Analysis of Emergy Flow among Enterprises in Eco-Industrial Park

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Abstract: Firstly, the mode of material and energy flow among enterprises is analysed, and then the effectiveness of the system is studied. The effective scope of developing circular economy in eco-industrial parks increases with the increase of social cost input, and with the improvement of cleaner production technology and advanced management technology in the parks.

1. Introduction

Industrial Eco-Park was officially proposed by Indig Institute of Development in 1992[1]. Research Triangle Institute defines an eco-industrial park as an enterprise biological community composed of manufacturing and service industries. It achieves the optimization and coordinated development of economic development and ecological environment through the cooperation and management of environment and resources, including basic elements such as energy, water resources and raw materials. Finally, it enables the enterprise community to seek a much larger group benefit than the sum of individual benefits that can be achieved by optimizing individual performance of a single company [2].

Cote and Hall put forward another concept: Eco-Industrial Park is an industrial system that preserves natural and economic resources, reduces production, material, energy, insurance and processing costs and debts, improves operational efficiency and quality, improves workers' health and public image, and provides people with opportunities to benefit from the use and sale of waste [3].

Robert A. Froseh, the founder of industrial ecology, and Nicolas Gallopoulos put forward the concept of industrial ecological park through preliminary study of industrial ecology theory. An eco-industrial park can completely circulate like a biological ecosystem. Plants absorb nutrients, synthesize branches and leaves for herbivores to enjoy. The herbivores themselves are predated by predators, and their excreta and debris become food for other organisms. [4] [5].

The Presidential Commission for Sustainable Development of the United States has proposed two implications of eco-industrial parks: (1) Industrial communities that cooperate with each other and with local communities for the efficient sharing of resources (information, materials, water, energy, infrastructure and natural settlements), which lead to the improvement of economic and environmental quality and the fair increase of human resources used by industries and local communities. (2) Planned industrial systems for material and energy exchange seek to minimize energy and raw material consumption and waste generation, and strive to establish sustainable economic, ecological and social relationships. Eco-industrial parks are fully integrated with regional transformation and industrial restructuring to promote large-scale, scientific and technological enterprises, high efficiency and low pollution in the parks, gradually realize the core of leading industries, ecological coupling and resource sharing among different industries and natural ecosystems, and multi-level utilization of material and energy. There are various by-products and wastes exchange, energy and material cascade utilization, infrastructure sharing and perfect information exchange system in the EIP. The goal is to increase the overall value of high-quality resources in a region [6]. Eco-industrial parks recombine the elements of industrial productivity and have new breakthroughs and innovations in the organizational forms of industrial production, to optimize the allocation of environmental resources in the parks, which is conducive to the development of productive forces and become the commanding heights of the development of industrial productivity [7]

2. Emergy Flow among Enterprises

2.1 Emergy Flow in Industrial Systems

Enterprises in eco-industrial parks simulate natural ecosystems and form symbiotic networks among enterprises through the correct selection of material flow and energy flow. The waste of one enterprise becomes the raw material of another enterprise [8]. The energy resources of heat and water among enterprises can be utilized step by step, forming a closed-circuit cycle in the park, optimizing the material and energy, thus achieving a balance in the region, making the efficient use of internal resources and energy, and minimizing the discharge of external waste. Enterprises in eco-industrial parks form an interdependent industrial ecosystem similar to natural ecosystem process. By establishing industrial metabolic relationship, natural resources can be closed-circuit circulated throughout the production process, industrial pollution can be effectively controlled, environmental problems can be fundamentally solved, enterprise costs can be reduced, and both natural environment and economic benefits can be achieved.

2.2 Effectiveness Analysis among Enterprises

If there are n enterprises or departments in the park, the economic system needs to import u kinds of primary raw materials and “V” kinds of energy, materials and services. The system has a total output of P kinds of products, and produces “Q” kinds of recyclable wastes and “O” kinds of non-recyclable wastes. W kinds of energy, materials and services are imported in the process of recyclable wastes treatment. The vectors in the economic system represent the following meanings:

$X_{nu}=\begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1u} \\ x_{21} & x_{22} & \cdots & x_{2u} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nu} \end{bmatrix}^{-1}$ Input Matrix Representing *n*th Enterprise Primitive Resources; $X_{nv}=\begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1v} \\ x_{21} & x_{22} & \cdots & x_{2v} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nv} \end{bmatrix}^{-1}$, $X_{nw}=\begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1w} \\ x_{21} & x_{22} & \cdots & x_{2w} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nw} \end{bmatrix}^{-1}$, represents the input matrices of energy, material and service in the process of production and waste disposal in the nth enterprise respectively.

$T_{a,\ np}=\begin{bmatrix} t_{a,11} & t_{a,12} & \cdots & t_{a,1p} \\ t_{a,21} & t_{a,22} & \cdots & t_{a,2p} \\ \vdots & \vdots & \ddots & \vdots \\ t_{a,n1} & t_{a,n2} & \cdots & t_{a,np} \end{bmatrix}^{-1}$, $T_{b,\ np}=\begin{bmatrix} t_{b,11} & t_{b,12} & \cdots & t_{b,1p} \\ t_{b,21} & t_{b,22} & \cdots & t_{b,2p} \\ \vdots & \vdots & \ddots & \vdots \\ t_{b,n1} & t_{b,n2} & \cdots & t_{b,np} \end{bmatrix}^{-1}$, represent the output matrix of the two production modes of the *n*th enterprise respectively.

$S_{no}=\begin{bmatrix} s_{11} & s_{12} & \cdots & s_{1o} \\ s_{21} & s_{22} & \cdots & s_{2o} \\ \vdots & \vdots & \ddots & \vdots \\ s_{n1} & s_{n2} & \cdots & s_{no} \end{bmatrix}^{-1}$ is the waste matrix of the *n*th enterprise. $S_{nq}=\begin{bmatrix} s_{11} & s_{12} & \cdots & s_{1q} \\ s_{21} & s_{22} & \cdots & s_{2q} \\ \vdots & \vdots & \ddots & \vdots \\ s_{n1} & s_{n2} & \cdots & s_{nq} \end{bmatrix}^{-1}$ is the *n*th enterprise in the system to produce recyclable waste matrix. The emergy conversion matrix of the initial input material is R_{nu}, and r_{nu} represents the emergy transformity of the raw material of the *n*th enterprise.

$$R_{nu}=\begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1u} \\ r_{21} & r_{22} & \cdots & r_{2u} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nu} \end{bmatrix}$$

In the production process, the emergy conversion matrix of input energy, material and service is $F_{i,\ nv}$, $f_{i,\ nv}$,which represents the emergy conversion rate of the V energy, material and service of the *n*th enterprise.

$$F_{i,\ nv}=\begin{bmatrix} f_{i,11} & f_{i,12} & \cdots & f_{i,nv} \\ f_{i,21} & f_{i,22} & \cdots & f_{i,nv} \\ \vdots & \vdots & \ddots & \vdots \\ f_{i,n1} & f_{i,n2} & \cdots & f_{i,nv} \end{bmatrix}$$

In the process of waste disposal, the energy conversion rate matrix of energy, material and service input is $F_{w,\ nt}$, $f_{w,\ nt}$, represents the energy conversion rate of energy, material and service of the *n*th enterprise.

$$F_{w,\ nt}=\begin{bmatrix} f_{w,11} & f_{w,12} & \cdots & f_{w,nt} \\ f_{w,21} & f_{w,22} & \cdots & f_{w,nt} \\ \vdots & \vdots & \ddots & \vdots \\ f_{w,n1} & f_{w,n2} & \cdots & f_{w,nt} \end{bmatrix}$$

The emergy conversion matrix of the output products of the two modes in the system is Y_{np}, y_{np} represents the emergy conversion rate of the *P* product of the *n*th enterprise.

$$Y_{np}=\begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1p} \\ y_{21} & y_{22} & \cdots & y_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ y_{n1} & y_{n2} & \cdots & y_{np} \end{bmatrix}$$

The energy conversion matrix of recyclable waste in the system is W_{nq}, which represents the energy conversion rate of the Q product of the *n*th enterprise.

$$W_{nq}=\begin{bmatrix} w_{11} & w_{12} & \cdots & w_{1q} \\ w_{21} & w_{22} & \cdots & w_{2q} \\ \vdots & \vdots & \ddots & \vdots \\ w_{n1} & w_{n2} & \cdots & w_{nq} \end{bmatrix}$$

The energy conversion matrix of the final waste discharged by the system is W_{no}, which represents the energy conversion rate of waste in the nth enterprise.

$$W_{no}=\begin{bmatrix} w_{11} & w_{12} & \cdots & w_{1o} \\ w_{21} & w_{22} & \cdots & w_{2o} \\ \vdots & \vdots & \ddots & \vdots \\ w_{n1} & w_{n2} & \cdots & w_{no} \end{bmatrix}$$

Under the traditional economic model, waste is directly discharged into the natural environment after treatment. The input of raw materials and energy, materials and services in the park is equal to the output of products and wastes. The emergy equation of industrial production system in the park is as follows:

$$R_{nu}X_{nu}+F_{i,\ nv}\ X_{nv}=Y_{a,\ np}T_{a,\ np}+W_{no}S_{no}+W_{nq}S_{nq} \tag{1}$$

Under the mode of circular economy, the recyclable part of the waste produced in the production process of the product is treated and used as the raw material input for the re-production. The emergy equation of the industrial production system in the park is as follows:

$$R_{nu}X_{nu}+F_{i,n}X_{nv}+W_{nq}S_{nq}+F_{w,nt}X_{nw}=Y_{b,np}T_{b,np}+W_{no}S_{no} \quad (2)$$

According to the actual situation, the supply of waste is absolutely greater than the demand. If the social cost (expressed as energy, material and service energy) consumed in the treatment of recyclable waste is greater than the input energy value of waste which can be used as raw material, the activity is meaningless. At the same time, in the production process, it is also required that the energy value of the final product produced in the production system is the largest and the energy value of the discharged waste is the smallest. In this way, the objective conditions of the above equation are given.

$$\max(Y_{np}T_{np})$$

$$\min(W_{no}S_{no})$$

$$W_{nq}S_{nq}\geq F_{w,nt}X_{nw}$$

By subtracting formula (2) from formula (1), we can obtain:

$$T_{b,np}=Y_{a,np}T_{a,np}\ Y^{-1}{}_{b,np}+(2W_{nq}S_{nq}+F_{w,nt}\ X_{nw})\ Y^{-1}{}_{b,np} \quad (3)$$

In the equation, $F_{w,nt}$ and X_{nw} are the energy, material and service values invested in the production system of circular economy mode to realize the reuse of waste. If the energy value W_{nq} and S_{nq} of recyclable waste is larger than that of $F_{w,nt}$ and X_{nw} of waste disposal, it shows that adding a small amount of energy, material and service energy input in the production system of circular economy mode will lead to more product output and reduce waste emissions.

From equation 2:

$$T_{b,np}=(R_{nu}X_{nu}+F_{i,n}X_{nv}+W_{nq}S_{nq}+F_{w,nt}X_{nw}\ -W_{no}S_{no})Y^{-1}{}_{b,np} \quad (4)$$

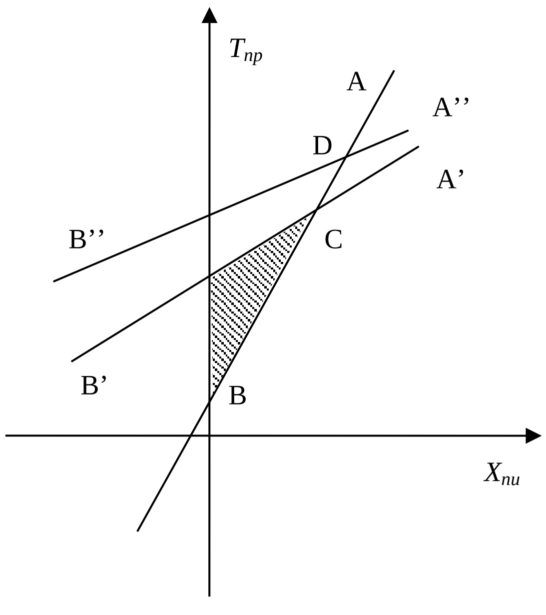

Figure 1. Scope of Effective Operation of Circular Economy System in Eco-Industrial Park

Figure 1 shows the relationship between $T_{b,np}$ and X_{nu}. Linear AB is the production equilibrium of traditional economic model. With the continuous recycling of waste in the production process, the energy conversion rate of product production is increasing. The slope $R_{nu}X_{nu}Y^{-1}{}_{b,np}$ of straight-line AB decrease continuously, while the output of the product increases continuously. The straight-line

AB rotates clockwise and moves to straight line A'B on the upper right. In fact, the quantity and quality of raw materials and recyclable wastes are declining in the course of use, and complete recycling is impossible. Matter has not disappeared; it has only become difficult to obtain in the end. That is matter also obeys entropy reduction [9]. When the output of recyclable waste is zero, the straight line A'B' stops rotating, and the system needs to put new raw materials in order to continue production. The values of each parameter in the model are greater than 0, so the part enclosed by ordinates and straight lines AB and A'B' is the scope of effective operation of circular economy system, as shown in the shadow part.

3. Conclusion

According to the principle of maximizing product output, max ($Y_{np}T_{np}$), the energy output of the circulating system is the largest at the intersection point C of straight-line AB and straight line A'B'. According to the principle of minimum waste discharge, min($W_{no}S_{no}$), with the upgrading and implementation of cleaner production technology in the park, it can theoretically realize the whole material cycle in the park area ($W_{no}S_{no}=0$), and move straight A'B' up to straight A"B', where straight AB and straight A"B" intersect D, the energy output of the system is the largest.

Therefore, the effective scope of developing circular economy in eco-industrial parks increases with the increase of the social cost (energy, material and service) of the parks on the one hand, and with the improvement of cleaner production technology and advanced management technology on the other.

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