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System dynamics analysis of industrial waste recycling network—taking Poyang Lake ecological economic zone as example

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ABSTRACT

As an important way to realize the sustainable development of environment and resources, the circular economy well harmonizes the regional economic development and protection of the water resources. Under this background, this paper aims to discuss the running of the circular economy in Poyang Lake ecological economic zone. Based on system dynamics, this paper analyzes the relationship of the elements in Poyang Lake eco-economic zone and abstracts five pairs of level and rate variables from the system. Then, it builds the basic in-tree model and uses computer to simulate the system. The result shows that the model can well simulate the evolutionary tendency of the system, and the data have high reliability. It indicates that the system can well reduce the operation cost of enterprises, improve the income of member enterprises, and promote the smooth operation of circular economy. It also provides practical reference and theoretical support for the operation of the circular economy.

Keywords: Industrial waste; Recycling utilization; System dynamics

1. Introduction

Water resources, as one of the most important natural resources in the world, are not only a crucial component of people's life, but also an important element that can bring economic and social benefits. The sustainable development of water resources plays a significant role in the development of regional economy. For example, the "Poyang Lake ecological economic zone" of Jiangxi Province, which has risen to the national strategy, is an ecological plate which is divided based on the boundary of the Poyang Lake. The purpose of building this zone is to make better use of the ecological advantages of water resources to plan municipal development and thereby promote the development of regional economy.

Circular economy provides a new path to balance economy and environment. In a circular economy, the resources are made the best use of, the wastes are turned into products, and the efficiency of resource utilization is significantly improved. In 1997, Schwarz and Steininger [1] proposed to establish the "recycling network." They posited that a single enterprise could not complete the whole recycling process. Ernestl [2] further proposed that the links between enterprises could help to form an industrial community. The ecological industrial park is an industrial system in which a number of enterprises cluster. Connected by the recycling activities, the eco-industrial park can contribute to reducing the consumption of raw material, which protects the natural resources and at the same time cutting the production cost. Such enterprises clustering can increase the social and economic benefits of the whole society [3–6]. Afterwards, Liwarska-Bizukojc et al. [7] systematically discussed the relationship between the ecosphere and the industrial economic circle. And transforming the traditional economic system into an industrial ecological system is an inevitable requirement of sustainable development [8–10].

Based on the above analysis, the purpose of the circular economy is to protect the ecological environment and the water resources. It is necessary to maintain a certain level of enterprise agglomeration in order to effectively realize the interfirm circulation. Thereby, to protect the environment

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and develop economy, China has developed a number of ecological economic zones. From the system dynamics perspective, the ecological economic zone is a complex system including both enterprises and the government. The previous studies are mainly conducted based on the macro perspective. Different from the previous studies, this paper tries to take the microperspective to explore the waste recycling mechanism among enterprises and the interest relationship between enterprises and government. What is more, a systematical view is adopted to take the whole recycling network into account. By taking Poyang Lake ecological economic zone as an example, based on circular economy and regional economy, this paper builds a system dynamics model on Poyang Lake economic system and uses this model to simulate. In doing so, it contributes to formulating governmental policies regarding industrial waste recycling and promoting the formation and operation of the industrial waste recycling network.

2. Literature review

The concept of circular economy was introduced into China in the 1990s. There are two understandings. The narrower one refers to the reuse and recycling of waste, whereas in the broader sense circular economy refers to the "resources-products-renewable resources" circular economic process. And it mainly has two types of modes: the new economic mode of transition and development and the economic mode of circular development [11].

Murray et al. [12] discussed the origins of circular economy and explored the conceptualization of circular economy. According to them, circular economy is an economy that has no negative effect on the environment. According to Chertow [13], industrial symbiosis is a subfield of industrial ecology that engages different industries and involves the exchange of materials, energy, and services. Furthermore, Chertow and Ehrenfeld [14] divided the industrial symbiosis network into four types: the circular economic ecological industrial park mode in China, the Kalundborg mode of self-organizing symbiosis in Denmark, the mode of planned ecological industrial park in United Kingdom, and the mode of national reformed industrial park in Korea. Su et al. [15] pointed out that industrial symbiosis could be run at different scales. It varies from the microlevel of a single plant to the macrolevel of a global network of companies and regional clusters. The circular network is in nature a set of transactions and consists of separate enterprises. It includes product transactions, talent transactions, resource transactions, knowledge transactions, and natural resource transactions [16–18]. Based on it, Qiaozhi et al. [19] discussed the coordination network of industrial symbiosis. Furthermore, by using an input-output approach, Fraccascia et al. [20] discussed the technical exchange efficiency of industrial symbiosis network and developed a method to measure its efficiency. Bellantuono et al. [21] proposed a framework that characterizes the circular network in two dimensions: the organization dimension and the sustainability dimension.

In 1958, American professor Forrester [22] of Massachusetts Institute of Technology established system dynamics. System dynamics is built based on system theory. In addition, it is also involved in the controlling theory, information theory, feedback theory, complexity theory, and nonlinear system theory. It well combines the logical analysis of causal relationship and the controlling theory of information feedback. System dynamics models can well deal with the complex system problems which are multifeedback, nonlinear, high ordered, and varying with time. In particular, it is good at studying the evolutionary rule of complex nonlinear and dynamic system and thereby provides simulation proof for decision-makers [23–25].

Thanks to these characteristics of system dynamics, this paper builds a system dynamics model on Poyang Lake ecological zone. The purpose is to analyze the interplaying relationship among the elements within the zone and to forecast the development tendency. In doing so, it tries to provide proof for the design of industrial policies of circular economy and references for the operation of industrial waste recycling network.

3. Model construction

Based on survey, we find in the Poyang Lake ecological economic zone the representative enterprise is Jiangxi Xinghuo Organic Silicone Plant. The waste Jiangxi Xinghuo Organic Silicone Plant produced are mainly high-boiling residues, low-boiling residues, and azeotrope. High-boiling residues and azeotrope are the raw materials of the downstream enterprises. And the upstream and downstream enterprises form a vertical interest relationship. However, due to the barriers of technology, there are not many downstream enterprises in the zone. It has not formed full competition relationship among these downstream enterprises. Hence, in this paper we have not considered the horizontal relationship.

Jiangxi Xinghuo Organic Silicone Plant is the leading enterprise in the park and is also the engine of the system. The profit of the enterprises and the pollution of the park are the restriction factors of the system. The supporting variables include the profits of enterprises, the scale of enterprises, the profits of recycling enterprises, the income of industrial parks, and the total amount of pollution in the industrial park. Therefore, in this paper there are five pairs of level variables and rate variables: {[profit of organosilicon enterprise (10,000 Yuan) L1(t), annual changes of profit of organosilicon enterprise (10,000 Yuan per year) R1(t)], [production scale of organosilicon enterprise (10,000 ton) L2(t), changes of production scale of organosilicon enterprise (10,000 ton per year) R2(t)], [profit of related recycling enterprise (10,000 Yuan) L3(t), annual changes of profit of related recycling enterprise (10,000 Yuan per year) R3(t)], [revenues of industrial park (10,000 Yuan) L4(t), changes of the revenues of industrial park (10,000 Yuan per year) R4(t)], [total amount of pollution of industrial park (10,000 ton) L5(t), changes of pollution of industrial park (10,000 ton per year) R5(t)]}.

There are five branches of the rate variable fundamental in-tree model of China Poyang Lake ecological economic zone (Figs. 1–5).

In the first branch, the profit of organosilicon enterprise is related with the price of the product, the production scale, the tax, the pollutant drainage fee, and the profit of waste processing. Enterprises hope that the bigger the profit the better. However, its profit is restricted by its production scale and market price. The equations of the first branch are as follows:

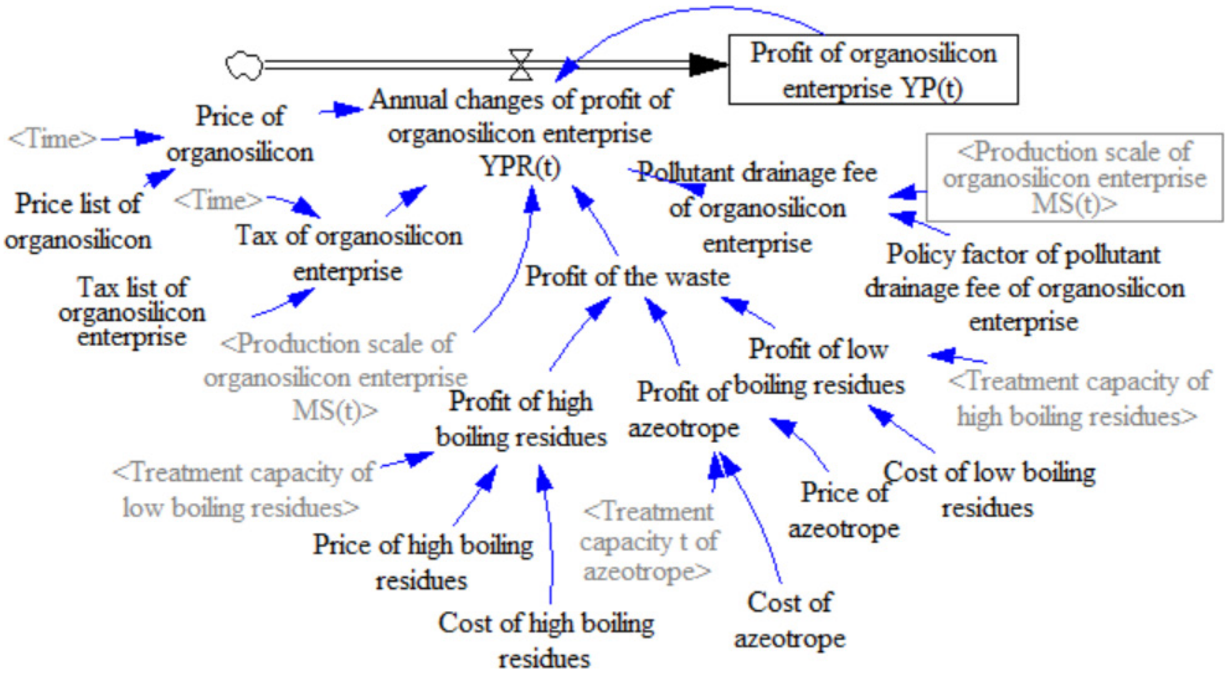

Fig. 1. Profit of organic silicon enterprise in-tree branch.

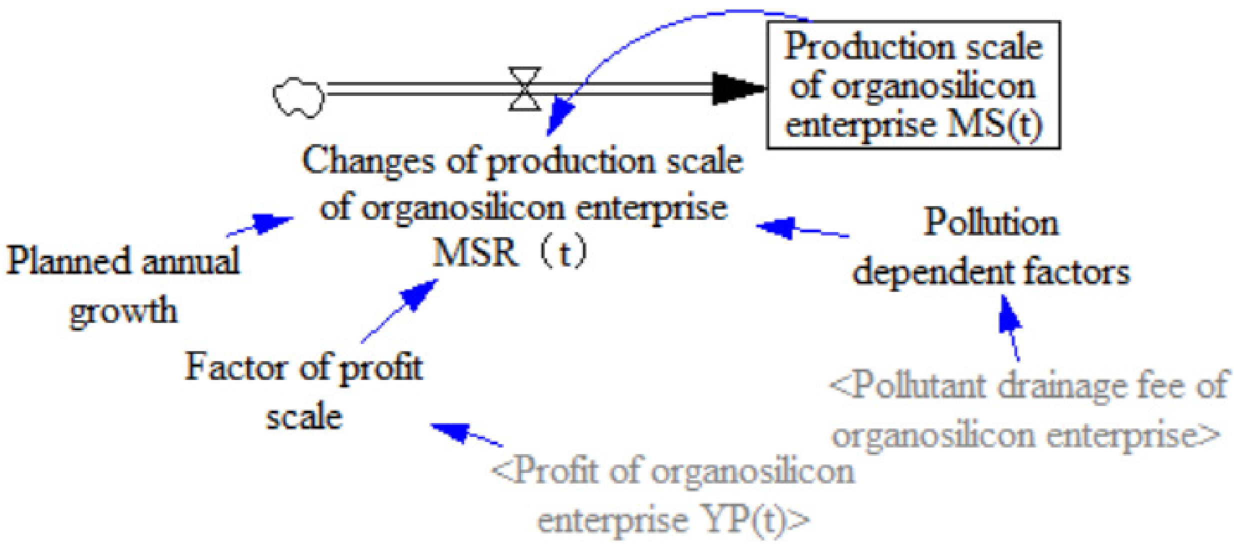

Fig. 2. Scale of organic silicon enterprise in-tree branch.

$$\begin{aligned} \mathrm{YPR}(t) &= \frac{\mathrm{dYP}(t)}{\mathrm{d}t} \\ &= \text{"production scale of organosilicon enterprise MS}(t)\text{"} \\ &\quad *\text{price of organosilicon enterprise} \\ &\quad -\text{"profit of organosilicon enterprise YP}(t)\text{"} \\ &\quad -\text{pollutant drainage fee of organosilicon enterprise} \\ &\quad -\text{tax of organosilicon enterprise} + \text{profit of the waste} \end{aligned} \tag{1}$$

In the second branch, the production scale of organosilicon enterprise is related with planned annual growth, factor of profit scale, and pollution dependent factors. The equations of the second branch are as follows:

$$\begin{aligned} \mathrm{MSR}(t) &= \frac{\mathrm{dMS}(t)}{\mathrm{d}t} \\ &= \text{planned annual growth} * \text{factor of profit scale} \\ &\quad *\text{pollution dependent factors} \\ &\quad -\text{"production scale of organosilicon enterprise MS}(t)\text{"} \end{aligned} \tag{2}$$

In the third branch, the profit of related recycling enterprise is related with the tax of related recycling enterprise, the pollutant drainage fee of related recycling enterprise, the profit of high-boiling residues, and profit of azeotrope. The current processing of low-boiling residues is to burn them and then bury them. There is no recycling enterprise participating in it. The equations of the third branch are as follows:

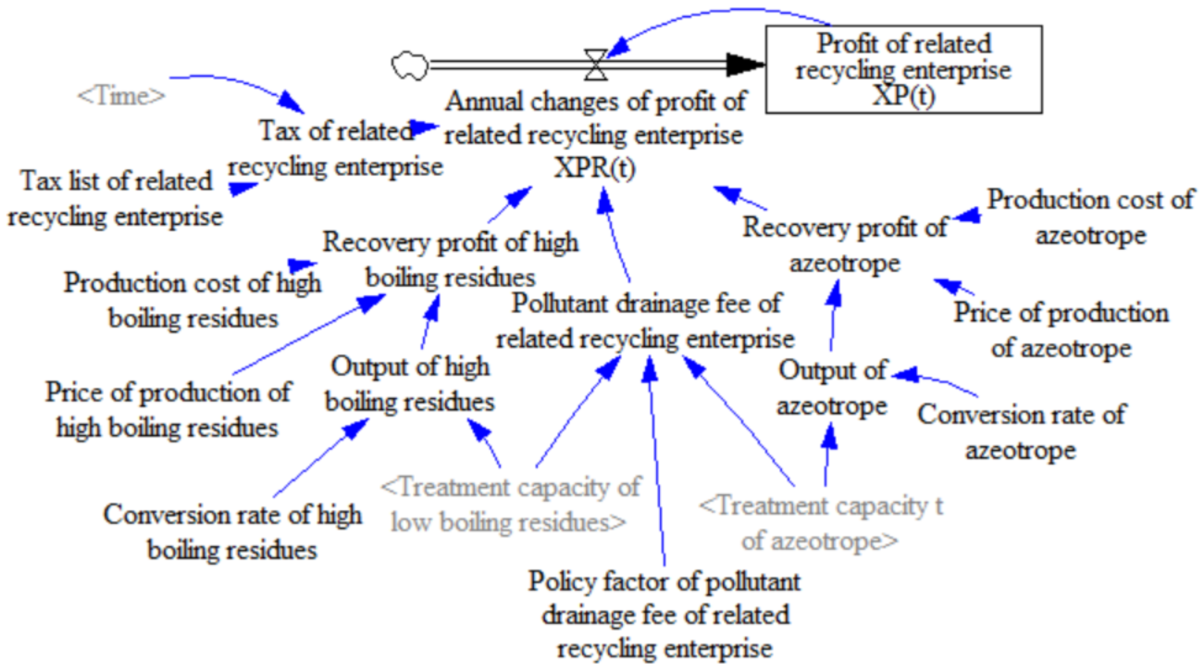

Fig. 3. Profit of recycling enterprise in-tree branch.

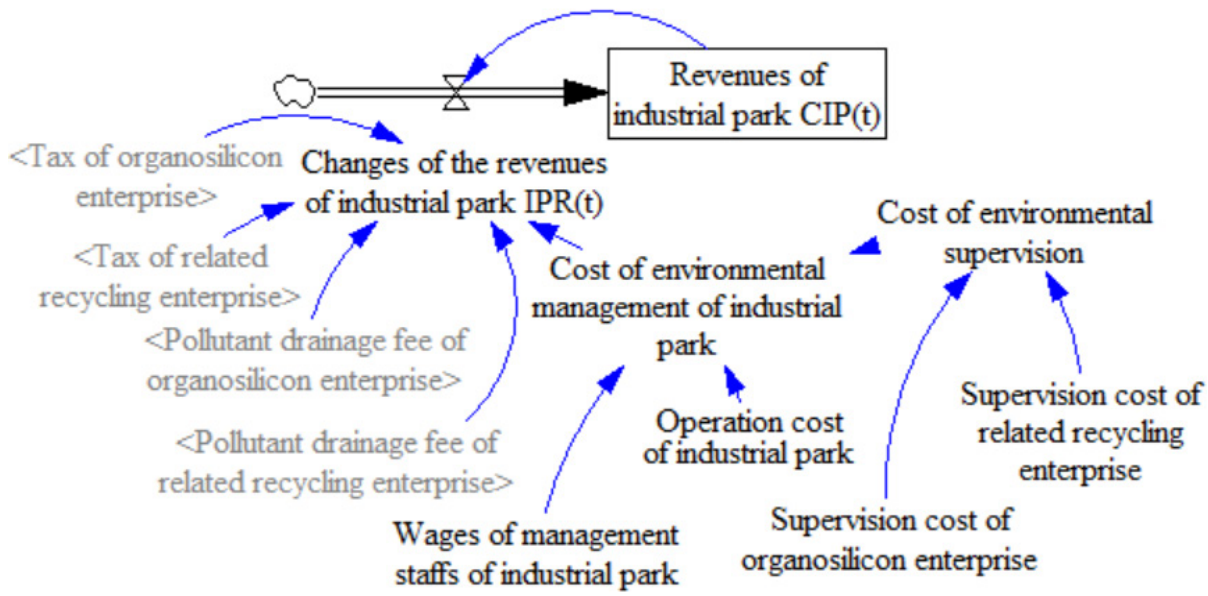

Fig. 4. Revenues of industrial park in-tree branch.

$$\begin{aligned}\mathrm{XPR}(t) &= \frac{\mathrm{dXP}(t)}{\mathrm{d}t}\\ &= \text{profit of high - boiling residues + profit of azeotrope}\\ &-\text{"profit of related recycling enterprise XP}(t)\text{"}\\ &-\text{tax of related recycling enterprise}\\ &-\text{pollutant drainage fee of related recycling enterprise}\end{aligned} \tag{3}$$

In the forth branch, the income of the park is related with the tax of organosilicom enterprise, the tax of related recycling enterprise, and management cost of the park. The equations of the forth branch are as follows:

$$\begin{aligned}\mathrm{CIPR}(t) &= \frac{\mathrm{dCIP}(t)}{\mathrm{d}t}\\ &= \text{tax of the organosilicon enterprise}\\ &+\text{tax of the related recycling enterprise}\\ &+\text{pollutant drainage fee of the organosilicon enterprise}\\ &+\text{pollutant drainage fee of the related recycling enterprise}\\ &-\text{management cost of the park environment}\\ &-\text{"income of the park CIP}(t)\text{"}\end{aligned} \tag{4}$$

In the fifth branch, the total amount of pollution of the industrial park is related with the emission and treatment capacity of the high-boiling residues, low-boiling residues, and azeotrope. The equations of the fifth branch are as follows:

$$\begin{aligned}\text{CICR}(t) &= \frac{\text{dCIC}(t)}{\text{d}t}\\ &= \text{emission of low - boiling residues}\\ &-\text{treatment capacity of low - boiling residues}\\ &+\text{emission of azeotrope} - \text{treatment capacity of azeotrope}\\ &+\text{emission of high - boiling residues}\\ &-\text{treatment capacity of high - boiling residues}\\ &+\text{emission of related recycling enterprise}\\ &-\text{"pollution of the park CIC}\ (t)\text{"}\end{aligned} \quad (5)$$

4. Simulation results

The regional boundary of the model system is China Poyang Lake ecological economic zone. The time boundary of the model system is from 2007 to 2020. The main historical data are from 2007 to 2016.

Jiangxi Xinghuo Organic Silicone Plant is the leading enterprise in Poyang Lake ecological economic zone. The downstream recycling enterprises all depend on Xinghuo Plant. If the profit of Xinghuo Plant decreases, their production scale will tend to decrease, and the quantity of the waste will go down too. It may greatly affect the production and operation of the downstream recycling enterprises. Therefore, the profit of Xinghuo Plant is of great importance. As such, this paper first simulates the profit of Jiangxi Xinghuo Organic Silicone Plant. The simulation curve (Fig. 6).

From Fig. 6, we can see the profit of the organosilicon enterprise drops quickly since 2007. In 2016, it reaches the lowest point and then began to rise rapidly. But until 2020, it still cannot get rid of the deficit. Table 1 is the comparison of the simulation data and the real data from 2007 to 2016.

From Table 1, we can see that the simulation data basically match the real data. The minimum value of the errors is 0.1%, whereas the maximum value of the errors is 11.36%. The errors are all almost controlled within 10%. Thus, the results show the data can roughly simulate the profit tendency of organosilicon enterprise and the simulation data have relatively high reliability.

For organosilicon enterprise, production scale is very important. In recent years, the Chinese organosilicon enterprises are vigorously expanding production capacity, hoping to reduce the price and expand the market occupation rate through huge production capacity to dilute the cost. Take Jiangxi Xinghuo Organic Silicone Plant as an example. Its production capacity expanded from 100,000 tons in 2007 to 700,000 tons in 2015. However, at the same time, other organosilicon enterprises also try to expand production capacity as possible. The price of organic silicon decreases greatly, which forces Xinghuo Organic Silicone Plant to cut down its plan. Until 2015, its production capacity reached 500,000 tons a year, which is the number one in Asia and the third in the world. Despite the huge production capacity, the operating rate of Xinghuo Organic Silicone Plant is not high. Fig. 7 shows the simulation of the production scale of Xinghuo Organic Silicone Plant.

From Fig. 7, we can see the production scale of Xinghuo Organic Silicone Plant increased quickly before 2011. However, after 2011, it has not run at full capacity. From 2011 to 2013, its output drops sharply. After 2013, it began to rebound. But the depressed price has hindered the rise in production. Take the year of 2015 as an example. In 2015, the production capacity of Xinghuo Organic Silicone Plant is 500 tons. However, the output is far from that figure. Due to the rebound of output, the price continues to slump, which leads to great loss. Table 2 is the comparison of the simulation data and the real data from 2007 to 2016.

From Table 2, we can see that the simulation data match the real data. The minimum value of the errors is 0.0%, whereas the maximum value of the errors is 11.11%. The errors are basically controlled within 10%. Hence, the results show the data can roughly simulate the production scale tendency of organosilicon enterprise and the simulation data have relatively high reliability.

During field investigation, we know there was no special support policy for the recycling enterprises. It runs totally

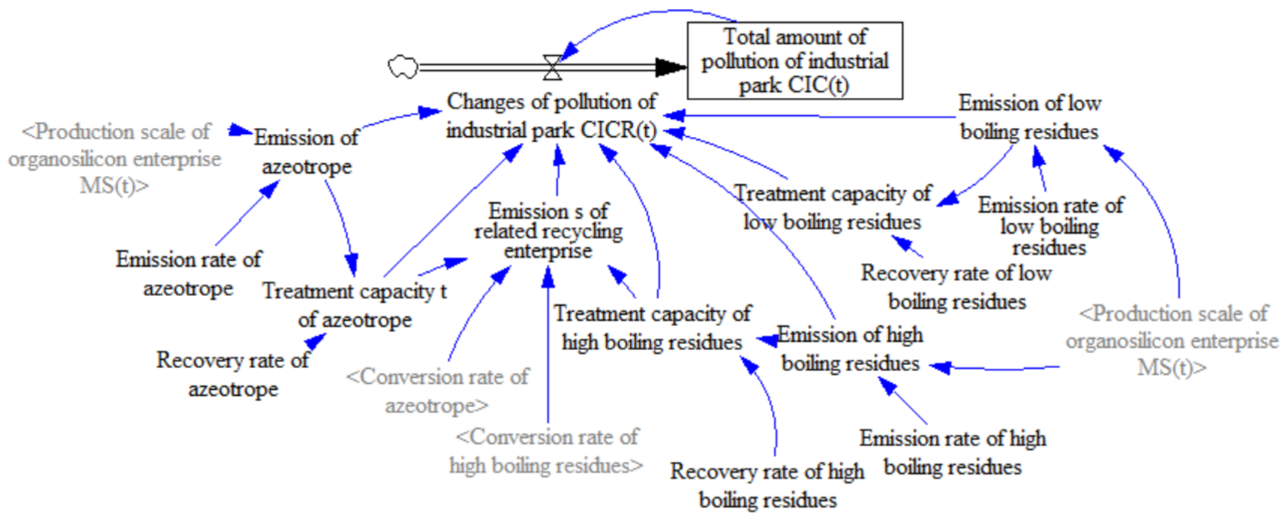

Fig. 5. Total amount of pollution of industrial park in-tree branch.

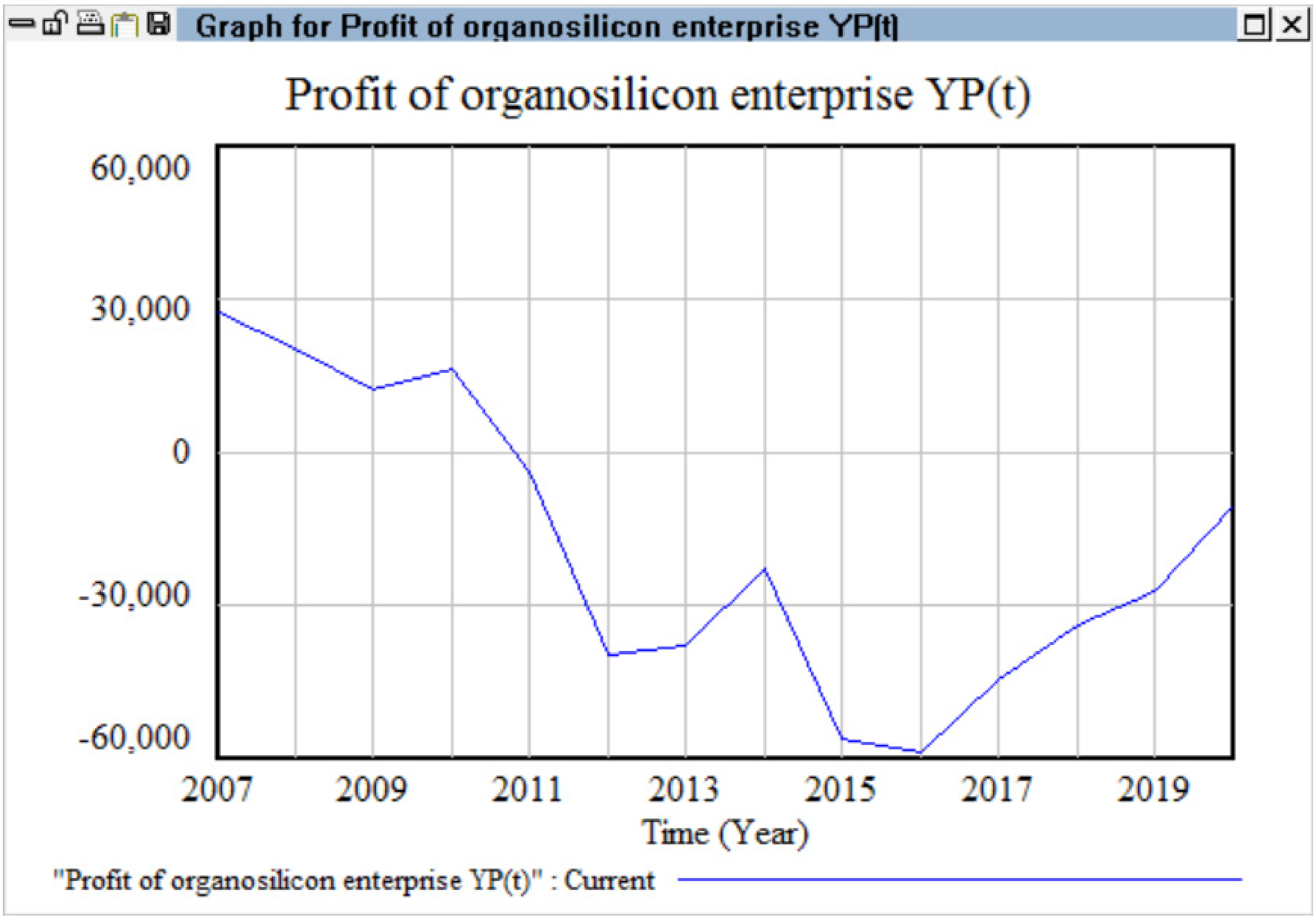

Fig. 6. Simulation of the profit of organosilicon enterprise.

Table 1
Comparison of the simulation data and the real data of the profit of organosilicon enterprise (10,000 Yuan)

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Real value	27,292	18,047	11,054	17,130	–4,383	–43,143	–34,979	–22,863	–63,368	–60,148
Simulation value	27,292	20,011	12,012	16,112	–3,998	–39,895	–38,120	–22,886	–56,170	–58,720
Deviation	0.00%	–10.88%	–8.67%	5.94%	–8.78%	–7.53%	–8.98%	–0.10%	–11.36%	–2.37%

based on the market mechanism. Therefore, if the downstream recycling enterprises do not have enough profits, the relationship cannot last long. The exit of the recycling enterprises may make the circular economic demonstration area not worth its name. Therefore, the profit of the recycling enterprises is the key of the whole circular economic demonstration area. Fig. 8 is the simulation of the profit of the recycling enterprises.

From the figure, we can see that the wastes are mainly high-boiling residues and azeotrope. Low-boiling residues are burnt by the organosilicon enterprise. Influenced by the international market environment, the price of organic silicon is keeping low. At the same time, the price of the downstream waste continues to decline since 2011. Take the high-boiling residues as example. The profit per unit of high-boiling residues dropped from 5,000 Yuan per ton in 2010 to 2,000 Yuan per ton in 2011, which affected the whole profit of the recycling enterprises. However, because the production scale of the downstream enterprises continues to expand and the output is greatly increased, the profit of the recycling enterprises have not slumped a lot. And after 2012, there is a slow recovery. In future, with the increase of the output of the organosilicon enterprises, the profit of the recycling enterprises will increase correspondingly. Table 3 shows the comparison of the simulation data and the real data from 2007 to 2016.

From Table 3, we can see that the simulation data basically match the real data. The minimum value of the errors is 0.86%, whereas the maximum value of the errors is 5.58 %. The errors are basically controlled within 5%. Hence, the results show the data can roughly simulate the profit tendency of the recycling enterprises and the simulation data have relatively high reliability.

We define the income of the park as the sum of the tax of the organosilicon enterprise, the pollutant drainage fee of the organosilicon enterprise, the tax of the recycling enterprise, and the pollutant drainage fee of the recycling enterprise

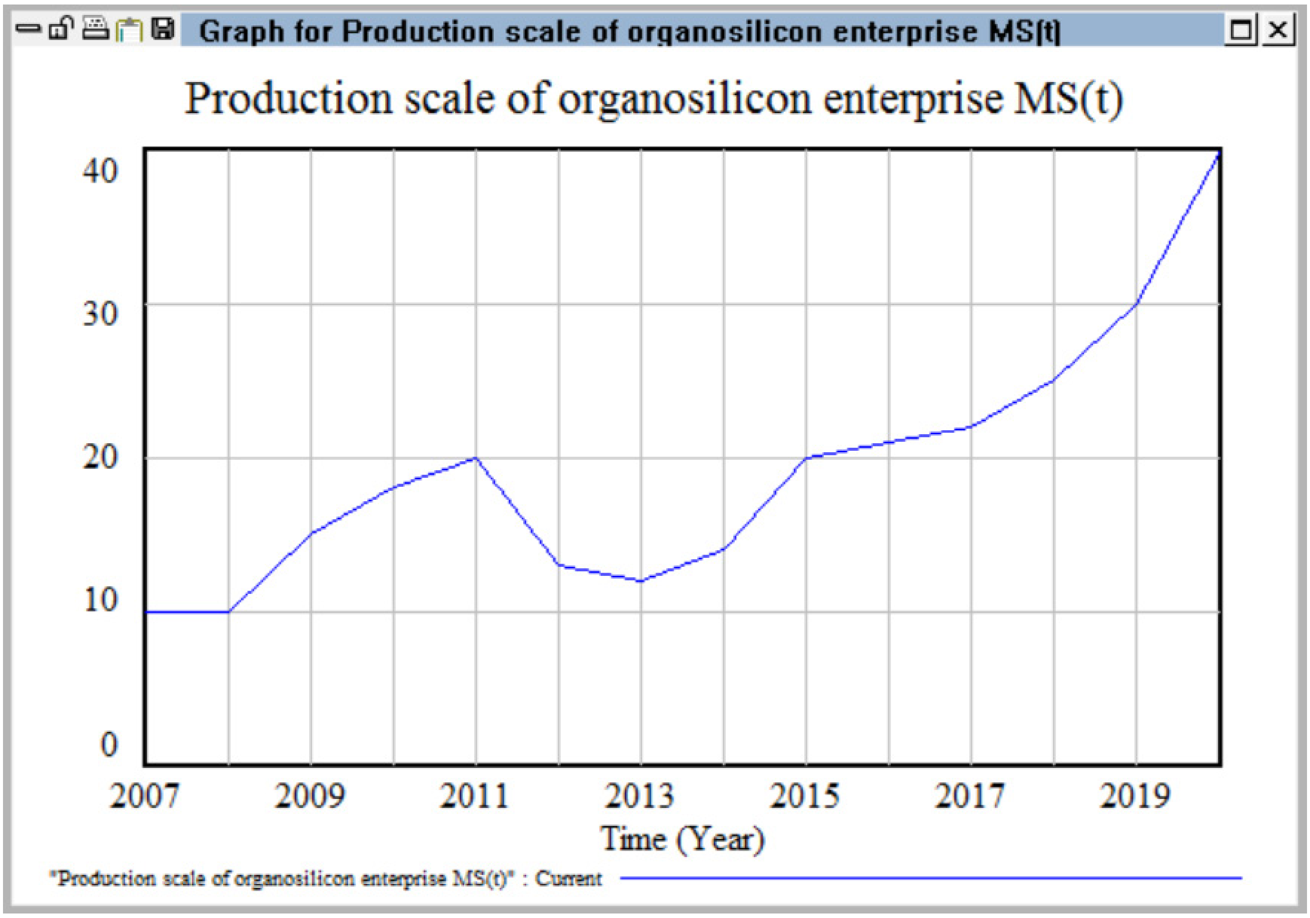

Fig. 7. Simulation of the production scale of organosilicon enterprise.

Table 2
Comparison of the simulation data and the real data of the production scale of organosilicon enterprise (10,000 ton)

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Real value	10	10	16	20	20	13	13	15	18	20
Simulation value	10	10	15	18	20	13	12	14	20	21
Deviation	0.00%	0.00%	6.25%	10.00%	0.00%	0.00%	7.69%	6.67%	–11.11%	–5%

to subtract the management cost of the park. The tax here includes the national tax, the local tax, and the corporate income tax. The pollutant drainage fee of the enterprises is charged according to the management measures of collection and use of sewage charges and funds in Jiangxi. Fig. 9 is the simulation of the income of the park.

From the figure, we can see that the income of the park between 2007 and 2008 reached the high point. From 2009, the income of the park dropped sharply and reached the bottom by 2012. Then from 2013, it started to show the tendency of slow recovery. The main reason is that since 2010, the profit of the organosilicon enterprises has started to fall year by year. Although the profit of the recycling enterprises has not been affected much, due to the fact that the leading enterprise Xinghuo Organic Silicone Plant is a big profit and tax in the region, the decrease of the tax of Xinghuo Organic Silicone Plant still leads to the drop of the income of the park. The simulation results show that after 2016, the income of the park continues to slow down. Until 2018, it will recover slowly. And this is benefited from the substantially increase of the profit of the recycling enterprises. Table 4 shows the comparison of the simulation data and the real data from 2007 to 2016.

From Table 4, we can see that the simulation data basically match the real data. The minimum value of the errors is 0.79%, whereas the maximum value of the errors is 8%. The errors are basically controlled within 7%. Hence, the results show the data can roughly simulate the income tendency of the park and the simulation data have relatively high reliability.

This paper mainly considers the relationship of waste emission and waste disposal. The pollution index of this paper is different from the restrictive index of the National Assessment on Energy Saving and Emission Reduction. The restrictive index of the National Assessment on Energy Saving and Emission Reduction is aiming at the result of the

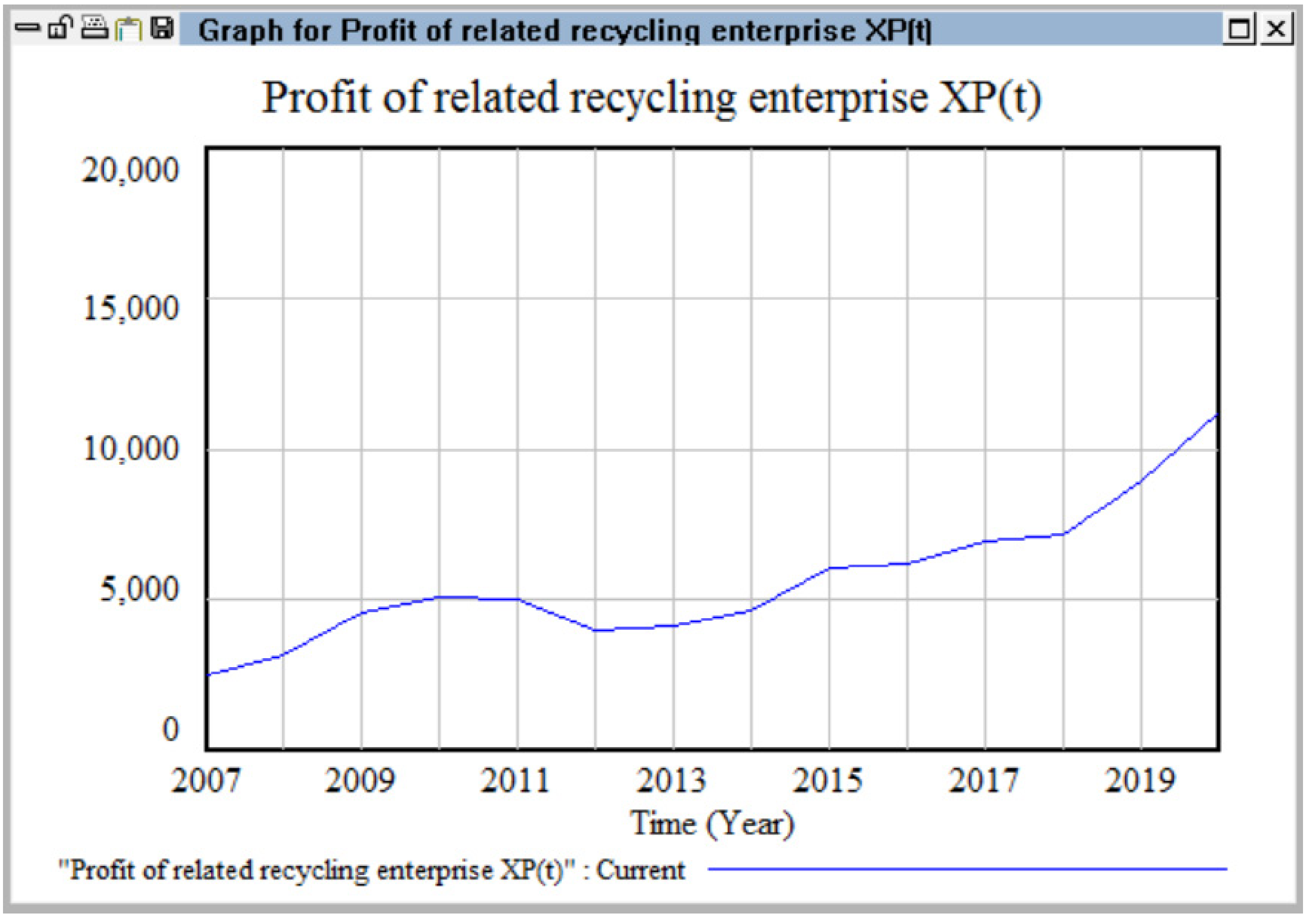

Fig. 8. Simulation of the profit of related recycling enterprise.

Table 3
Comparison of the simulation data and the real data of the profit of related recycling enterprise (10,000 Yuan)

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Real value	2,500	3,300	4,550	4,900	4,600	4,080	4,100	4,400	5,700	5,950
Simulation value	2,500	3,133	4,589	5,091	5,021	3,978	4,135	4,634	6,018	6,214
Deviation	0.00%	5.06%	–0.86%	–3.90%	–9.15%	2.50%	–0.85%	–5.32%	–5.58%	–4.44%

environment pollution, whereas the pollution index of this paper is aiming at the source of the environment pollution. Fig. 10 is the simulation of the total amount of pollution of industrial park.

From Fig. 10, we can see that the pollution of the park reduces quickly in 2008. And this is mainly because after the park was established in 2007, the park has introduced Cabot and Runhong recycling enterprises, which reduced the pollution of the park a lot. From 2009 to 2011, the pollution of the park has picked up. The reason is that Xinghuo Organic Silicone Plant has largely increased its output. Meanwhile, due to the restriction of the production capacity, the recycling enterprises such as Cabot cannot completely process the waste produced by Xinghuo Organic Silicone Plant. Then after 2011, the pollution of the park reduced a lot. There are mainly two reasons. First, influenced by the international environment, the production of Xinghuo Organic Silicone Plant decreased rapidly, which leads to the reduction of the emission of the waste; second, with the large expansion of the production capacity of the recycling enterprises, they can completely digest all the waste produced by Xinghuo Organic Silicone Plant. Take Cabot as example. In 2007, its production capacity is 5,000 tons per year. In 2013, it expanded to 15,000 tons a year. After 2015, the pollution of the park shows a slow growth trend. And this is the result of the expansion of the production capacity of Xinghuo Organic Silicone Plant. Table 5 is the comparison of the simulation data and the real data between 2007 and 2016.

From Table 5, we can see that the simulation data basically match the real data. The minimum value of the errors is 0.16%, whereas the maximum value of the errors is 9.69%. The errors are basically controlled within 8%. Hence, the results show the data can roughly simulate the pollution tendency of the park and the simulation data have relatively high reliability.

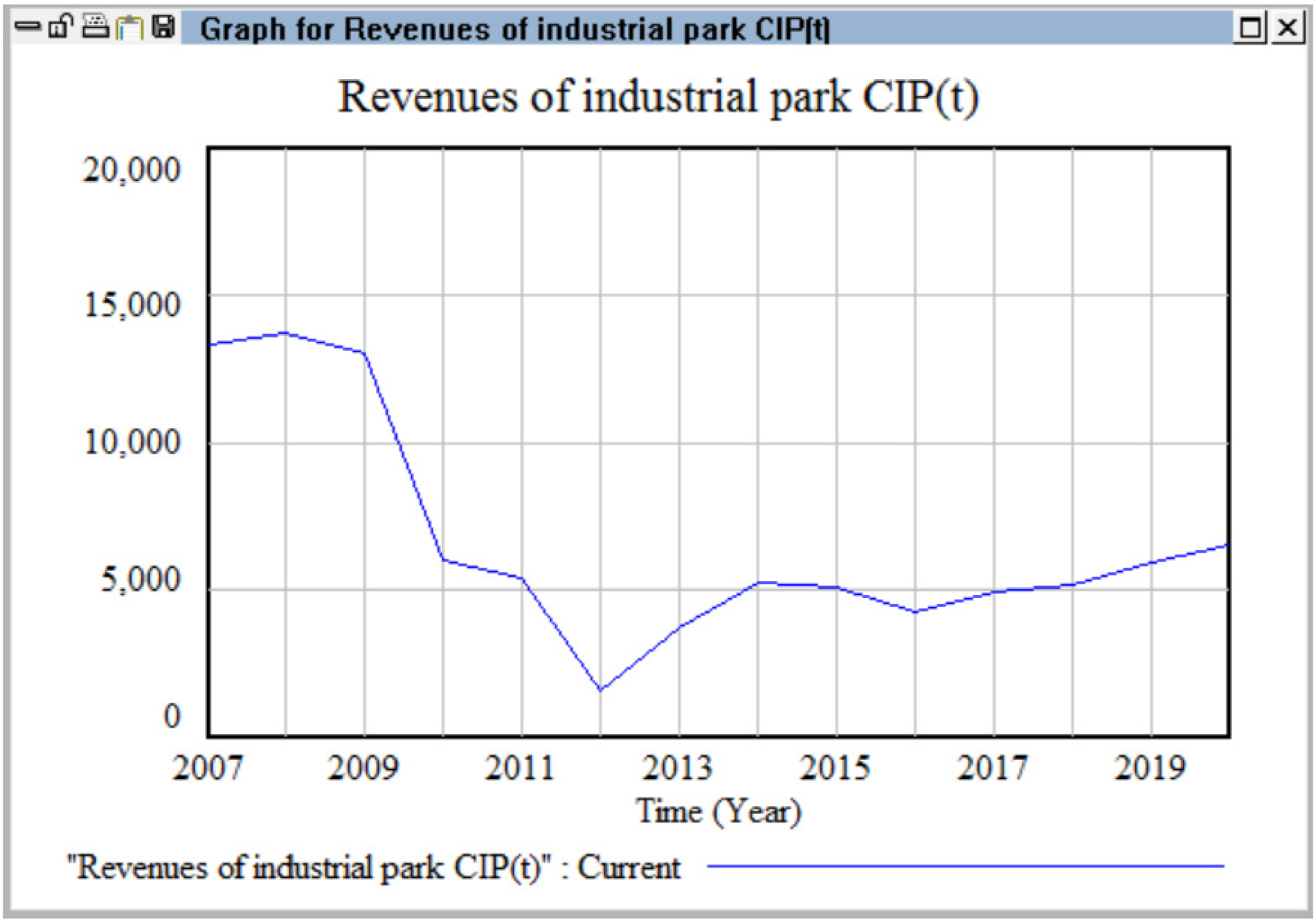

Fig. 9. Simulation of the revenues of industrial park.

Table 4
Comparison of the simulation data and the real data of the revenues of industrial park (10,000 Yuan)

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Real value	13,356	13,387	12,934	6,266	5,625	1,437	3,975	5,546	4,717	4,537
Simulation value	13,356	13,689	13,036	6,012	5,379	1,531	3,692	5,209	5,094	4,214
Deviation	0.00%	–2.26%	–0.79%	4.06%	4.37%	–6.53%	7.13%	6.08%	–8.00%	7.12%

5. Discussions

In the system dynamics analysis, we find the influence of governmental supervision on the waste emission is not very significant. The main reasons are as follows: first, the pollutant drainage fee charged by the government is too low, which cannot exercise actual deterrence on the core enterprise of the park. Each year, the pollutant drainage fee government charged Xinghuo Organic Silicone Plant is about 3 million Yuan. However, the profit or loss of Xinghuo Organic Silicone Plant is 100 million Yuan, and its output value is even more than a billion Yuan. So, the pollutant drainage fee cannot deter the enterprise at all. Second, since 2007, the price of the organosilicon has been high, and the recycling enterprises are keeping making profits. Without the governmental supervision, the enterprises are operating at their maximum capacity. In the investigation, we also find these enterprises are actively introducing new technologies and improving the conversion rate of the waste to realize higher profits. Although currently the market mechanism works well, it is hard to predict the changes of the market. If the market does not work, it needs the joint efforts of the government and the enterprises to further improve the allocation efficiency of the resources and realize the triple wins of the upstream enterprises, the downstream enterprises, and the local government. By doing so, the goal of sustainable development is achievable.

6. Conclusion

Based on investigation of Poyang Lake ecological economic zone and the relationship between member enterprises in the park, this paper discusses the causal relationship of elements in the park and builds a system dynamics model. Through the feedback loop, it qualitatively describes

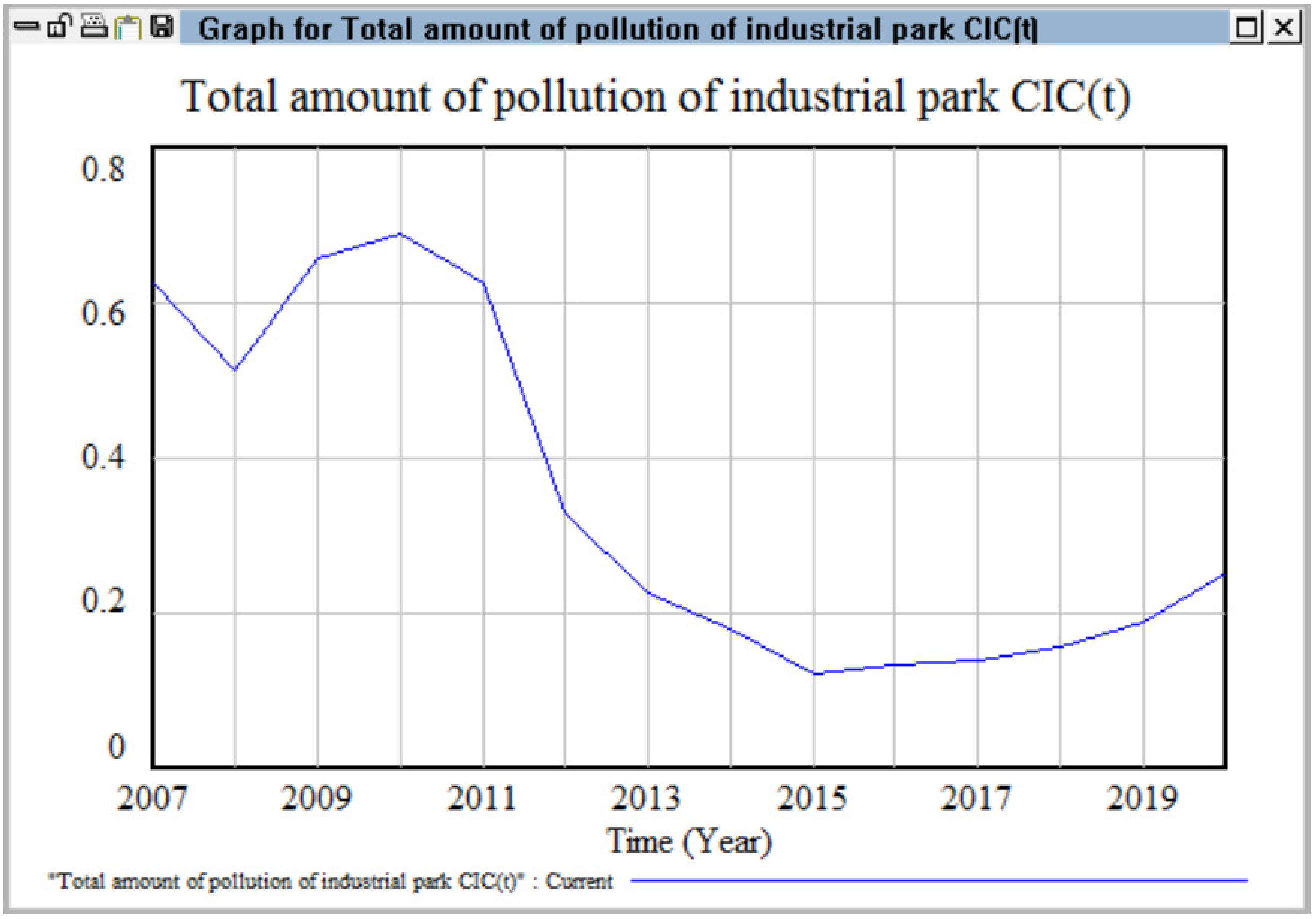

Fig. 10. Simulation of the pollution of industrial park.

Table 5
Comparison of the simulation data and the real data of the pollution of industrial park (10,000 ton)

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Real value	0.6250	0.5000	0.7000	0.7500	0.6250	0.3250	0.2438	0.1875	0.1125	0.1197
Simulation value	0.625	0.511	0.657	0.689	0.624	0.328	0.225	0.179	0.121	0.1313
Deviation	0.00%	–2.20%	6.14%	8.13%	0.16%	–0.92%	7.69%	4.53%	–7.56%	9.69%

the interplaying relationship among variables in the system and constructs five pairs of level and rate variables. Then it uses the computer to simulate the evolutionary results of the system. The simulation results match the historical data well and it can simulate the development tendency of the park, which provides a new analysis angle and platform for studying the industrial waste recycling network.

This paper takes the Poyang Lake ecological economic zone as study object. But the Poyang Lake ecological economic zone has a wide area and many enterprises and has formed a number of industrial parks. Due to the limitations of time and funds, this paper only chooses an industrial waste recycling network in which Xinghuo Organic Silicone Plant is the leading enterprise. Although this network can well represent the development of circular economy in Poyang Lake ecological economic zone, with the development vision, this zone is now actively conducting fundamental changes to adapt to the national macro strategy. Besides, the Poyang Lake ecological economic zone has introduced 10 strategic emerging industries, and this article only discusses one of them. Therefore, the representativeness of this paper is slightly insufficient.

Acknowledgments

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