An Approach to stimulate the sustainability of Eco-industrial Park using a coupled emergy and system dynamics

Yu Zhao
Shenyang Jianzhu University
Miao Yu (yumiao1213@126.com)
Shenyang Jianzhu University
Yinghui Xiang
Shenyang Jianzhu University
Chunguang Chang
Shenyang Jianzhu University

Research Article

Keywords: Sustainability, Eco-industrial Park, Emergy, System dynamics, Scenario analysis

Posted Date: April 3rd, 2021

DOI: https://doi.org/10.21203/rs.3.rs-366658/v1

An Approach to stimulate the sustainability of Eco-industrial Park using a coupled emergy and system dynamics

Yu Zhao, Miao Yu*, Yinghui Xiang, Chunguang Chang

School of Management, Shenyang Jianzhu University, Shenyang, 110168, PR China

ABSTRACT: In this paper, we study the emergy evaluation index system of the sustainable development of Shenyang Economic and Technological Development Zone (SETDZ) by system dynamics model, and employ the simulation of dynamic evaluation analysis. By the simulation of system dynamics model, four SETDZ's development scenarios are designed, including inertia scenario, economic scenario, environmental protection scenario and science and technology scenario, and the sustainable development status of each scenario is simulated and dynamically evaluated. The results show that under the background of coordinated development of economy and environment, science and technology scenario based on high-tech investment is the most dynamic, and it also is the best development strategy of SETDZ. Furthermore, SETDZ could achieve the coordinated development of economy and environment by reasonable layout of industrial enterprises, integration of public resources, effective utilization and disposal of waste, establishment of enterprise symbiosis system, development of cleaner production and other measures.

KEYWORDS: Sustainability; Eco-industrial Park; Emergy; System dynamics; Scenario analysis

* Corresponding author. Miao Yu (yumiao1213@126.com).

1. **Introduction**

An eco-industrial park (EIP) could improve the efficiency of material and energy use, could reduce the generation of waste, and strive to balance the inputs and outputs of natural ecosystems. In 2015, China's Ministry of Environmental Protection, Ministry of Commerce, and Ministry of Science and Technology promulgated the "Administrative Measures for the National Eco-industrial Demonstration Park" and "National Ecological Industrial Demonstration Park Standard." The measures indicated that China would focus on the promotion of national-level economic and technological development areas, national high-tech industrial development areas, and provincial-level industrial parks with higher levels of development, or other characteristic parks. Moreover, China would actively launch the establishment of eco-industrial demonstration areas. The efforts to promoting Chinese pilot EIP practices mainly concentrated on clearer and coordinated division work of the competent authorities more scientific and standardized procedures and standards, more investment on relevant researches, and that the capacity for the government agency can be improved. By the end of January 2017, the National Ecological Industry Demonstration Park Construction Leading Group Office demonstrated the adoption of 48 national eco-industrial demonstration parks.

Accordingly, Shenyang Economic and Technological Development Zone (SETDZ) passed the national eco industrial demonstration park certification in the first batch. As an important industrial city, Shenyang is located in Liaoning Province of China, and SETDZ has attracted much attention from researchers. A specific emergy index of industrial symbiosis has been formulated for a comprehensive measurement of industrial symbiosis (Geng et al. 2014), by contrast to the effect of the industrial symbiosis system of SETDZ.

To assess the sustainability of EIPs, it is necessary to measure factors in a unified way. The ability to evaluate energy, materials, and currency in equal terms allows researchers to perform sustainability assessments for all types of systems. Given the vigorous industrial park construction in China, many studies have focused on emergy evaluations of industrial parks(Tianjin, Liu et al. 2016;). As an environmental audit technology, emergy analysis is a systematic approach to balance the development of natural environment and social economy. In addition, emergy indicator systems are established for some EIPs (Dalian, Zhe et al. 2016).

With emergy accounting developed, some studies have combined additional technical methods with emergy accounting. Giannetti et al. (2006) introduced the ternary diagrams commonly used in materials science into emergy calculation and environmental accounting and created graphical tools for the ternary graphs. Subsequently, the emergy ternary diagrams were used to compare environmental and energy diagnoses between Brazil, Russia, India, China, South Africa, and the United States (Giannetti et al. 2013). Vega-Azamar et al. (2013) assessed urban environmental sustainability by using the resource flow lines of an emergy ternary diagram and compared the Island of Montreal with nine other urban centers in Canada.

Most of the above research results on the sustainability of EIP focus on the static evaluation of the system, describe the historical sustainable development of the system, and predict according to the historical development situation. Based on the analysis of system structure and planning, there are few research results on system dynamic (SD) of the sustainable development of the system. SD is used to operate with different dimensions and different types of data, widely used in the comprehensive research of

social, economic and ecological complex systems. With the combination of qualitative and quantitative analysis, the application of SD model in the field of sustainability and structural analysis is extended. Guan et al. (2011) applied SD model to evaluate the development of resource exhausted cities with environmental degradation. Wu and Ning (2018) proposed a spatiotemporal analysis method based on SD model for each influencing factor in the system. Liu et al. (2018) employed a SD model to analyze the coordinated degree of urban green town development. Franco (2019) used SD model to simulate the effect of slowing down and closing the resource cycle in the product supply chain design process of circular economy mode. Inês et al. (2020) established a SD model of information transparency based on fuzzy cognitive mapping to analyze the impact of energy change on the sustainability.

Combined with other simulation models, SD could be used in the field of sustainability. The combination of SD model and emergy accounting can clearly describe the coupling effect and feedback of various influencing factors, and can simulate the trend prediction of sustainable development system. Wei et al. (2017) established SD model of emergy flow of eco-economic system, and considered different scenarios to study the impact of different economic growth rate and the investment in environmental protection on the sustainability of cities.

This paper mainly focuses on SETDZ and comprehensively analyzes an evaluation method of sustainability for EIPs. After 2010, SETDZ has continuously enhanced the capacity of waste recycling and upgraded the industrial chain network. By the end of 2016, the integration of industrial ecological chain has been generally completed. According to case study, relevant research findings have been carried out in Shenyang,

China in 2018.

The rest of this paper is organized as follows. In Section 2 we present an overview of this study and the source of data acquisition. In Section 3, we propose the methodology, including the establishment of evaluation index system and SD model of SETDZ. In Section 4, We design inertia, economic development, environmental protection, science and technology four scenarios, analyze the industrial ecological networking of the park, and combine emergy index system and SD model to evaluate SETDZ's sustainability. In Section 5, we provide concluding remarks.

2. Materials

SETDZ was built in June 1988, was approved as a National Economic and Technological Development Area by the State Council in April 1993, and was approved as a National Eco-industrial Demonstration Park by the Ministry of environmental protection, Ministry of Commerce and Ministry of science and technology in January 2014. SETDZ is located in the southwestern part of Shenyang. The completed area was 448 km^2 in 2015. There are 2021 types of industrial enterprises in SETDZ, including 83 transnational corporations and 231,000 employees. SETDZ is an organic integration consisting of enterprises, governments, infrastructure providers, suppliers, customers, research and development institutions, and financial institutions. As a comprehensive EIP, SETDZ is mainly composed of four parts: enterprise production area, resource recycling center, information management center, and research and development center. The community of the industrial ecosystem is joined by products, energy, and water in a cascade, and those form the ecological chain of various material energies.

SETDZ employs a circular economic model by fostering cleaner production companies

and thereby realizes a reduction of waste emissions. SETDZ has six major industrial clusters, which are equipment manufacturing, automobile and parts manufacturing, pharmaceutical and chemical, food processing, building materials, and textile industries. Since 2010, SETDZ's industrial eco-chains have been constructed. Companies in EIPs are guided by high value-added, low-pollution, high-tech industries, and gradually accomplish the adjustment, reconstruction, transformation, and upgrading of the industrial structures of their EIPs. This paper uses the pharmaceutical and chemical industry as an example, to illustrate the symbiosis in industrial network integration and thereby get more the circular economic model at the industry network level. The symbiotic relationship among the pharmaceutical, chemical industries and their surrounding industries is analyzed as follows. Accordingly, Figure 1 illustrates the eco-industrial network of the pharmaceutical and chemical industries and their surrounding industries in SETDZ.

This paper focuses on SETDZ's sustainability from emergy accounting. In 2010, SETDZ formulated a plan for a circular economy demonstration project for the entire region. The plan identifies and develops a three-tier circular economic system for enterprises, ecological parks, and conservation-oriented society. It establishes and improves comprehensive utilization management systems for resources, extends industrial chains, increases resource utilization, and builds demonstration bases for the sustainable development. The data were drawn from "Shenyang Statistical Yearbooks (2008-2018)", "Tiexi Statistical Yearbook (2008-2018)", "Environmental quality report of SETDZ (2009-2019)", "Construction planning of Shenyang Tiexi ecological industry". In addition, first-hand data were obtained through visit to the Industrial Clusters Office,

the Environmental Protection Bureau, the Economic Development Bureau, the Planning and Land Resources Bureau, and the Development and Reform Bureau of SETDZ.

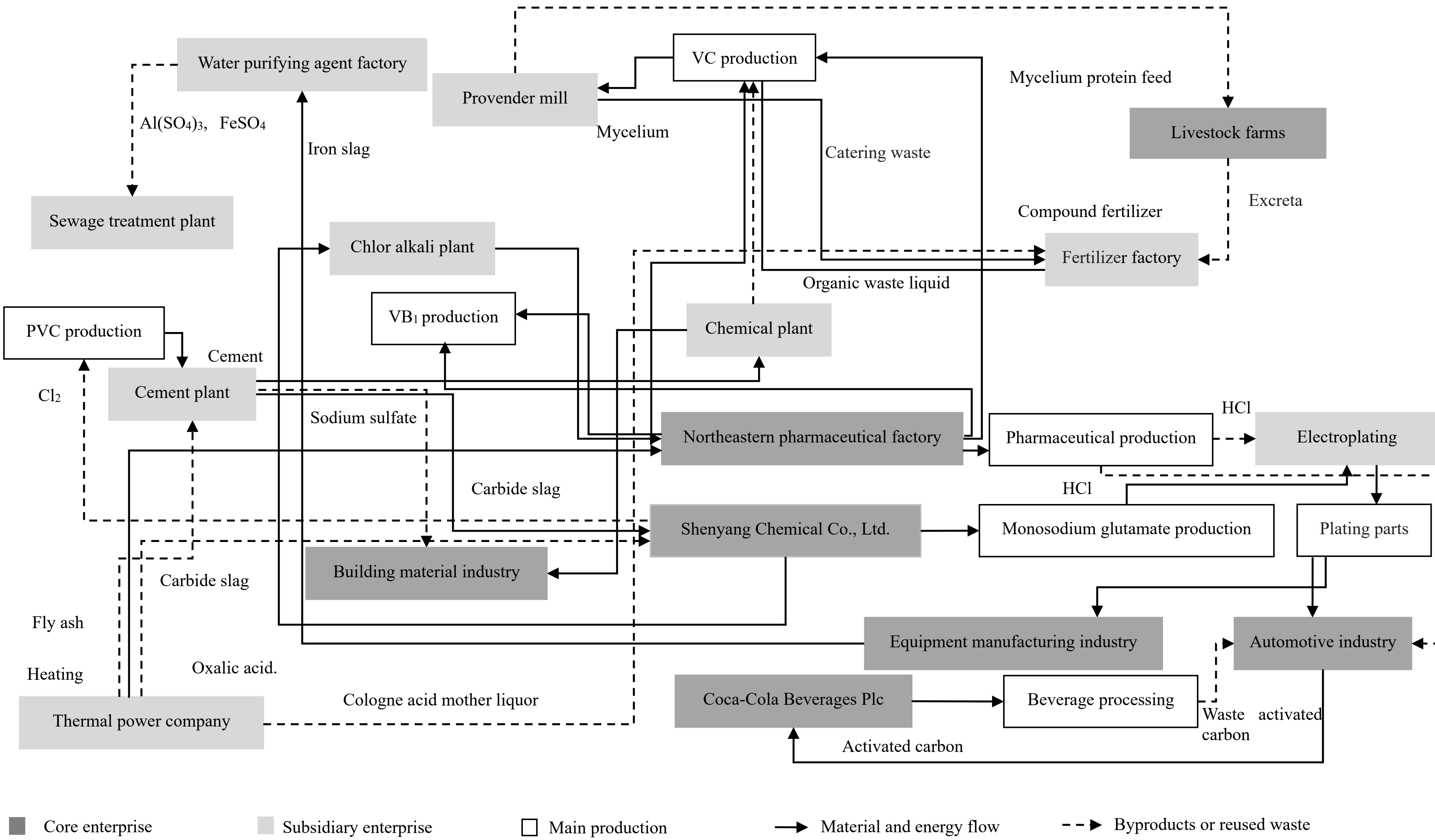

Figure 1 Eco-industrial network of pharmaceutical and chemical industries and their surrounding industries in SETDZ

3. Methodology

3.1 Emergy index system

The theory of emergy accounting was established in the 1980s by Odum (1996) et al. By means of a unit emergy value (UEV), different types of emergy and substances flowing and stored in the ecosystem can be converted into the same standard emergy. A quantitative analysis is to assess the utilization of natural resources in the ecosystem. A UEV refers to the amount of solar energy contained per unit of material or energy (Odum 1996). Some major kinds of UEVs include the transformity (sej/j), specific emergy (sej/g), emergy per unit money ($sej/\$$), and emergy per unit labor (sej/y, sej/h or $sej/\$$) (Zhao, et al. 2019). The geobiosphere emergy baseline (GEB) is the emergy of the geobiosphere that primarily drives the emergy flow, and it has reference value for emergy flows in emergy evaluation process using UEVs. The total emergy of the geobiosphere, as calculated by Brown and Ulgatia (2016), is 12.0E + 24 sej/y, which is used as the emergy baseline for this paper.

For a quantitative comparison, emergy analysis can be used to measure the true value of natural resources, goods, and services, through unifying different kinds of emerge. By emergy accounting, the ecosystem and socio-economic system are unified in order to reflect the mutual influence and contributions of each subsystem. Song et al. (2012) divided the sustainable development of EIPs into three dimensions: social, economic, and environmentally sustainable development. According to the three-dimensional positioning of the EIP, this measure is taken to assess the ecological efficiency and sustainability of the compound eco-economic system. When an EIP's sustainability is

evaluated, it is necessary to distinguish the utilization of resources in the socio-economic and environmental subsystems. Therefore, the sub-objectives of resource utilization, economic development, environmental compatibility, and social acceptability are considered as sub-objectives within the overall EIP assessment. Each sub-objective set includes indicators which address different terms, consequently they constitute a comprehensive framework for EIP evaluation.

There are multiple emergy flows in EIPs. The emergy of renewable natural resources (waves, tide, earth cycle) is denoted by R, indicating the emergy of the renewable natural resource in the system. The emergy of a nonrenewable resource in the system is denoted by N. Purchased emergy is denoted by F, indicating inputs imported from outside of the system. Yield emergy is denoted by Y, indicating the emergy of the outputs. The emergy of wastes is denoted by W, indicating wastes that are ultimately excluded. The total emergy in the system is denoted by U, and is the sum of R, N, and F.

Based on emergy accounting and the characteristics of material, energy, and information flow in the EIP, an emergy analysis system is established. The emergy analysis system comprehensively reflects the structure, function, and efficiency in eco-economic systems in EIPs and assesses both the relationships between environment and economy, as well as society and nature in the EIPs. This provides a scientific basis for the development of circular economies in EIPs. First, comprehensive indicators describe the sustainable development capabilities of EIPs. Second, the system-level indicators include three subsystems, which are economic development, social acceptability and environmental compatibility, to assess the comprehensive performance of the complex ecological economies in an EIP. Third, a variable layer employing a

specific variable based on emergy analysis is employed. The various emergy indicators and their meanings are shown in Table 1.

Table 1 Eco-industrial park sustainability evaluation index system

Indicators	**Definition and Meaning**
Indicators of economic development	
Ratio of emergy to GDP (EDR)	A measure of emergy inputs for generating per unit of money
Emergy yield ratio (EYR)	A measure of outputs a process will contribute to the economy
Indicators of environmental compatibility	
Environmental load ratio (ELR)	A measure of ecosystem stress resulting from production
Ratio of wastes to the total emergy (EWR)	A measure of pressure of waste to the system environment
Indicators of social acceptability	
Emergy density (ED)	A measure of intensity of the emergy inputs per unit area
Carrying population (CP)	A measure of capacity of the population under the current environment
Indicator of sustainable development	
Sustainable development indicator (ESI)	A measure of the contribution of a resource or process to the economy per unit of environmental load

The evaluation indicators of economic development include EDR and EYR. EDR is the ratio of total emergy use and industrial added value of the park in one year (Ascione, et al., 2009; Tao et al., 2013).

$$EDR = \frac{U}{GDP} \tag{1}$$

The indicator synthetically evaluates the degree of development of the EIP. The more developed the industrial park is, the lower EDR is, since the base of industrial added value is bigger and the utilization efficiency of various resources is higher.

EYR is generated by production activities in the EIP to the emergy inputs from the outside world (Ulgiati S. et al. 1998, Mu et al. 2011), and the emergy is converted from total emergy of the industry.

$$EYR = \frac{Y}{F} \tag{2}$$

The indicator reflects the utilization efficiency of resources. When EYR value is high, it reflects the production efficiency of the system is high and also indicates that industrial production and the economic benefits are great.

The evaluation indicator for environmental compatibility includes EWR and ELR. EWR is the ratio of the sum of emergy of “three wastes” (waste gas, wastewater, solid wastes) to the total emergy, which is used to measure the pressure of wastes on the ecosystem.

$$EWR = \frac{W}{U} \tag{3}$$

ELR is the ratio of purchased and nonrenewable local emergy to the free/renewable resource emergy (Ulgiati S. et al. 1998, Mu et al. 2011).

$$ELR = \frac{F + N}{R} \tag{4}$$

EIPs only provide a small number of natural resources, and most renewable resources need to be purchased from the outside world. EIPs with a high degree of industrialization have high emergy utilization in the system. When ELR is higher, it indicates that the utilization ratio of nonrenewable resources and the load-bearing pressure of entire ecological environment are both greater.

The evaluation indicators for social acceptability includes ED and CP. The ED is created by production processes for the area of EIP (Ascione, et al. 2009, Tao et al. 2013).

$$ED = \frac{U}{A} \tag{5}$$

In the formula, A represents the land area. This indicator reflects the degree of intensive land use in the park. The higher ED is, the more the output of the land per unit

of the EIP is.

The CP is the ratio of available and per capita emergy usage (Ulgiati et al. 1994, Nakajima et al. 2016).

$$CP = \frac{(R+N)P}{U} \tag{6}$$

This indicator calculates the population carrying capacity by using the available emergy. P represents the population of the park, and the available emergy in the park does not include purchased emergy. The higher the indicator, the more population the park can carry.

The evaluation indicator for sustainable development is ESI. The ESI is the ratio of the emergy output rate to the ecological environmental load rate, and is used to evaluate the sustainable development ability of the system (Ulgiati S. et al. 1998, Mu et al. 2011).

$$ESI = \frac{EYR}{ELR} \tag{7}$$

Th indicator EYR is to evaluate the output efficiency of the system and ELR is to evaluate the environmental pressure. The higher ESI is, the greater the sustainable development ability of EIP is (Zhao, et al. 2019).

The emergy analysis method is to draw an actual emergy flow system diagram for SETDZ through actual investigation, and then a detailed emergy diagram of SETDZ is drawn to characterize the flows of various streams in the park. All processes are involved in industrial metabolism, such as physical, chemical, biological, and information transfer, and that needs to obtain definite objection. The emergy flows diagram includes the main components and interrelationships of the system and the directions of material flows, energy flows, and currency, as shown in Figure 2.

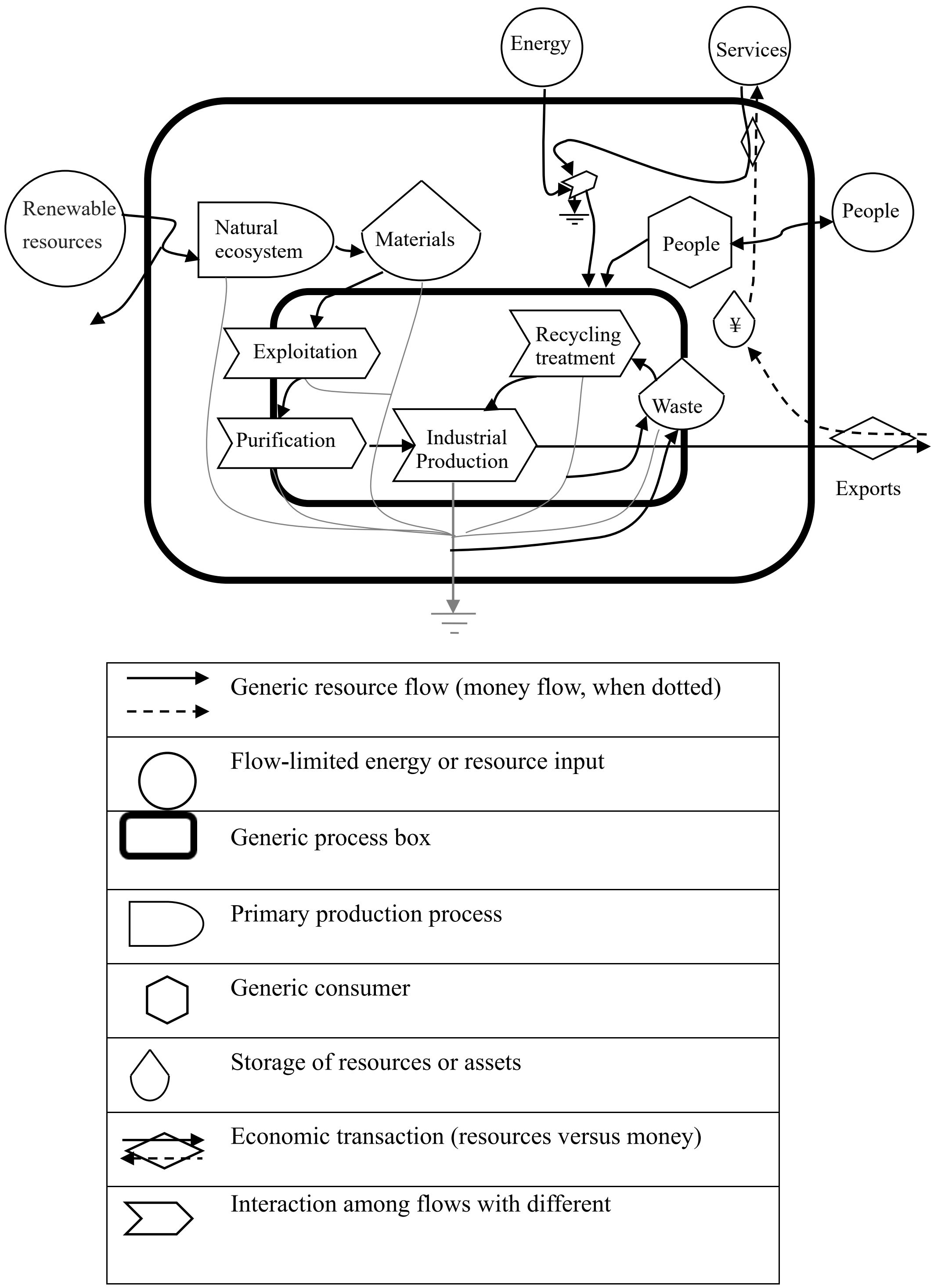

Figure 2 Emergy flows of SETDZ

An emergy analysis table is usedto determine the number of emergy flows, including energy (J), material (g), and currency ($) flows. Based on the related UEVs, we convert

different energy units into unified energy units. The main emergy flows of implementation of the circular economy program of SETDZ during 2008 and 2018 are shown in Table 2.

Table 2 Emergy on material, energy and labor flows for SETDZ

Note	Item	Raw data		UEV	Reference	solar emergy	
		2008	2018	(sej/unit)		2008	2018
Renewable resources							
1	Sunlight	1.24E+17	1.24E+17	1.00E+00 sej/j	a	1.24E+17	1.24E+17
2	Wind	3.12E+14	3.12E+14	1.58E+03 sej/j	b	4.93E+17	4.93E+17
3	Rain, geopotentia	1.19E+14	1.19E+14	1.09E+04 sej/j	b	1.30E+18	1.30E+18
4	Rain, chemical	5.24E+13	5.24E+13	6.36E+03 sej/j	b	3.33E+17	3.33E+17
5	Tide	2.10E+13	2.10E+13	2.82E+04 sej/j	c	5.92E+17	5.92E+17
6	Geothermal heat	5.82E+13	6.83E+13	2.03E+04 sej/j	d	1.18E+18	1.39E+18
S1	Subtotal (1- 6) **(R_1)**					4.02E+18	4.23E+18
Nonrenewable inputs from the park							
7	Sand	2.90E+12	2.97E+12	5.96E+08 sej/g	e	1.73E+21	1.77E+21
8	Gravel	1.42E+12	1.58E+12	3.04E+09 sej/g	f	4.32E+21	4.80E+21
S2	Subtotal (7- 8) **(N)**					6.05E+21	6.57E+21
Nonrenewable inputs out of the park							
9	Thermal Power	3.86E+15	4.31E+15	1.59E+05 sej/j	g	6.14E+20	6.85E+20
10	Water	1.89E+13	2.12E+13	2.88E+06 sej/g	h	5.44E+19	6.11E+19
11	Electricity	3.24E+15	3.14E+15	2.99E+05 sej/j	c	9.69E+20	9.39E+20
12	Coal	2.10E+15	2.12E+15	1.32E+05 sej/g	d	2.77E+20	2.80E+20
13	Natural gas	6.30E+14	6.19E+14	1.78E+05 sej/j	d	1.12E+20	1.10E+20
14	Crude oil	1.21E+15	1.31E+15	9.07E+04 sej/j	a	1.10E+20	1.19E+20
15	Diesel	5.84E+14	6.10E+14	1.81E+05 sej/j	i	1.06E+20	1.10E+20
16	Cement	9.45E+10	9.50E+10	3.04E+09 sej/g	j	2.87E+20	2.89E+20
17	Glass	1.13E+10	1.25E+10	3.49E+09 sej/g	k	3.94E+19	4.36E+19
18	Steel	4.20E+10	4.46E+10	3.16E+09 sej/g	l	1.33E+20	1.41E+20
19	Iron	8.92E+10	8.25E+10	1.24E+10 sej/g	m	1.11E+21	1.02E+21
20	Limestone	7.71E+10	7.95E+10	1.62E+09 sej/g	a	1.25E+20	1.29E+20
21	Brick	1.81E+12	1.20E+12	3.74E+09 sej/g	n	6.77E+21	4.49E+21
22	Tiles	4.55E+10	4.25E+10	3.53E+09 sej/g	n	1.61E+20	1.50E+20

23	Rubber	3.55E+09	4.14E+09	9.47E+09 sej/g	n	3.36E+19	3.92E+19
24	Plastic	5.40E+09	5.49E+09	6.22E+09 sej/g	o	3.36E+19	3.41E+19
25	Wood	9.95E+10	1.10E+11	2.30E+09 sej/g	p	2.29E+20	2.53E+20
26	Copper	2.96E+09	2.73E+09	1.02E+11 sej/g	o	3.02E+20	2.78E+20
27	Aluminum	2.03E+09	2.17E+09	5.73E+09 sej/g	o	1.16E+19	1.24E+19
28	Wool	9.57E+11	1.10E+12	8.51E+04 sej/g	c	8.14E+16	9.36E+16
29	Cotton	5.79E+13	5.01E+13	1.06E+06 sej/g	a	6.14E+19	5.31E+19
30	Timber	9.23E+13	1.13E+14	4.53E+04 sej/g	a	4.18E+18	5.12E+18
31	Paper	2.11E+09	2.12E+09	7.49E+09 sej/g	a	1.58E+19	1.59E+19
32	Chemicals (mixed)	4.80E+10	4.33E+10	9.70E+09 sej/g	q	4.66E+20	4.20E+20
33	Nitrogen fertilizer	5.09E+09	5.42E+09	4.62E+09 sej/g	g	2.35E+19	2.50E+19
34	Phosphate fertilizer	3.80E+08	3.71E+08	6.88E+09 sej/g	g	2.61E+18	2.55E+18
35	Pesticides	9.87E+07	1.06E+08	1.62E+09 sej/g	g	1.60E+17	1.72E+17
S3	Subtotal (9-35) **(F_1)**					1.20E+22	9.71E+21
Nonrenewable outputs							
36	Chemicals (mixed)	4.90E+11	4.47E+11	9.70E+09 sej/g	q	4.75E+21	4.34E+21
37	Machines and Equipments	2.43E+11	2.21E+11	2.00E+10 sej/g	q	4.86E+21	4.42E+21
38	Commodities and Buildings	1.65E+08	1.49E+09	5.20E+12 sej/$	q	8.58E+20	7.75E+21
39	Service	7.68E+06	7.23E+06	5.20E+12 sej/$	q	3.99E+19	3.76E+19
S4	Subtotal (36-39) **(Y)**					1.05E+22	1.65E+22
Labor and service							
40	Utilization of foreign investment	5.53E+06	5.53E+06	5.20E+12 sej/$	q	2.88E+19	2.88E+19
41	Research and development fee	1.26E+06	1.26E+06	5.20E+12 sej/$	q	6.55E+18	6.55E+18
42	Depreciation cost	5.70E+06	5.70E+06	5.20E+12 sej/$	q	2.96E+19	2.96E+19
S5	Subtotal (40-42) **(F_2)**					6.49E+19	6.49E+19
Wastes							
43	Wastewater	9.13E+13	3.25E+13	6.39E+05 sej/g	r	5.83E+19	2.08E+19
44	Waste gas	8.71E+12	4.03E+12	6.66E+05 sej/g	g	5.80E+18	2.68E+18
45	Solid wastes	4.72E+14	3.06E+14	1.73E+06 sej/g	r	8.17E+20	5.29E+20
S6	Subtotal (43-45) **(W)**					8.81E+20	5.53E+20
Emergy of cyclic utilization							
46	Solid waste utilization	2.62E+14	3.60E+14	1.73E+06		4.54E+20	6.23E+20
S7	Subtotal (46) **(R_2)**					4.54E+20	6.23E+20

References in Table 2 are as follows. a:Odum (1996), b:Mellino et al. (2014), c:Odum et al. (2000), d:Brown and Ulgiati (2010), e:Zhang et al. (2014), f:Mellino et al. (2013), g:Lan et al. (2002), h:Pulselli (2010), i:Brown et al. (2011), j:Mellino et al. (2013), k:Brown and Buranakarn (2003), l:Bargigli and Ulgiati (2003), m:Brown and Ulgiati (2012), n:Brown and Buranakarn (2003), o:Brown et al. (2012), p:Mellino et al. (2015), q:Lou and Ulgiati (2013), r:Huang and

Chen (2005).

According to the emergy flows chart, the emergy evaluation indicators of SETDZ are are shown in Table 3.

Table 3 Emergy Indicators of SETDZ

Emergy indicators	**Expression**	**Unit**	**2008**	**2018**
The emergy flow				
Emergy of renewable natural resources (R)	R_1+R_2	Sej	4.58E+20	6.27E+20
Emergy of nonrenewable resource (N)		Sej	6.05E+21	6.57E+21
Purchased emergy (F)	F_1+F_2	Sej	1.21E+22	9.77E+21
Yield emergy (Y)		Sej	1.05E+22	1.65E+22
Emergy of wastes (W)		Sej	8.81E+20	5.53E+20
Total emergy (U)		Sej	1.86E+22	1.70E+22
Emergy analysis indicators of economic subsystem				
Ratio of emergy to GDP (EDR)	(1)	Sej/$	1.13E+12	1.17E+12
Emergy yield ratio (EYR)	(2)		8.68E-01	1.69E+00
Emergy analysis indicators of natural subsystem				
Environmental load ratio (ELR)	(3)		3.96E+01	2.61E+01
Ratio of wastes to the total emergy (EWR)	(4)		4.74E-02	3.25E-02
Emergy analysis indicators of social subsystem				
Emergy Density (ED)	(5)	Sej/m^2	3.84E+15	3.51E+15
Carrying population (CP)	(6)	persons	3.19E+05	3.86E+05
Emergy analysis indicators of sustainable development				
Sustainable development indicator (ESI)	(7)		2.19E-02	6.48E-02

The datum in Tables 2 and 3 are related to the production methods of basic industries such as the equipment manufacturing, metallurgy, pharmaceutical, and chemical industries in SETDZ. The development of such industries consumes a large number of natural resources, and the demand for natural resources also increases with the expansion of the scale.

3.2 System dynamics model

The establishment steps of the EIP's system dynamic model are as follows: the first is

to determine the system boundary of the EIP's industrial scope, then determine the endogenous and exogenous variables of the system. The second is to find out the feedback loop in the EIP system, explain the causal relationship and changes of various variables in the system, and describe the operation process of the industrial ecological chain among enterprises in the park. The third is to find out the state variables and rate in the feedback loop, and determine the rate structure through the collection and processing of information flows and material flows. The fourth is to establish SD model. The fifth is to test and confirm whether the model can reproduce the behavior of EIP system. The sixth is to use the model to choose the development strategy of sustainability.

In this paper, Vensim software is used to sort out the flow chart of the system, compile the model equation, debug and test. The research base year is 2008, the time step is one year, and the operation cycle is 2008-2028. Taking region of SETDZ as the system boundary, the EIP is regarded as an emergy system, and the relationship among the social, economic and ecological subsystems is analyzed. According to the quantitative relationship and emergy flows of SETDZ ecosystem, the system dynamics equations are established. Combined with the comprehensive index of emergy analysis, it is simulated about the development status and sustainable development level of SETDZ, and finally the system dynamics flow chart is as shown in Figure 3.

In the SD model of SETDZ, the average method is used to calculate some parameters of GDP and the capital flow of new fixed asset investment, and the exponential smoothing method is used to process the time series data. Population is the consumer of various resources, and outputs products and services, and it is simulated by birth rate and mortality, immigration rate and emigration rate. The key of industrial ecological chain is

the material emergy in the system, which can collect data and calculate constant value through UEV. As is shown in Table 2 and Table 3 for details.

In SD analysis, it is necessary to confirm whether the model can reproduce the behavior of EIP system. In this paper, the reliability of the simulation model is judged by comparing the difference between the simulation value and the existing statistical data. Table 4 shows the test results of model authenticity, these results are basically consistent with the development of industrial ecosystem in the new area, with a relative error between - 8% and 10%. This model can accurately describe the current situation of SETDZ's development, and has a better prediction function, and can effectively simulate the development level and sustainability in the future.

Table 4 Authenticity test of SD model

Year	GDP ($)			Population (persons)			Total emergy (Sej)		
	Reality	Simulation results	relative error	Reality	Simulation results	relative error	Reality	Simulation results	relative error
2008	1.62E+10	1.62E+10	6.19E-04	9.07E+05	9.09E+05	-2.21E-03	1.86E+22	1.68E+22	9.68E-02
2010	1.49E+10	1.54E+10	-3.29E-02	9.08E+05	9.10E+05	-2.20E-03	1.91E+22	1.78E+22	6.81E-02
2012	1.38E+10	1.41E+10	-2.24E-02	9.11E+05	9.09E+05	2.20E-03	1.86E+22	1.96E+22	-5.38E-02
2014	1.50E+10	1.52E+10	-1.82E-02	9.08E+05	9.09E+05	-7.37E-04	1.88E+22	1.81E+22	3.70E-02
2016	1.30E+10	1.39E+10	-7.25E-02	9.08E+05	9.14E+05	-6.61E-03	1.82E+22	1.66E+22	8.79E-02
2018	1.48E+10	1.51E+10	-2.23E-02	9.39E+05	9.17E+05	2.34E-02	1.70E+22	1.59E+22	6.47E-02

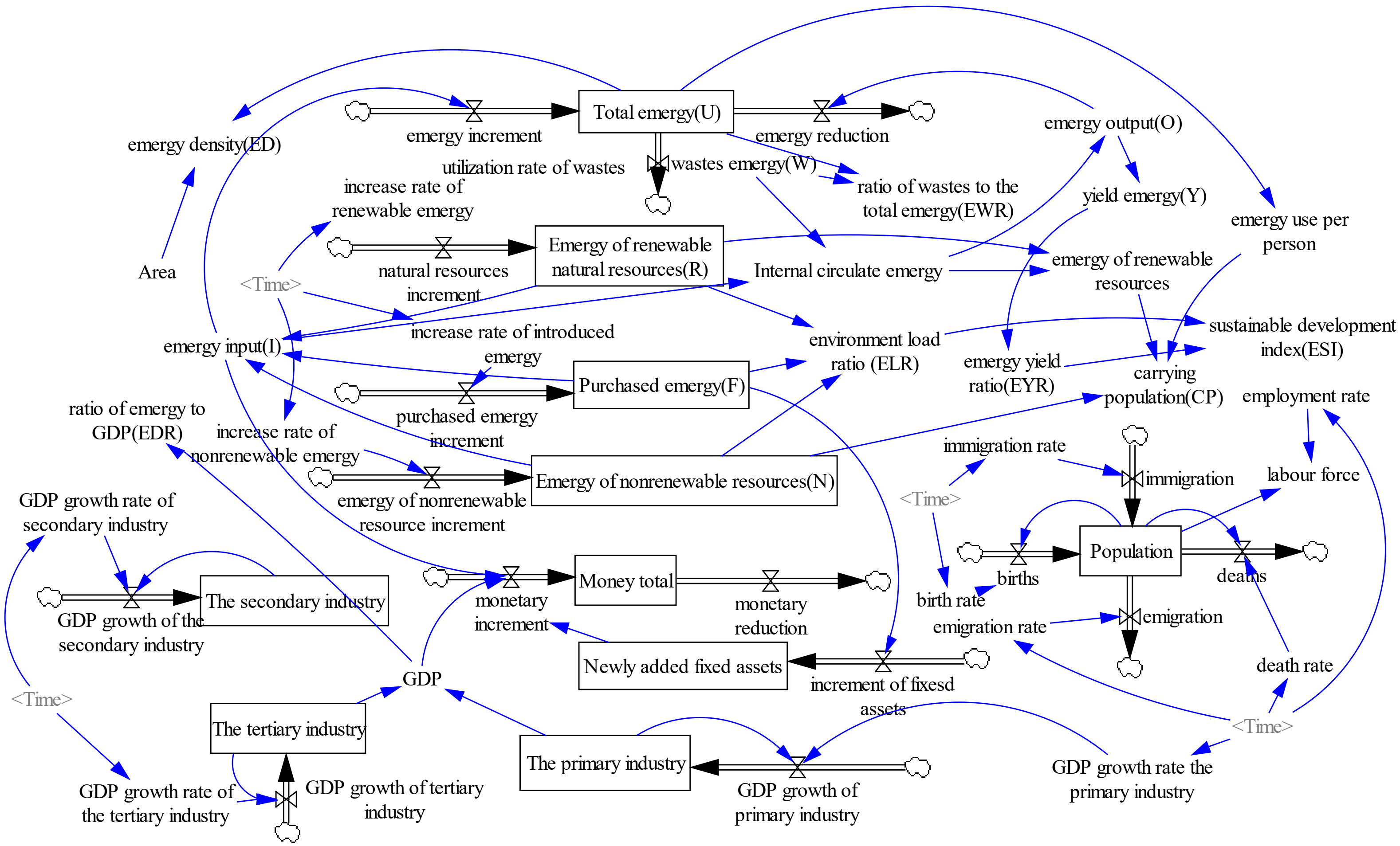

Figure 3 System dynamics flow diagram of SETDZ

4. Results and discussion

In this paper, increment of purchased emergy, increment of renewable natural resources, increment of nonrenewable resources, utilization of waste emergy, employment rate and GDP growth rate are selected as the control parameters, and combined with the planning of SETDZ, fore typical scenarios are designed, including inertia scenario, economic scenario, environmental protection scenario and science and technology scenario. The purpose is to comprehensively analyze the impact of development path and industrial layout policy on SETDZ's sustainability, and to explore the best scenario for SETDZ sustainable development by comparing various scenarios.

Denote Inertia scenario by Scenario 1. Based on the current science and technology investment, industrial layout and waste treatment level, the evolution process of ecosystem are simulated, and the sustainable development situation is obtained.

Denote economic scenario by Scenario 2. Reduce the proportion of investment in other industries, increase the investment in the secondary industry and nonrenewable resources which contribute the most to GDP, so as to maximize economic benefits.

Denote environmental protection scenario by Scenario 3. Reduce the proportion of investment in the primary and secondary industries with larger negative environmental effects, increase the investment in the tertiary industry and purchase emergy with smaller negative environmental effects, so as to maximize environmental benefits.

Denote science and technology scenario by Scenario 4. On the premise that the proportion of investment and labor force in each industry remain unchanged, the science and technology factor of the industry is improved by introducing new technology and new equipment, and the impacts of different utilizations of waste emergy and increment

of purchased emergy on the sustainability are considered.

4.1 Analysis of economic development

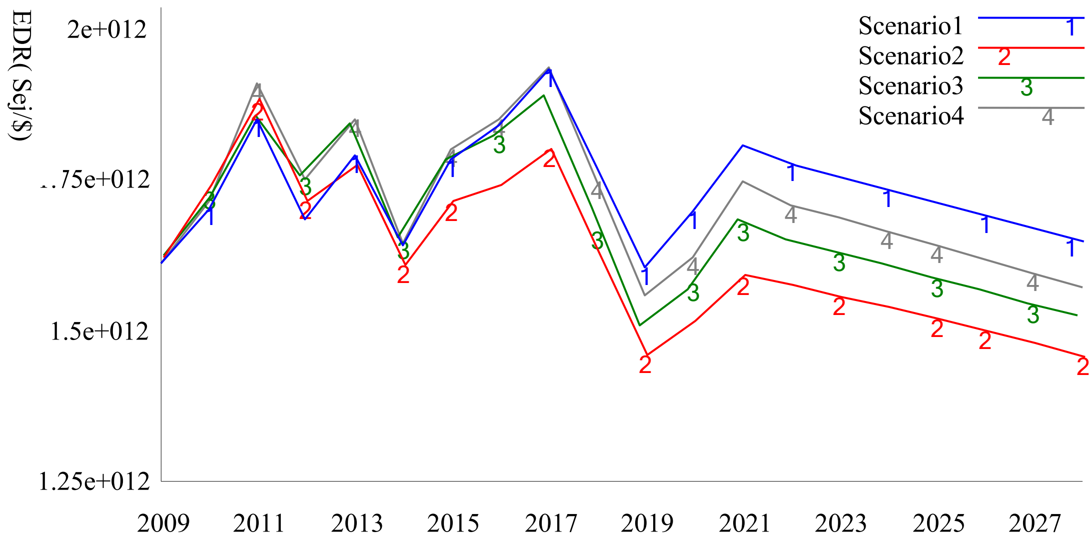

Figure 5 Simulation results of EDR

In recent years, the economy of SETDZ has developed rapidly. Figure 5 shows that the EDR is dropping after the implementation of circular economic model. The lower the EDR is, the higher the economic benefits. The production efficiency and emergy application efficiency of SETDZ have been continuously improved, mainly owing to the measures taken by the park, in addition to constantly adjusting reform measures. Scenario 2, which focuses on economic development, has the fastest GDP growth. GDP growth rates in Scenario 3 and Scenario 4 decreases in turn. Scenario 1 has the slowest GDP growth and cannot meet the economic expectations. It can be seen that the economic benefit in SETDZ increasingly depends on natural resources less, as economy is nearly involved in few direct applications of the environmental resources without any capital exchange. SETDZ requires less emergy inputs than before implementing the circular

economic model to produce the same GDP.

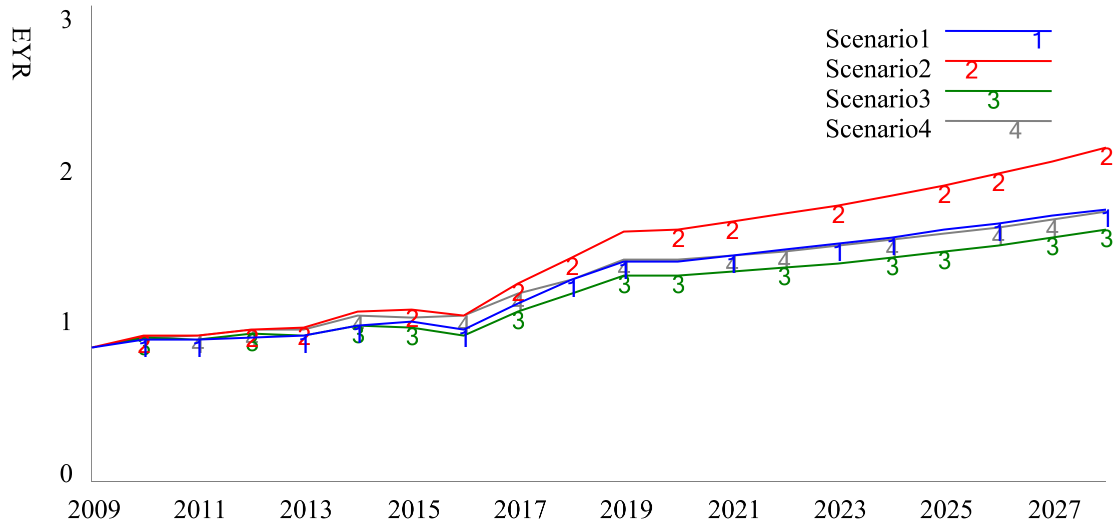

Figure 6 Simulation results of EYR

The EYR indicates locally available renewable or nonrenewable emergy flows that are exploited by emergy investments from outside of the system. In Figure 6, the EYR of SETDZ has been stably increased due to the circular economic model, and the value in 2028 of EYR is nearly twice than the value in 2008 (from 8.68E-01 to 1.79E+00) in Scenario 1. Meanwhile, the scale of the economy is expanding, SETDZ reliance on local resources remains basically unchanged. Although the single pursuit of economic development can meet the economic expectations, the coordinated development couldmake SETDZ full of vitality and conducive to the healthy development of the system. The emergy from Scenario 2 and Scenario 3 purchased from abroad is small, the development of SETDZ depends on local and domestic resources, and the resource base is strong, which can maintain sustainable and stable economic development. The EYR in Scenario 2 and Scenario 3 are higher than the current development model, while Scenario 4 has relatively less output due to the huge investment in the early stage of science and technology development.

4.2 Analysis of environmental compatibility

The ELR indicates the environmental load of nonrenewable flow dominated by human beings. The lower ELR is, the less pressure on the environment is (Jiang et al. 2007). In Figure 7, the ELR of Scenario 1 has dropped from 3.96E+01 to 2.27+01 in 2008 - 2028, ELR also decreases in the other three scenarios. With SETDZ industries continuing to expand the scale of the industrial economy, the pressure on the environment is declining. However, it is very difficult to completely reduce the pressure on the system environment for economic development. The ELR simulation results in Scenario 3 and Scenario 4 are slightly different, and the result in scenario 4 is better than in Scenario 3.

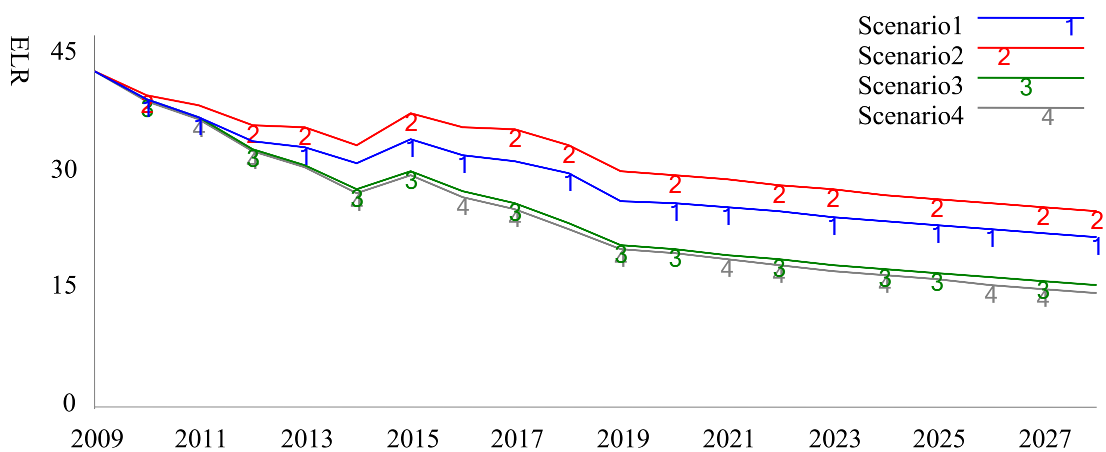

Figure 7 Simulation results of ELR

Before 2019, the EWR is on a downward trend. After 2020, the waste emission tends to be stable. In Figure 8 environmental protection is payed attention in Scenario 3, and the output value increases while the utilization rate of waste treatment is also higher. Scenario 2 and scenario 4 increase the input of production factors, and the utilization rate of waste is lower, resulting in greater pressure on the environment. The growth rate of the final waste discharge in SETDZ lags behind the growth rate of the total emergy

consumption, and the resource utilization efficiency and the pollution discharge treatment need to be effectively controlled.

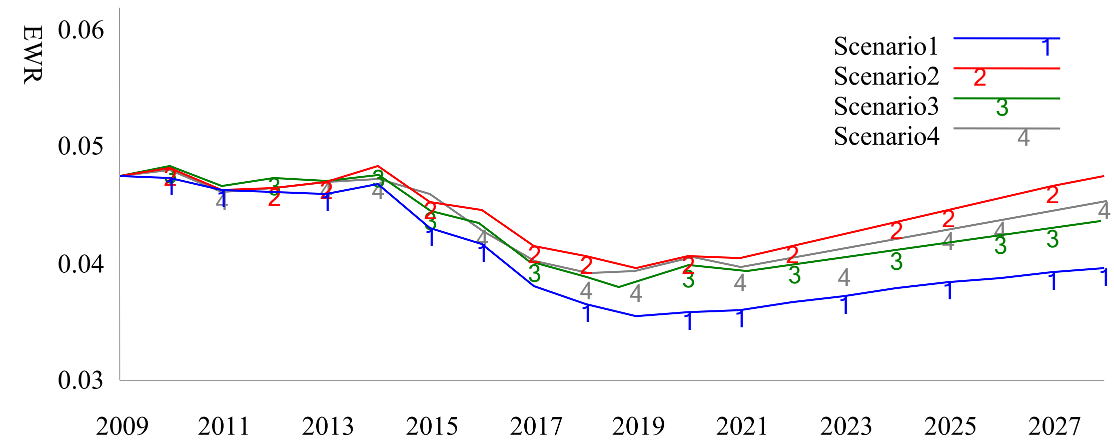

Figure 8 Simulation results of EWR

4.3 Analysis of social acceptability

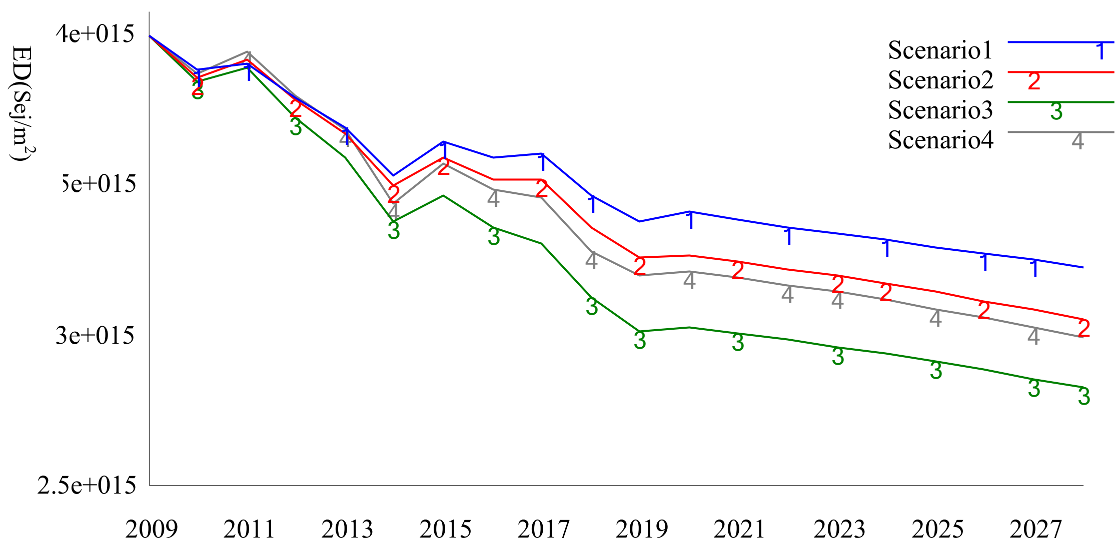

Figure 9 Simulation results of ED

In Figure 9, the ED of SETDZ decreases slightly in all scenarios. The intensity of the emergy inputs per unit area is gradually declining, and the available emergy in the park is

decreasing. The economy growth of SETDZ has brought serious challenges to the local ecosystem. There are still some practical difficulties and obstacles in promoting the development of circular economy, mainly including the imperfect laws and regulations, the ineffective implementation of policies and guidelines, the weak awareness of national economy of residents in the EIP, the unreasonable consumption psychology and consumption mode, resulting in the waste of resources.

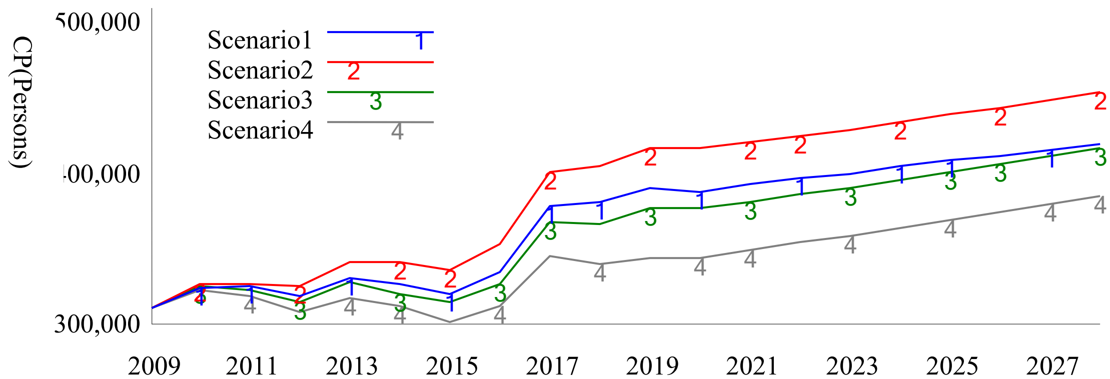

Figure 10 Simulation results of CP

In Figure 10, CP is the highest in Scenario 2 and the lowest in Scenario 4. This shows that economic development can attract a large number of people to support, while the improvement of science and technology limits the migration of population, because the development of high and new technology does not simply rely on the increase of population. Economic development and social progress have led to urban agglomeration, along with increasing population and environmental problems in the region. The main pratical problem of some contemporary industries still exists, the wasteful ways are at environmental and economically expense.

4.4 Analysis of the comprehensive indicator

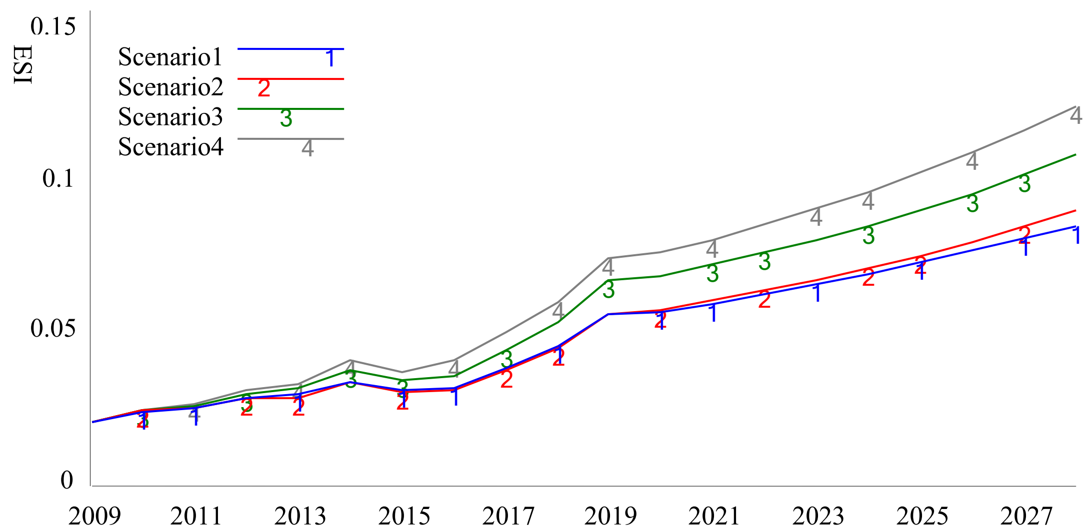

Figure 11 Simulation results of sustainable development

In Figure11, the ESI of SETDZ increases in all four scenarios. Specially, ESI is less than 1 in the four scenarios, SETDZ is a typical resource consumption ecosystem. In Scenario 4, Science and technology developsrapidly, and the sustainable development capacity of the system is also improving. In Scenario 1 and Scenario 2, the emergy of the import resources and labor services in the total emergy usage has gradually increased, and dependence on local nonrenewable resources remains high.

The sustainability of SETDZ is gradually improving, as the main resources depend on external purchase, there are relatively more residents and high resource consumption industries, less renewable resource use and waste discharge. In the long run, ESI shows a trend of recovery, and the proportion of nonrenewable emergy decreases, which drives the development capacity of EIP improved continuously.

5. Conclusion

In this paper, the emergy analysis and SD method are combined, and the dynamic model of SETDZ's eco-economic system is established by using Vensim software, and the related emergy evaluation index is analyzed and simulated. This paper provides four scenarios and implementable strategies for the development of SETDZ. The results show that: the GDP and EYR of SETDZ are on the rise as a whole. Scenario 4 has the least CP, which indicates that high-tech has the least dependence on labor force. The ESI of scenario 4 is higher than that of other scenarios in the same period, which has the least pressure on the environment and the best sustainability.

With the continuous expansion of SETDZ's industry scope, it is difficult to reduce the environmental pressure on the system when focusing only on economic development. The urban agglomeration effect has led to increasing population and environmental problems in the region. The economic development of SETDZ has been relatively rapid, whereas its sustainability has not grown consistently. Considering economy, environment and society, Scenario 4 is the best development strategy. In the later development of SETDZ, the policy should focus on the adjustment of industrial layout and the improvement of science and technology factors. First, we should further expand the development of service industry and environmental protection industry. Through the preferential policies formulated by the government, well-known enterprises and institutions at home and abroad will be attracted to settle in SETDZ to reduce waste discharge from the source. Second, we should improve the supporting system of industrial innovation in SETDZ, increase investment in research and development of environmental protection technology; pay attention to the research and development,

introduction of core environmental protection technology, and related environmental protection equipment such as desulfurization, denitration, sludge treatment and industrial wastewater degradation, and improve the recovery and utilization rate of waste; set up superior salary, welfare and household registration policies to attract relevant talents to settle down, with talents and capital as the driving force to promote industrial technological innovation and improve the technological factors of the industry.

The combination of emergy analysis and SD makes up for the deficiency of single research method. The relationship between different function flows in the eco-economic system is shown in the form of system flow diagram, which makes the relationship between various function flows in the eco-economic system clearer. Based on the historical development of the system, the emergy analysis and SD method can be combined to simulate the changes of the system function flow elements, and emergy evaluation index by using simulation technology, then grasp the sustainability of the system.

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Appendix 1 Dynamic equations of the ecosystem

(1) INITIAL TIME=2009

(2) FINAL TIME=2028

(3) TIME STEP=1

(3) SAVEPER=TIME STEP

(4) Urban eco-efficiency indicator (UEI)=Emergy yield ratio (EYR)*(1-Ratio of wastes to the total emergy (EWR))*(1-Ratio of wastes to the total emergy (EWR))*(1-Emergy of nonrenewable resource (N)/Total emergy (U))*(1-"Emergy of nonrenewable resource (N)/Total emergy (U))

(5) Increment of nonrenewable resources= WITH LOOKUP (Time, ([(0,-0.08)-(4000,20)], (2008,0),(2009,0.0098),(2010,0.0023),(2011,-0.0545),(2012,0.0103),(2013,-0.06),(2014,0.017142),(2015,0.0304),(2016,0.1315),(2017,-0.0327),(2018,-0.01063),(2019,0.002),(2020,0.002),(2021,0.002),(2022,0.0019),(2023,0.0018),(2024,0.0017),(2025,0.0016),(2026,0.0015),(2027,0.0014),(2028,0.0013)))

(6) Emergy of nonrenewable resource (N)= INTEG (Emergy of nonrenewable resource (N)*Increment of nonrenewable resources, 6.05e+021)

(7) Increment of renewable natural resources (R)= WITH LOOKUP (Time, ([(0,-0.1)-(4000,20)], (2008,0),(2009,0.0602),(2010,0.0624),(2011,0.0602),(2012,-0.00424),(2013,0.016),(2014,-0.0609),(2015,0.0479),(2016,0.0299),(2017,0.0109),(2018,0.09642),(2019,0.016),(2020,0.016),(2021,0.016),(2022,0.016),(2023,0.016),(2024,0.016),(2025,0.016),(2026,0.016),(2027,0.016),(2028,0.016)))

(8) Emergy of renewable natural resources (R)= INTEG (Emergy of renewable natural resources (R)*Increment of renewable natural resources (R), 4.54e+020)

(9) Increment of purchased emergy= WITH LOOKUP (Time, ([(0,-0.1)-(4000,4000)], (2008,0),(2009,-0.0486),(2010,0.0043),(2011,-0.0183),(2012,-0.0453),(2013,-0.0344),(2014,0.04317),(2015,-0.0395),(2016,-0.0665),(2017,-0.0425),(2018,-0.03959),(2019,0.013),(2020,-0.014),(2021,-0.014),(2022,-0.014),(2023,-0.014),(2024,-0.014),(2025,-0.014),(2026,-0.014),(2027,-0.014),(2028,0.041)))

(10) Purchased emergy (F) = INTEG (Increment of purchased emergy*"Purchased emergy (F), 1.25e+022)

(11) Total emergy (U)= Emergy of nonrenewable resource (N)+Emergy of renewable natural resources (R)+Purchased emergy (F)

(12) Population = INTEG (births + immigration - deaths - emigration, 907000)

(13) births = Population * birth rate

(14) deaths= Population * death rate

(15) emigration = Population * emigration rate

(16) immigration = Population * immigration rate

(17) immigration rate =0.33–STEP(0.2,2015)–STEP(0.1,2018)

(18) Internal circulate emergy =waste emergy(W)* utilization of waste emergy

(19) ratio of wastes to the total emergy= waste emergy(W)/ Total emergy (U)

(20) emergy of renewable resource = Internal circulate emergy+ Emergy of renewable natural resources (R)

(21) emergy ratio of circulation system= Internal circulate emergy / Total emergy (U)

(22) yield emergy(Y)= Total emergy (U) - emergy reduction

(23) labour force=employment rate*Population

(24) emergy input(I)= Emergy of nonrenewable resource (N)+Emergy of renewable natural resources (R)+Purchased emergy (F)+Monetary total

(25) emergy ratio of renewable resource=emergy of renewable resource/ Total emergy (U)

(26) Newly added fixed assets = WITH LOOKUP (Time, ([(0,-0.4)-(4000,20)], (2008,0),(2009,-0.078),(2010,-0.073),(2011,0.065),(2012,-0.083),(2013,0.044),(2014,-0.0483),(2015,-0.04445),(2016,-0.0437),(2017,0.0487),(2018,0.0729),(2019,-0.0437),(2020,-0.065),(2021,-0.00437),(2022,-0.00437),(2023,-0.00437),(2024,-0.00437),(2025,-0.00437),(2026,-0.00437),(2027,-0.00437),(2028,-0.00437)))

(27) monetary increment =Newly added fixed assets* Depreciation rate

(28) GDP= GDP of Primary industry + GDP of Secondary industry + GDP of tertiary industry

(29) GDP of Primary industry = GDP growth of Primary industry / GDP growth rate of Primary industry

(30) GDP of Secondary industry = GDP growth of Secondary industry / GDP growth rate of Secondary industry

(31) GDP of tertiary industry = GDP growth of tertiary industry / GDP growth rate of tertiary industry

(32) Monetary total =INTEG (monetary increment- monetary reduction, 790000)

(33) emergy output(O)= yield emergy(Y)+ emergy reduction- Internal circulate emergy

(34) Sustainable development index (ESI) = Emergy yield ratio (EYR)/Environmental load ratio (ELR)

(35) Environmental load ratio (ELR) = (Emergy of nonrenewable resource (N) + Purchased emergy (F))/Emergy of renewable natural resources (R)

(36) Ratio of emergy to GDP (EDR) = Total emergy (U)/GDP

(37) Ratio of wastes to the total emergy (EWR) = Emergy of wastes (W)/Total emergy (U)

(38) Emergy use per person (EP) = Total emergy (U)/Population

(39) Emergy density (ED) = Total emergy (U)/Area

(40) Area= 4.84583e+006

(41) Emergy investment ratio (EIR) = Purchased emergy (F)/(Emergy of nonrenewable resource (N)+Emergy of renewable natural resources (R))

(42) Carrying population rate = (Emergy of renewable natural resources (R)+Emergy of nonrenewable resource (N))/Total emergy (U)

(43) Carrying population (CP) = Carrying population rate*Population

Figures

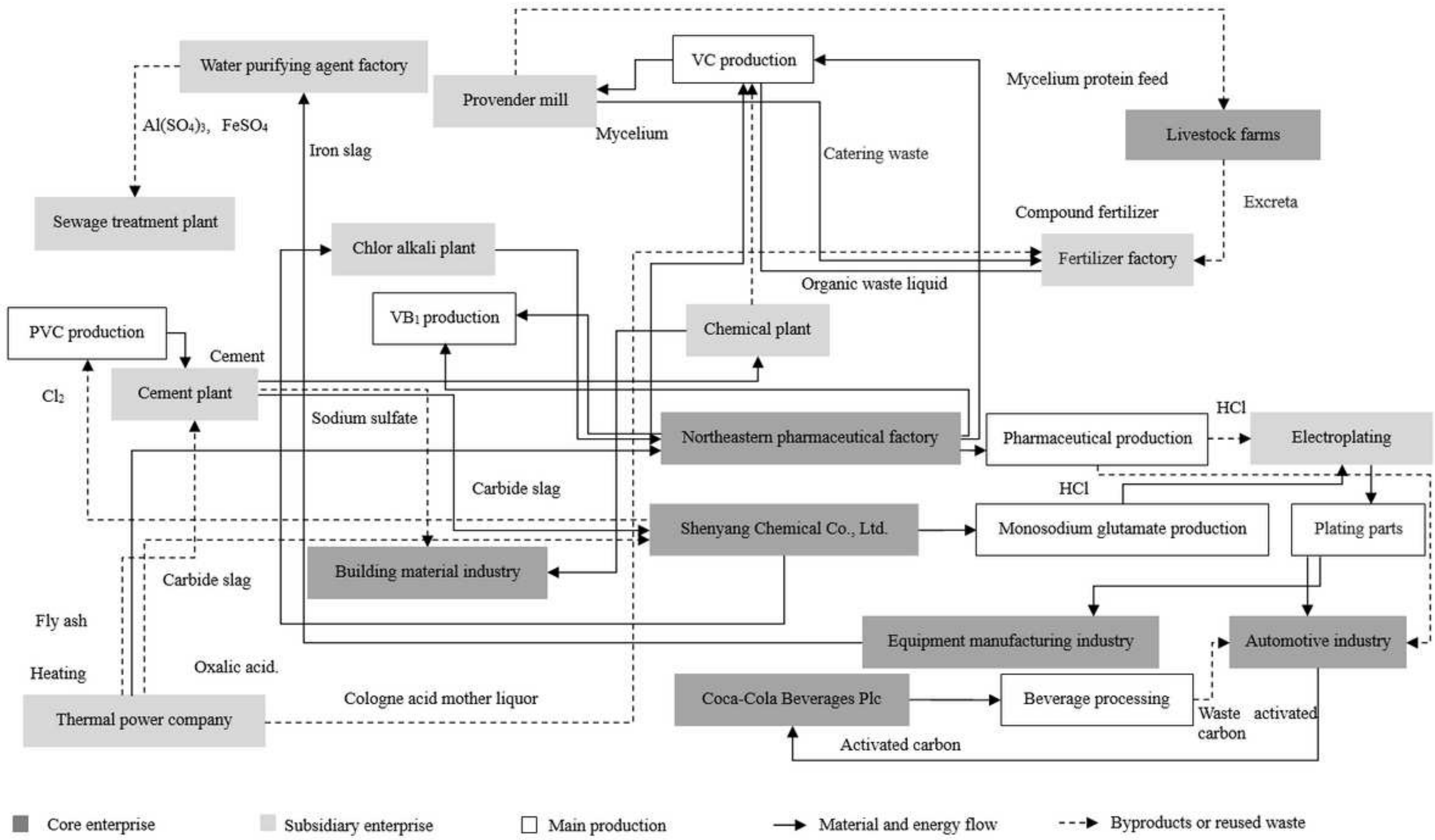
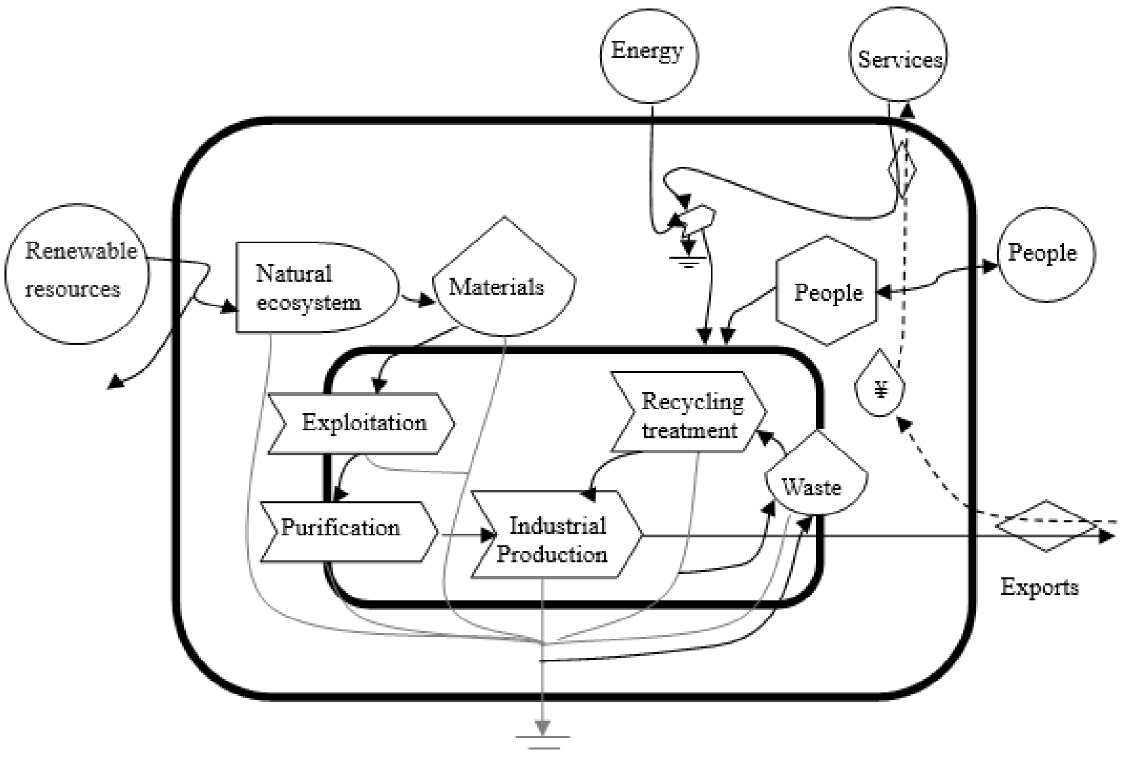


Figure 1

Eco-industrial network of pharmaceutical and chemical industries and their surrounding industries in SETDZ



	Generic resource flow (money flow, when dotted)
	Flow-limited energy or resource input
	Generic process box
	Primary production process
	Generic consumer
	Storage of resources or assets
	Economic transaction (resources versus money)
	Interaction among flows with different

Figure 2

Emergy flows of SETDZ

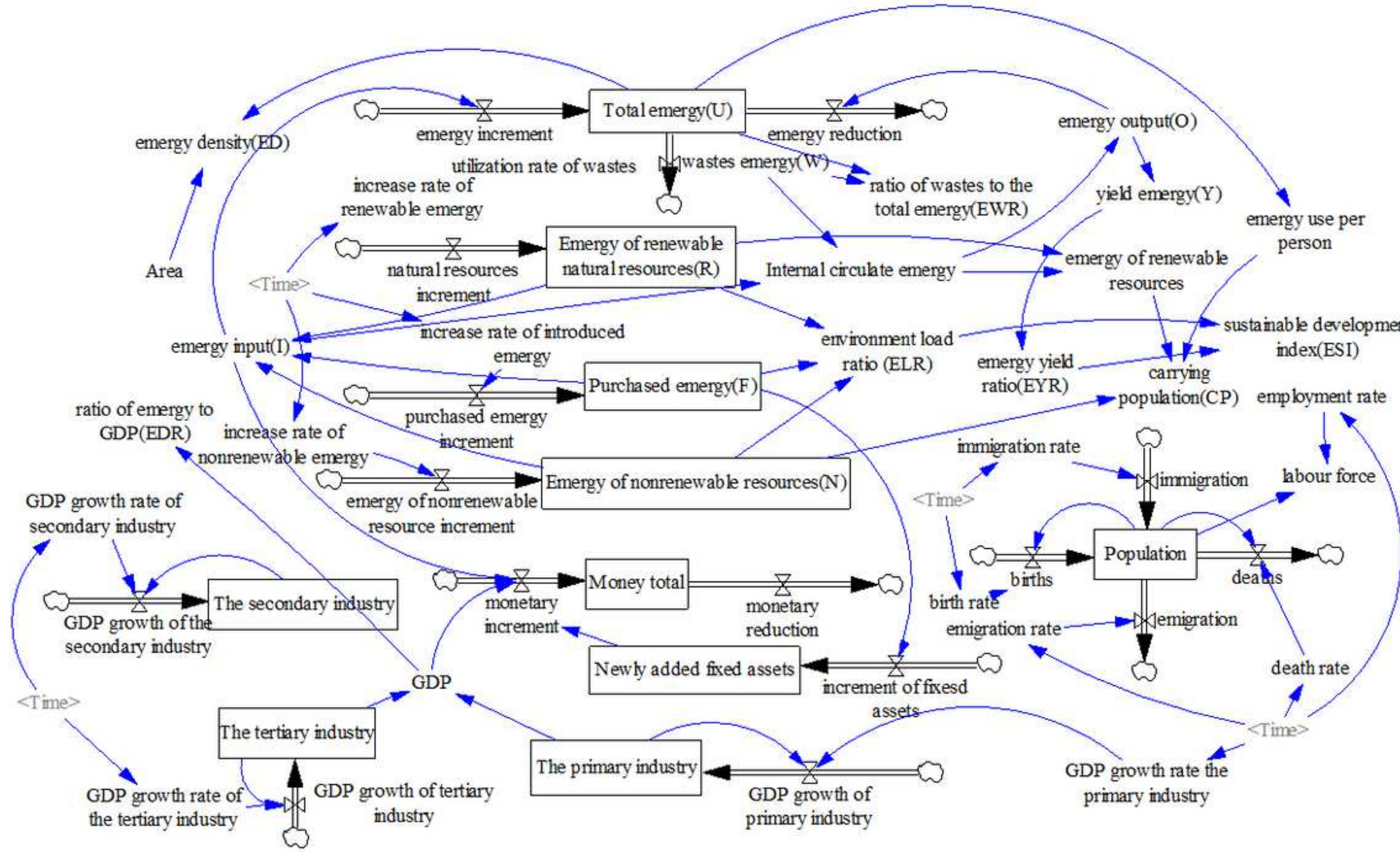


Figure 3

System dynamics flow diagram of SETDZ

Figure 4

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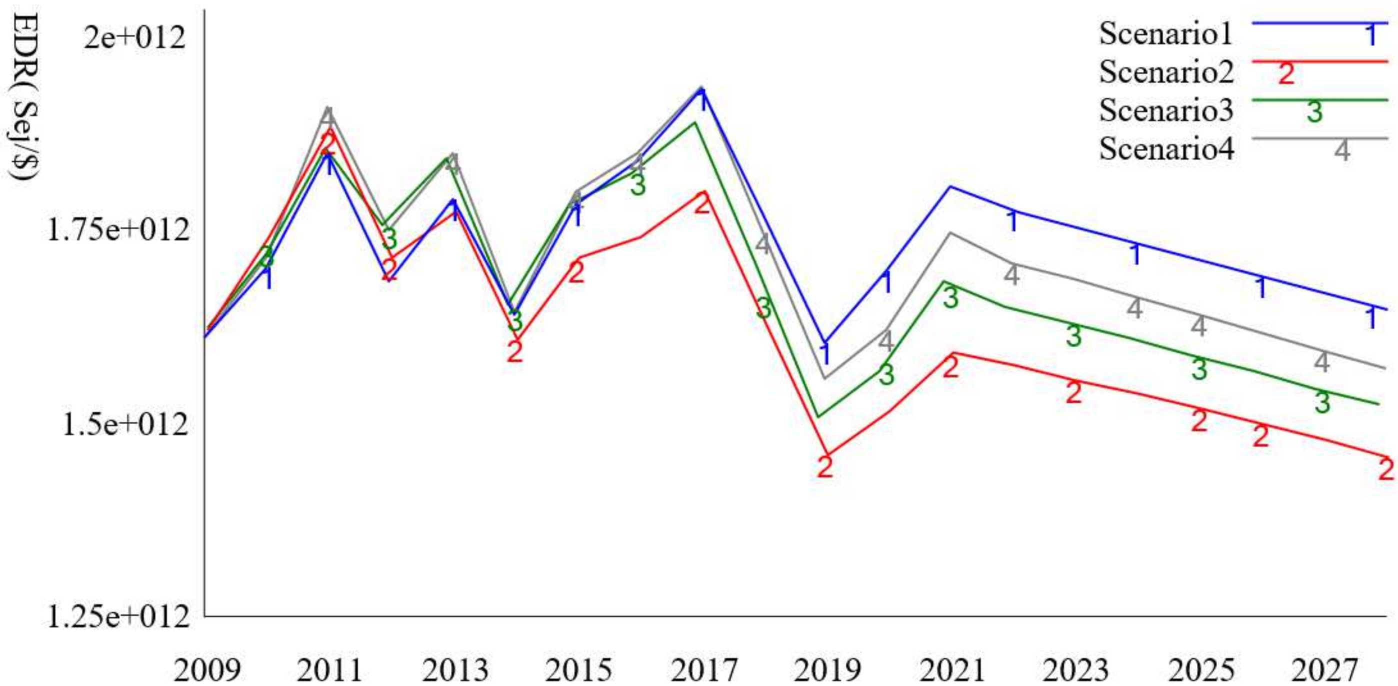

Figure 5

Simulation results of EDR

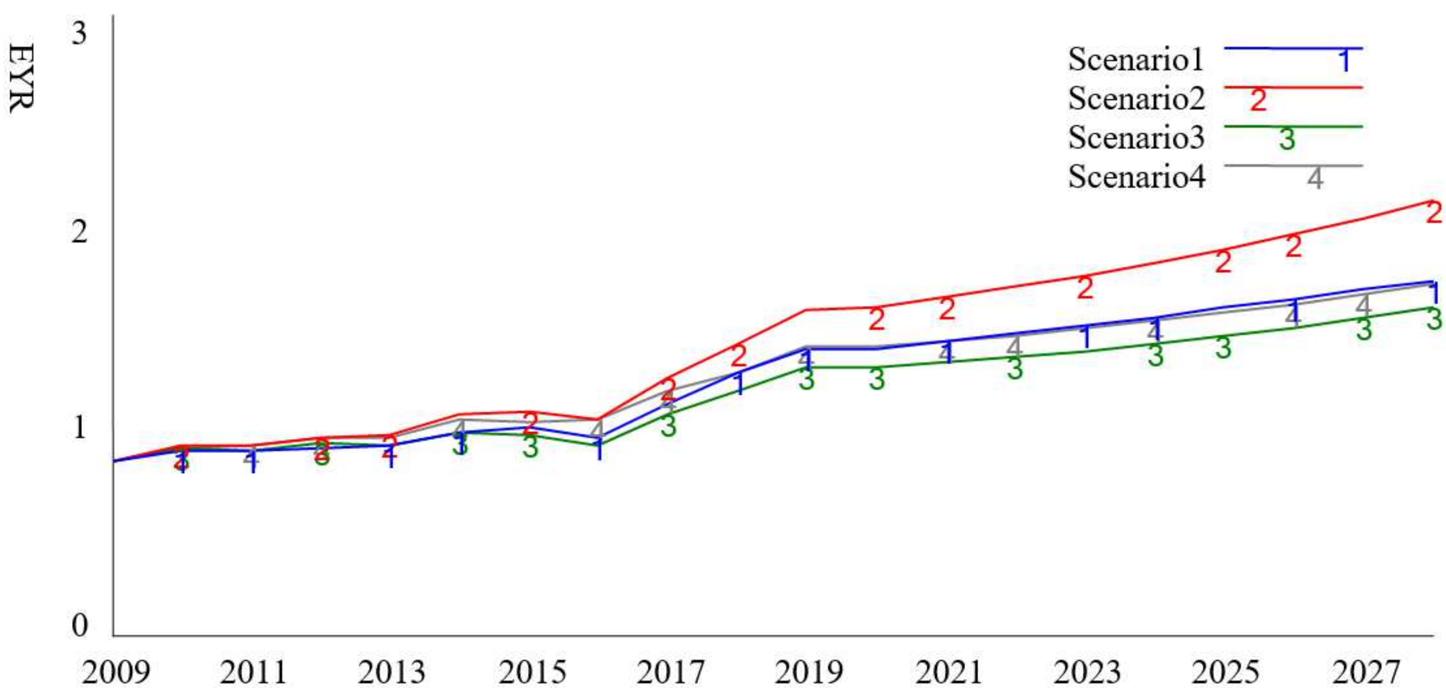

Figure 6

Simulation results of EYR

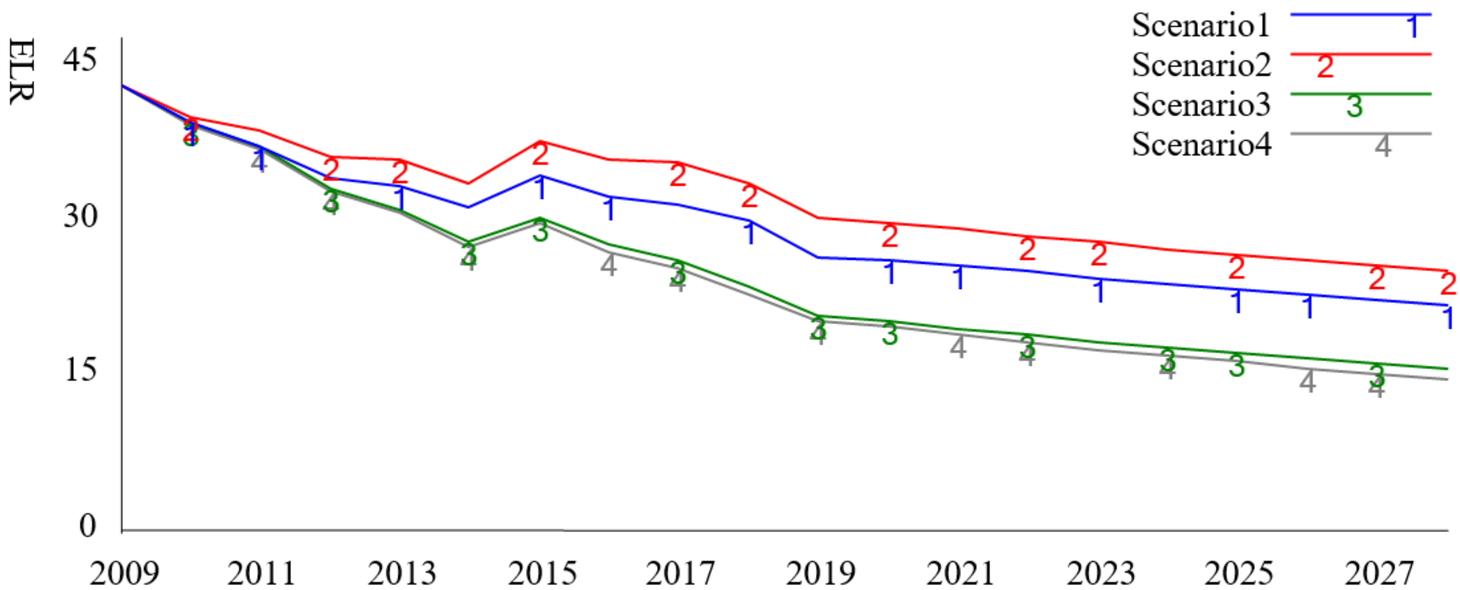

Figure 7

Simulation results of ELR

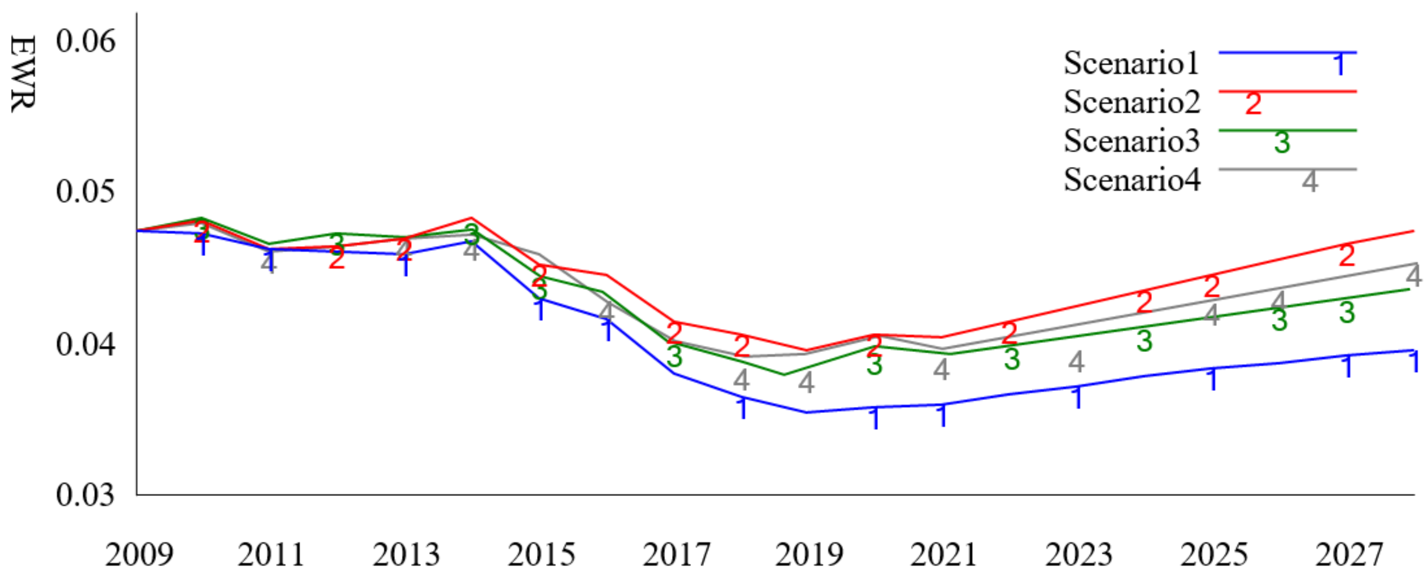

Figure 8

Simulation results of EWR

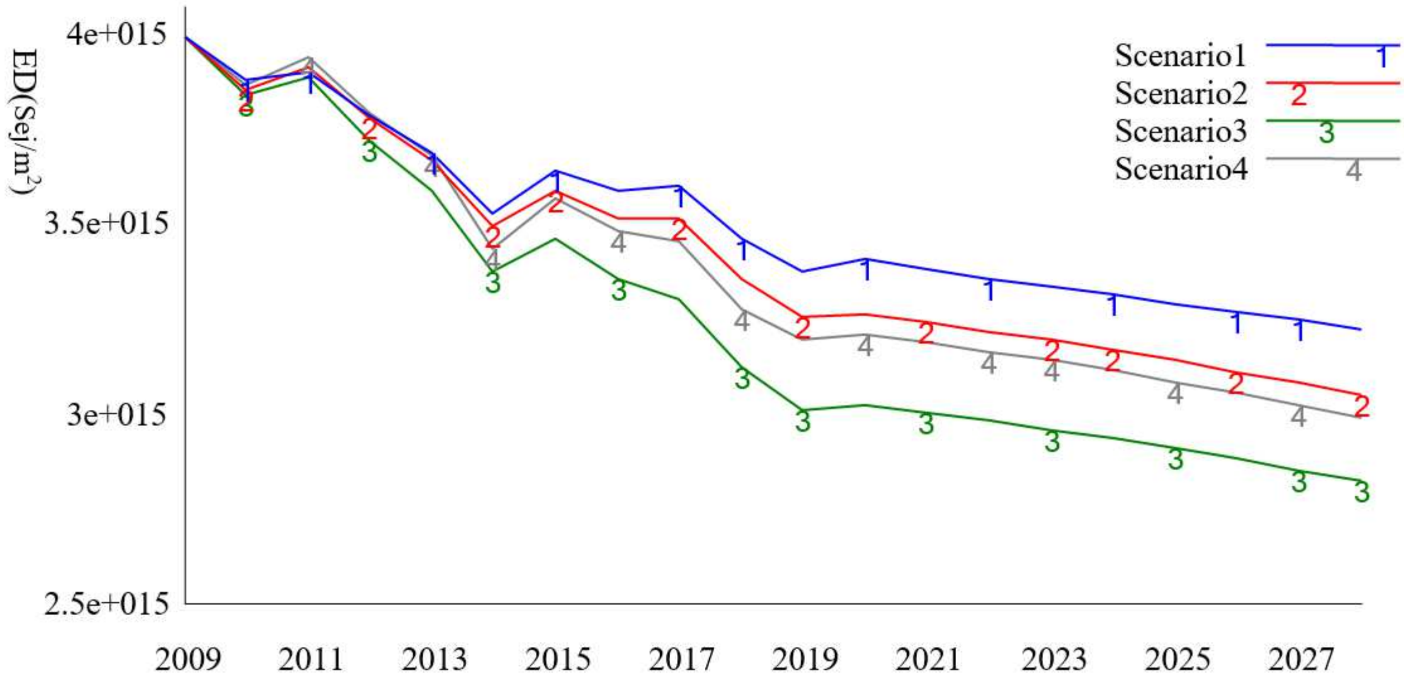

Figure 9

Simulation results of ED

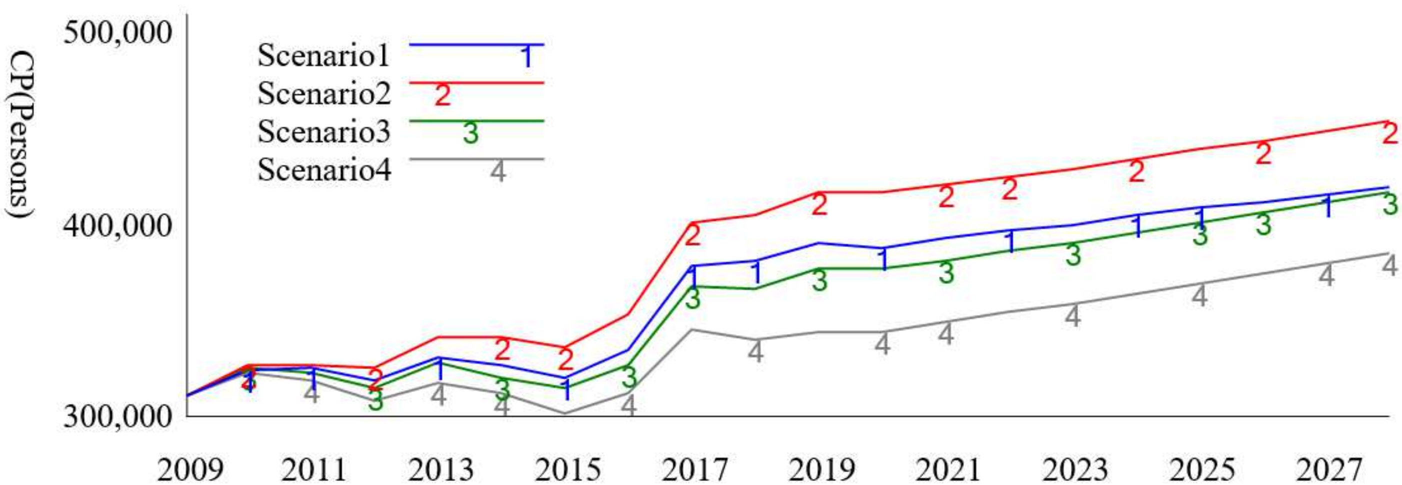

Figure 10

Simulation results of CP

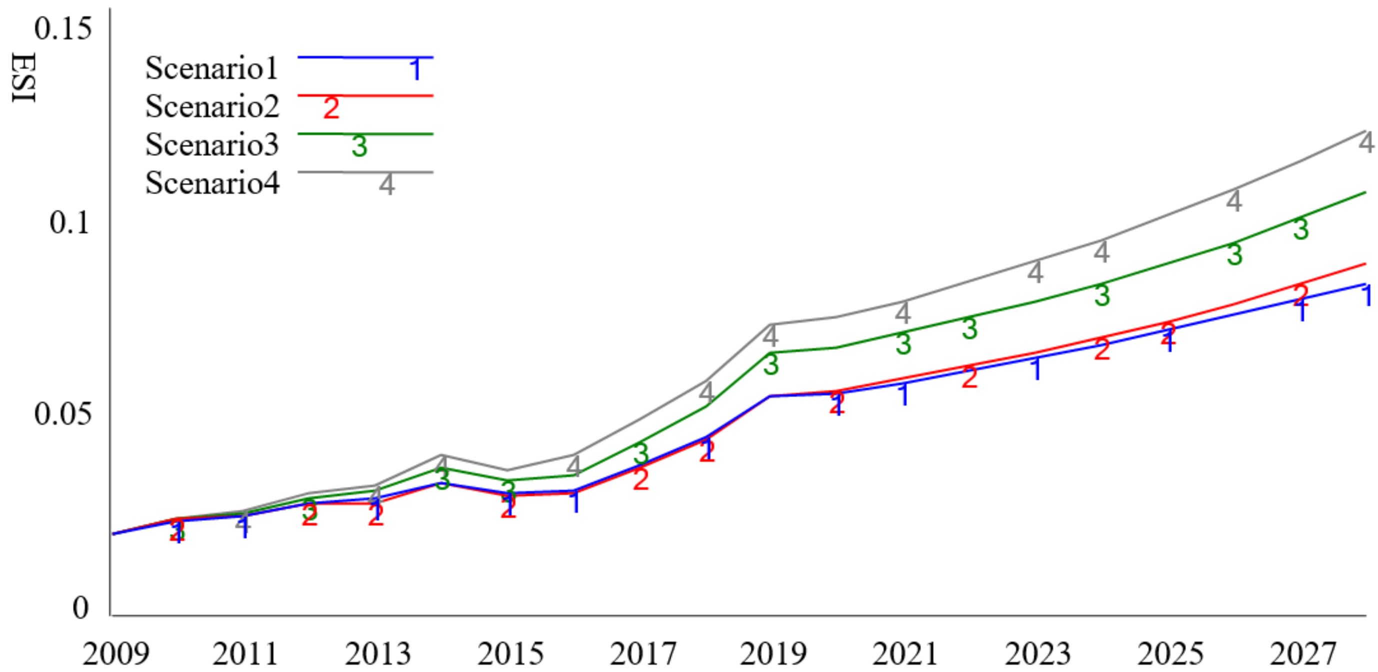

Figure 11

Simulation results of sustainable development

Supplementary Files

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- GraphicalAbstract4.docx