er_{k_{\max}} \tag{15}$$

In equation (15), the highest standard for pollutant emissions in the region where the industrial chain is located is $Er_{k_{\max}}$. To comprehensively consider economic and environmental benefits, the NSGA-II of multi-objective genetic algorithm is used to optimize complex multi-objective problems. The specific steps are shown in Fig. 3.

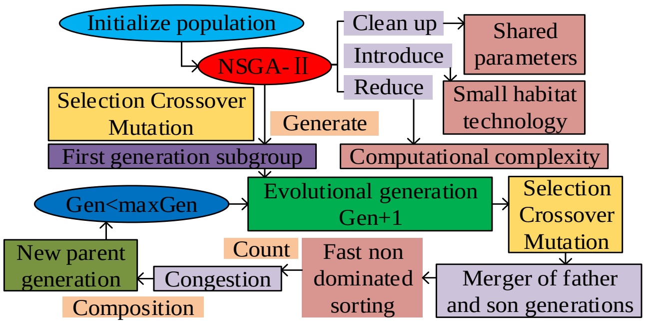


Fig. 3. Schematic diagram of multi-objective optimization based on NSGA-II

From Fig. 3, it can be seen that the NSGA-II algorithm initially performs non dominated sorting calculations on the initialized population to generate a new generation of subgroups. Afterwards, a new population is generated through evolutionary algebra and merging. Then, the new population is quickly non dominated sorted and combined with crowding calculation to form a new parent group. Finally, a multi-objective solution is obtained. The NSGA-II is applied to the multi-objective programming model, clearing and introducing shared parameters and niche techniques, while reducing time complexity and ensuring diversified solutions. In addition, the NSGA-II algorithm simplifies the energy structure calculated by non dominated sorting in the industrial ecological industry structure to maximize the utilization of overall industry resources. In response to the industrial and economic construction in a rural area, the government has developed an ecological industrial park to analyze the resources, environment, and industrial structure of the industrial economy. The energy and its industries include coal mining, coking, steelmaking, ironmaking, and shale oil. Water resources can allocate approximately 50 million tons of water usage. Multiple heavy industrial productions have caused significant damage to the local environment. The production structure of the main industries is investigated on site to quantify energy consumption, product output, waste emissions, and pollution emissions of each industry, as shown in Fig. 4.

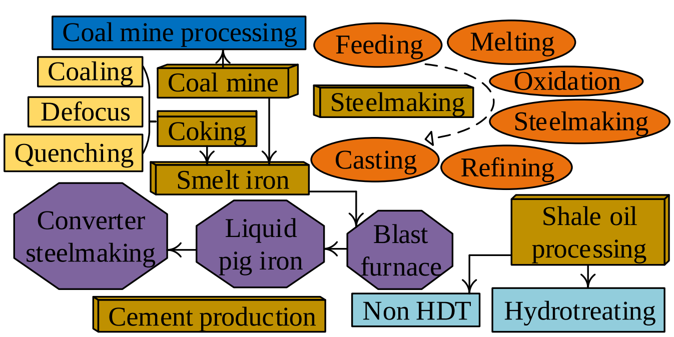


Fig. 4. Distribution and structure of rural industrial industries

From Fig. 4, the agricultural industry mainly includes coal mine processing, coking and steelmaking factories, iron smelting industry, shale oil processing, and cement production. The coal mine treatment provides coal resources for the coking industry. Coking involves the loading coal, discharging coke, and quenching coke. Steelmaking includes the feeding, low-temperature melting, oxidation, tapping, refining, and pouring. Subsequently, under the requirements of ecological civilization construction, ecological industrial parks will be established in rural areas to manage the production scale and resource utilization of various industries, thereby forming an ecological industrial chain for resource recycling. Abandoned coal mines can lead to wastage of existing resources. Based on the concept of ecological environment, underground resources are gasified and extracted to achieve maximum resource utilization. Finally, the overall model of resource utilization and output for each industry is constructed, as shown in Fig. 5.

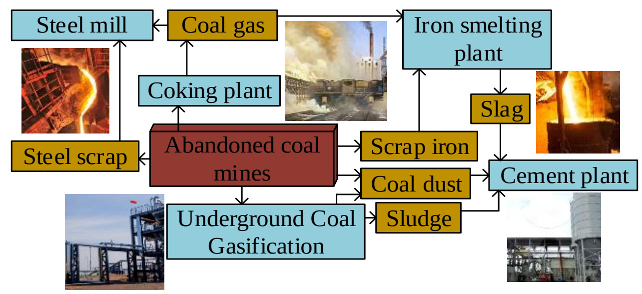
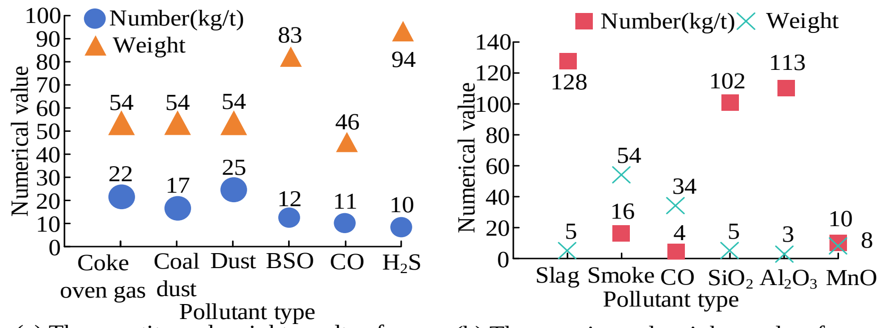


Fig. 5. Mutual benefit and symbiosis model of coal gasification industry chain

From Fig. 5, the inputs or outputs of various industries are interrelated. Coal dust, sludge, scrap iron, and scrap steel from abandoned coal mines are respectively invested in cement plants, iron smelting plants, and steelmaking plants. The slag generated from steelmaking and ironmaking is then fed into the cement plant. Coking gas and scrap iron are put into ironmaking. This mutual input mode fully utilizes waste resources, reduces resource waste, and promotes the mutually beneficial development of the industrial chain. The industry of the overall model still generates unusable waste and pollutants, which can easily cause environmental pollution and resource consumption. To fully leverage the maximum connections between various industries, qualitative and quantitative parameter judgments are conducted separately. Then the degree of mutual benefit and symbiosis and environmental index of the industries are calculated.

IV. Development Analysis of Rural Industrial Ecological Economy

For the industrial production mode, the weight of waste or pollutant emissions is determined. Combined with the mutually beneficial symbiosis degree results of the industrial chain model, parameter targets are provided for the industrial combination and environmental benefits of rural industrial ecological economy. Finally, the NSGA-II of the dual objective programming model is used to analyze the industrial scale and its benefits. Pollutants usually come in three forms: solid, liquid, and gas, with varying degrees of harm and weight. To unify the ecological management of industrial parks, the weights of the three types of pollutants are standardized. Based on the types and emission standards of each pollutant, the quantity and weight of pollutants in each industry are determined and analyzed. The results are shown in Fig. 6.

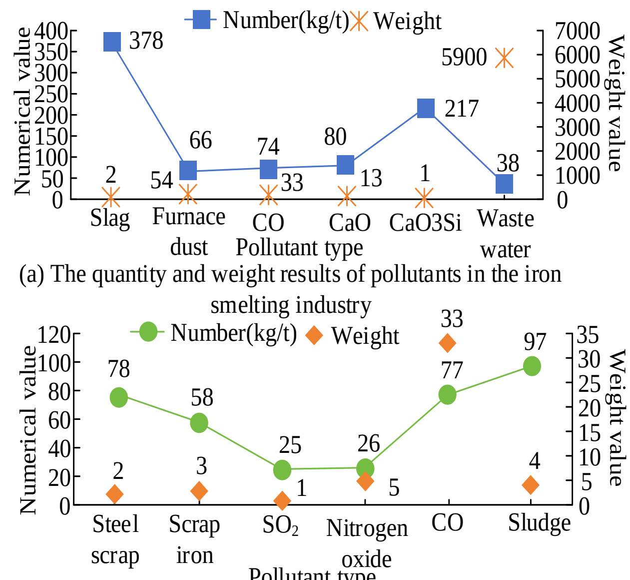


(a) The quantity and weight results of some pollutants in the coking industry
(b) The quantity and weight results of some pollutants in the steelmaking industry

Fig. 6. Results of the quantity and weight of some pollutants in the coking and steelmaking industries

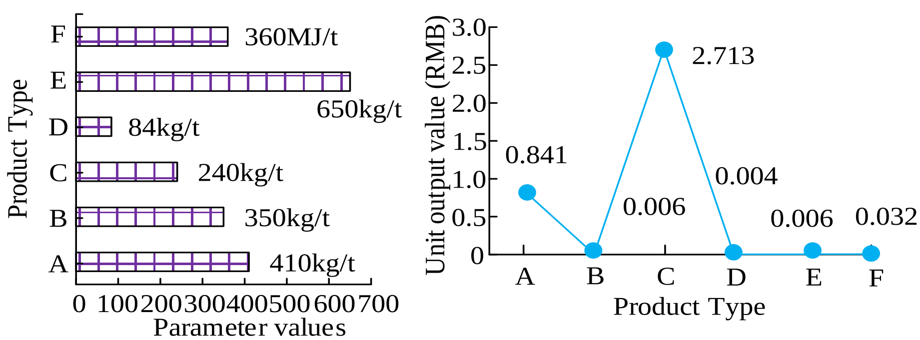
Fig. 6(a) shows the quantity and weight of some pollutants exported by the coking industry. The highest weight of hydrogen sulfide (H_2S) was 94, and the lowest quantity was 10kg/t. The weights of coke, coal, and dust were all 54, but the quantities were 22kg/t, 17kg/t, and 25kg/t, respectively. Fig. 6(b) shows the results of some pollutants in the steelmaking industry. The amount of slag, silicon dioxide (SiO_2), and aluminum oxide (Al_2O_3) produced was relatively high, at 128kg/t, 102kg/t, and 113kg/t, respectively, but their weights were low at 5, 5, and 3. The weights of smoke and carbon monoxide (CO) were relatively high, at 54 and 34. Afterwards, an analysis is conducted on the pollutants in the iron smelting plant and underground coal gasification industry, as shown in Fig. 7.

From Fig. 7(a), the wastewater discharge weight of the iron smelting plant was relatively high, which was 5900. The output quantity of slag and calcium silicate (CaO3Si) was relatively high, which were 378kg/t and 217kg/t, respectively. However, the corresponding weights were relatively low, which were 2 and 1. Fig. 7(b) shows the quantity and weight of pollutants in the underground coal gasification industry. The quantity and weight of sludge were 97kg/t and 4. The quantity and weight of CO were 77kg/t and 33, respectively. Based on the pollution emissions of various industries in the industrial chain, combined with the functions and equations of environmental and comprehensive benefits, the output of each industry is analyzed. The output parameters and unit output value of the coking and steelmaking industries for environmental benefits are represented using A-F to represent coke oven gas, coking water vapor, converter gas, steelmaking water vapor, steelmaking hot water, and steelmaking cold energy. The results are shown in Fig. 8.



(a) The quantity and weight results of pollutants in the iron smelting industry
(b) The quantity and weight of pollutants in the underground coal gasification industry

Fig. 7. Pollutant quantity and weight results of iron smelting and underground coal gasification industries



(a) Product parameter results for coking and steelmaking industries
(b) Results of unit product output value in coking and steelmaking industries

Fig. 8. Parameters and output value results of output products in the coking and steelmaking industries

From Fig. 8 (a), the output parameters of the coking and steelmaking industries were generally high. The parameter of hot water for steelmaking was 650kg/t, while the produced water vapor was relatively low, at 84kg/t. Fig. 8 (b) represents the unit output value of the output product. The converter gas for steelmaking was relatively high, at 2.713 yuan. The remaining output products of steelmaking had lower unit output values of 0.004 yuan, 0.006 yuan, and 0.032 yuan, respectively. The output value of coking coke oven gas was 0.841 yuan, and the unit output value of water vapor was 0.006 yuan. Based on the output product value of the coking and steelmaking industries, the economic benefits of this industry vary in terms of environmental benefits. However, the production essence of each industry needs to consider economic benefits, and then seek a balance between economic and environmental benefits. Therefore, the dual objective programming model is combined to analyze the economic and environmental benefits of rural industrial ecological economy and its industrial chain. The resource consumption results of the steelmaking industry are shown in Fig. 9.

In Fig. 9, there are many types of resource consumption in the steelmaking industry. The parameters of furnace gas for scrap steel were relatively high, at 128.76 and 168.11, respectively. The prices of the coolant and carburetor used in the production process were relatively high, at 12.21 yuan and 11.76 yuan, respectively. From this, the industry consumes a lot of resources. The available and circular resources can improve the environmental benefits of this industry chain, thereby increasing economic benefits and achieving optimal comprehensive benefits. In addition, based on the weight and indicator ratio of economic and environmental benefits, a combination analysis is conducted on the production scale and benefits of each industry. The results are shown in Table I.

Table I compares the combination methods of different industry scales and their comprehensive benefits. When the scale of the coking industry was 135600 tons, the steelmaking industry was 314900 tons, the ironmaking industry was 148100 tons, and the underground coal gasification (UCG) industry was 424.76 million Nm^3. The comprehensive benefits of economy and environment reached the optimal level, which was 0.6415. To expand the economic benefits and value of the industrial park, some enterprises can be added to enrich the products of the industrial chain. Based on the industrial processes of coking, steelmaking, ironmaking, and underground coal gasification, as well as the resource recycling mode, the gas power generation industry, chlor alkali industry, and synthetic ammonia industry can be introduced into the industrial ecological economy. The output of coke oven gas, converter gas, blast furnace gas, and synthesis gas from various industries is used as input to increase enterprise resources, thereby increasing resource utilization efficiency and improving comprehensive benefits. To visually compare the benefits brought by increasing industries, this study combines constraint conditions and objective functions. The NSGA-II is used to calculate and train the economic and environmental benefits indicators of the industrial chain. The results are shown in Fig. 10.

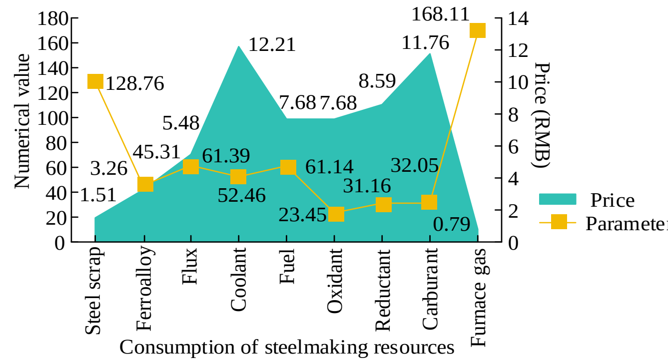
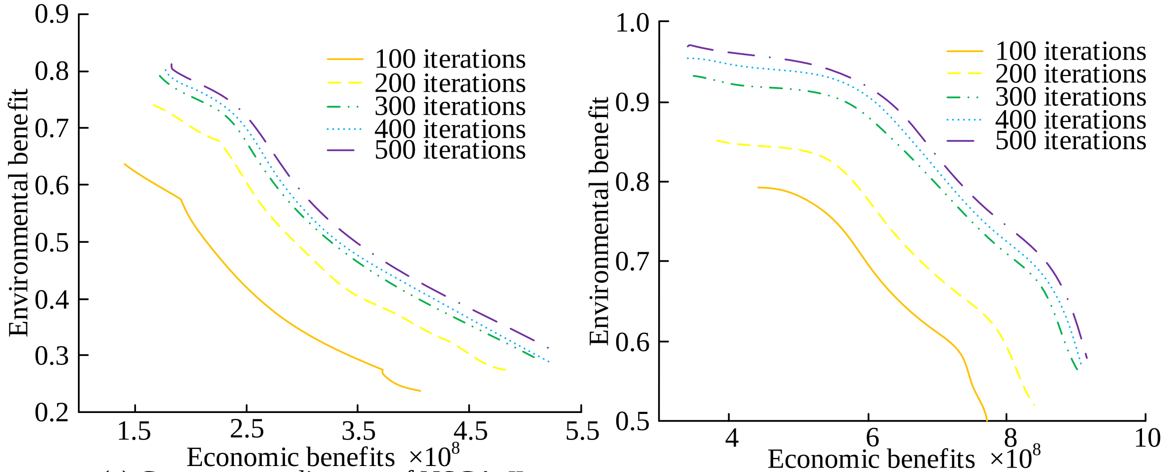


Fig. 9. Partial resource consumption results of the steelmaking industry

TABLE I. SCALE AND BENEFITS OF EACH INDUSTRY IN THE ECOLOGICAL INDUSTRIAL CHAIN

Production scale and combination				**Comprehensive benefits**	
Coking (10000 tons)	Steelmaking (10000 tons)	Smelt iron (10000 tons)	UCG (10000 Nm^3)	Environment	Comprehensive
13.56	31.49	14.81	42476	0.3655	0.6415
12.27	36.91	15.03	32142	0.3652	0.6043
17.27	37.94	25.15	34640	0.3650	0.5922
6.78	12.03	25.80	36633	0.3655	0.6389
18.75	29.71	25.15	38652	0.3652	0.6108
14.47	29.65	15.13	33634	0.3653	0.6199
15.67	20.93	25.15	37643	0.3653	0.6227
17.38	20.82	14.52	32561	0.3654	0.6386



(a) Convergence diagram of NSGA-II algorithm for initial industrial chain

(b) Convergence diagram of NSGA-II algorithm for added industrial chain

Fig. 10. Comparison results of convergence graphs for the NSGA-II in the industrial chain

From Fig. 10(a), as the number of iterations increases, the economic and environmental benefits of the industrial chain continue to increase. The convergence effect of Fig. 10(b) was consistent with the initial industrial chain, indicating that the NSGA-II had advantages in the convergence effect of the multi-objective programming model. Finally, the production scale and comprehensive benefits of the two industrial chains are compared, as shown in Table II.

TABLE II. COMPARISON OF PRODUCTION SCALE AND COMPREHENSIVE BENEFITS OF INDUSTRIAL CHAIN

The benefits of the industrial chain		Environmental benefit	Comprehensive benefits
Initial industrial chain	Coking (10000 tons)	14.98	13.56
	Steelmaking (10000 tons)	19.98	13.81
	Smelt iron (10000 tons)	24.97	31.49
	UCG (10000 Nm^3)	58786	42476
The added industrial chain	Coking (10000 tons)	14.98	17.77
	Steelmaking (10000 tons)	19.98	24.50
	Smelt iron (10000 tons)	24.97	38.39
	UCG (10000 Nm^3)	34399	32643
	Electric power generation (100 million degrees Celsius)	64.98	40.87
	Chlor-alkali (10000 tons)	27.89	32.69
	Synthetic ammonia (10000 tons)	12.96	13.51

According to Table II, the comprehensive benefit of the underground coal gasification industry in the initial industrial chain was 42476. The comprehensive benefits of the increased industrial chain decreased to 32643. The added environmental benefits from the power generation industry were 64.98, with a comprehensive benefit of 40.87. After improving the industrial chain through the model, the comprehensive efficiency of the coking industry has increased by 31.05%, and the economic and environmental benefits of the steelmaking industry have also significantly increased by 77.41%. The environmental benefits of the iron smelting industry have increased by 21.91% compared to the initial industrial chain, while the economic and comprehensive benefits of underground coal gasification have changed, with a decrease of 70.89% in economic benefits and an increase of 30.12% in comprehensive benefits. Therefore, it indicates that the industrial chain after increasing industries improves the utilization and processing of output products and pollutants, thereby improving the resource utilization rate of industries and their products, and reducing environmental pollution. This also proves the superiority of the multi-objective programming model of NSGA-II algorithm.

V. DISCUSSION

Regarding the impact of rural industrial ecological economy, this study utilizes the industrial chain model of ecological industrial parks and the mutual conversion of resources and waste to calculate the weight of pollutants and waste emissions in rural industrial economy. The highest weight of hydrogen sulfide output from the coking industry is 94, and the lowest quantity is 10kg/t. The amount of slag, silicon dioxide, and aluminum oxide produced by the steelmaking industry is relatively high, at 128kg/t, 102kg/t, and 113kg/t, respectively. The weight of wastewater discharge from iron mills is the highest at 5900, and the weight of carbon monoxide in the underground coal gasification industry is 33. The above data can provide a parameter basis for the industrial combination of industrial parks. Combined with the dual objective programming model, the comprehensive benefit indicators of ecological industrial economy were evaluated, and the multi-objective genetic algorithm NSGA-II algorithm was used to optimize the multi-objective problem. After optimizing the industrial chain, the environmental benefits of coking, steelmaking, and ironmaking industries increased by 31.05%, 77.41%, and 21.91%, compared with energy-saving and emission reduction technologies in the coking coal industry, the adoption of symbiotic technologies also significantly improves environmental benefits. The underground coal gasification industry has reduced economic benefits by 70.89% while increasing environmental benefits by 30.12%. The balance between economic and environmental benefits is also reflected in the underground coal gasification hydrogen production process. This is consistent with the conclusion drawn by Xue R et al. [20] and Han X et al. [21]. Therefore, it indicates that the optimization of the industrial chain model has maximized the utilization of industrial resources and production output, and promoted the construction of ecological economy.

In the construction of ecological industry chain models and the evaluation of comprehensive benefits, research mainly focuses on environmental indicators and their impact on benefits, and calculates the degree of mutual benefit and environmental index of the ecological industry chain. Through the development model of reducing resource waste and strengthening industrial connections, the optimal industrial structure of rural industrial ecological economy can be achieved. However, in the current research results, the green and sustainable development of industrial economy mainly involves the construction of evaluation models for industrial economy and environmental indicators, combined with multi-level analysis and other methods to analyze the development problems of industrial economy, and propose corresponding improvement measures to achieve the development of industrial ecological economy. This article mainly uses the NSGA-II algorithm to comprehensively calculate the comprehensive benefits of multi-objective factors, taking into account the actual industrial structure of the industrial economy, providing a mutually beneficial and harmonious development mode for various industries in the industrial ecological economic park, while improving resource utilization and promoting sustainable development of the industrial ecological economy cycle. However, in the industrial chain structure of industrial ecological economy, there is still a lack of specific explanations on the actual types of industries and resource utilization methods in research. Therefore, in future research, it is necessary to conduct in-depth exploration of different industry scales and production methods in the industrial chain, in order to develop feasible models and resource utilization methods for the development of industrial economic ecology.

VI. CONCLUSION

In response to the ecological development of industrial economy in rural areas, this study combines the industrial structure of industrial parks and a dual objective planning model. Then, the NSGA-II is used to calculate the degree of mutual benefit and symbiosis between resource cycles in the industrial chain, obtaining the optimal industrial structure and production mode for rural industrial ecological economy. The result analysis showed that some pollutants exported by the coking industry had the highest weights of 83 and 94. The highest weight of some pollutants in the steelmaking industry was 54 and 34, while the wastewater discharge from iron mills was relatively high, which was 5900. Based on the unit output value of industrial output, the converter gas for steelmaking was 2.713 yuan, while the other output products were 0.004 yuan, 0.006 yuan, and 0.032 yuan, respectively. The output value of coke oven gas in coking was 0.841 yuan, and the unit output value of water vapor was 0.006 yuan. The final comprehensive benefit index calculation showed that when the scale of the coking industry was 135600 tons, the steelmaking industry was 314900 tons, the ironmaking industry was 148100 tons, and the UCG industry was 42.476 million Nm^3. The comprehensive benefit of the initial industrial chain reached its optimal level. This proves that the dual objective programming model combining NSGA-II has advantages. However, there is a lack of extensive data and surveys on the input and output of specific industries. Therefore, subsequent research should be further improved and perfected.

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