Emergy Analysis of Industrial Symbiosis System Efficiency

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Abstract: According to the basic idea of emergy analysis and on the basis of industrial symbiotic emergy analysis, the evaluation index of industrial symbiotic system is put forward: the efficiency of symbiotic emergy. In order to facilitate calculation, the contribution coefficient of energy increment is also proposed.

1. Introduction

Since 1950s, H. T. Odum, a famous American system ecologist, has systematically and thoroughly studied the energetics of ecosystem, and put forward an important emergy theory, which links energy flow, information flow and economic flow [1]. The characteristic basis of energy flow is material, so these functional processes in ecosystem are no longer isolated. In the early 1990s, the emergy theory was introduced into China. Because emergy theory and analysis method are helpful to correctly analyze the value and relationship between human beings and natural environment, resources and social economy, and contribute to sustainable development strategy, it has attracted much attention from the international ecologists, economists and government decision makers.

Through emergy analysis, different kinds, and incomparable energy in ecosystem or eco-economic system can be transformed into the same standard emergy to measure and analyze, and its role and status in the system can be evaluated. A series of comprehensive emergy indicators can be obtained by comprehensive analysis of various ecological flows (energy logistics, currency flow, population flow and information flow) in the system. Ices, quantitative analysis of the structural and functional characteristics of the system and ecological and economic benefits.

The main indicators of emergy analysis are: solar transformity, net emergy yield ratio (NEYR), emergy investment ratio (EIR), emergy amplify ratio (EAR), emergy density (ED), and emergy per capita (EPC), carrying capacity (CC), emergy yield ratio (EYR), environmental loading ratio (ELR), and sustainable development index (ESI) [2].

Bastianoni and Archttini (2000) put forward the concepts of joint emergy conversion rate and weighted average emergy conversion rate, and evaluated the different output of the system [3]. Similarly, Ceglia et al. (2017) proposed to use the comparison between symbiotic replacement ratio and number-average replacement ratio to evaluate the coexistence efficiency between enterprises [4]. If the symbiotic replacement ratio is less than number-average replacement ratio, the efficiency of multi-product system is higher. In this case, if from an energy point of view, obtaining an equal number of products requires less work from the outside ecosystem. On the contrary, single product systems should be optimized to obtain products separately, rather than multi-product systems with lower efficiency. However, because the symbiotic replacement ratio is obtained by mathematical processing for the purpose of analysis and comparison, and is not an objective replacement ratio, in the process of evaluating industrial symbiotic replacement ratio, it is necessary to calculate the number-average replacement ratio, which increases the computational complexity accordingly.

2. Methodology

2.1 Emergy analysis of industrial symbiosis

Industrial symbiosis is an organizational innovation model of modern industrial enterprises which imitates natural ecosystem. It imitates the interaction principle of symbiotic relationship of natural biological population and establishes the symbiotic network structure of producer-consumer-decomposer food chain among enterprises. Symbiosis generally consists of three elements, including symbiotic unit, symbiotic environment and symbiotic mode. Therefore, symbiosis can also refer to the relationship between symbiotic unit and symbiotic mode in a certain symbiotic environment. Whether the symbiotic relationship can be established depends first on the relationship between the properties of the symbiotic units, that is, there must be compatibility of qualitative parameters between the symbiotic units. Compatibility of quality parameters means that the quality parameters on different symbiotic units have some corresponding relationship.

For the convenience of analysis, suppose that any two enterprises A and B in the industrial and commercial system have several quality parameters Z_i and Z_j, and the main quality parameters Z_{mi} and Z_{mj}, respectively. Quantification of quality parameters is carried out by means of emergy analysis, $Z_i=R_iX_i$, $Z_{mj}=R_jX_j$. R_i and R_j denote the energy conversion rate of the principal mass parameters, while X_i and X_j denote the input of the principal mass parameters in the symbiotic system.

The degree of symbiosis of the symbiotic system is not only related to the input of the principal mass parameter, but also to the energy conversion rate of the principal mass parameter.

When the degree of symbiosis is expressed by the principal mass parameter, $\delta_{ij}=\delta^m{}_{ij}$. $\delta^m{}_{ij}$ is the characteristic symbiosis degree of enterprise A and enterprise B. It is the most representative variable to represent the symbiosis characteristics of enterprise A and B.

If $\delta^m{}_{ij}=\delta^m{}_{ji}>0$, enterprise A and enterprise B are symmetrical symbiosis; if $\delta^m{}_{ij}\neq\delta^m{}_{ji}>0$, enterprise A and enterprise B are asymmetrical symbiosis. The characteristic symbiosis degree of $\delta^m{}_{ij}(\delta^m{}_{ji}>0)$ indicates that the cluster is an effective cluster. If one party's characteristic symbiosis degree is $\delta^m{}_{ij}=0$, it means that enterprise A has no influence on enterprise B, and they are in an irrelevant state of concurrence; if $\delta^m{}_{ij}<0$, it means that the main business activities of enterprise A cause substantial damage to enterprise B.

2.2 Symbiotic emergy efficiency

By using the method of emergy analysis, all the relevant data are summarized into a single emergy measure. Based on the cost-benefit analysis method and the symbiosis analysis of the system, the symbiotic emergy benefit rate is defined as the ratio of the increased emergy output of the industrial chain or the industrial symbiotic system after the symbiotic model is adopted to the energy input of the symbiotic system. The index can be used to predict, analyze, assess and evaluate the economic and environmental benefits of industrial symbiosis system and the coexistence efficiency of the system. By using the emergy input-output analysis method, the index can be used to conduct related qualitative and quantitative research. The formula of the efficiency of symbiotic emergy is as follows:

$$SEBR=Y/X \qquad (1)$$

In the formula: SEBR represents the efficiency of symbiotic emergy of industrial symbiotic system; Y represents the increased emergy output of industrial chain or industrial symbiotic system after adopting the symbiotic model; X represents the increased emergy input of the symbiotic system after adopting the symbiotic model. Symbiotic emergy benefit ratio SEBR means the value added of emergy benefit produced by the increment of unit emergy input in the symbiotic system. Accounting for the emergy increase of output includes the emergy increase of output products and the decrease of consumption resources, as well as the emergy increase of waste discharges.

Suppose that an industrial chain or industrial symbiosis system in an eco-industrial park consists of n enterprises/departments. The energy increment of the output of the symbiotic system is Y, which indicates that the energy increment of the whole system after adopting the symbiotic mode, obviously Y includes the cumulative sum of the energy increment of each enterprise/department that constitutes the symbiotic relationship, as compared with the energy increment before the N units did not participate in or establish the symbiotic relationship.

$$Y = \sum_{i=1}^{n} Y_i = Y_1 + Y_2 + \cdots + Y_i + \cdots + Y_{n-1} + Y_n \quad (2)$$

At the same time, for enterprise/department A, it may form a symbiosis with any other enterprise/department in the same symbiotic system. Therefore, the emergy increment Y_i of enterprise/department A is the sum of the emergy increments acquired or shared by enterprise/department A after it coexists with other enterprises/departments. In theory, Y_i can add up to n-1 values. It is assumed that a symbiotic $G_{a\times b}$ is formed between enterprise A and Enterprise B, and the energy increment of the output of the symbiotic system is $Y_{a\times b}$. $Y_{a,b}$ represents the increment of energy generated by enterprise/department A in $Y_{a\times b}$, and Yi can be expressed by formula (3).

$$Y_i = \sum_{j=1}^{n} Y_{a,b} \ (i \neq j) \quad (3)$$

Then, the systemic coexistence benefit Y of the whole industrial symbiosis system can be expressed as formula (4)

$$Y = \sum_{i=1}^{n} Y_i = \sum_{i=1}^{n} \sum_{j=1}^{n} Y_{a,b} \ (i \neq j) \quad (4)$$

In addition, assuming that the contribution coefficient of energy increment of enterprise/department A in Ya×b of $G_{a\times b}$ output is theta ab, and that of corresponding enterprise/department B is theta ba, there are formulas (5), (6) and (7).

$$\theta_{ab} = 1 - \theta_{ba} \quad (5)$$

$$Y_{a,\ b} = \theta_{ab} Y_{a\times b} \quad (6)$$

$$Y_{b,\ a} = \theta_{ba} Y_{a\times b} = (1-\theta_{ab}) Y_{a\times b} \quad (7)$$

It can be seen from the above that contribution coefficient refers to the distribution of energy increments generated by the symbiotic relationship among different symbiotic units. For a long-term stable symbiotic organization structure, the contribution coefficient can be calculated by the proportion of the energy increment obtained by the enterprise/department to the total energy increment of the symbiotic organization, and the type or state of the symbiotic relationship can be judged by the contribution coefficient. Whether it is θ_{ab}=1 or 0, and θ_{ab}=0 or 1, it shows that the symbiosis $G_{a\times b}$ between enterprise/department A and enterprise/department B belongs to "preferential benefit symbiosis"; otherwise, it is mutually beneficial symbiosis. In mutualism, if $\theta_{ab}=\theta_{ba}$, the symbiosis $G_{a\times b}$ between enterprise/department A and enterprise/department B is symmetric and mutually beneficial symbiosis; if $\theta_{ab}\neq\theta_{ba}$, the symbiosis $G_{a\times b}$ between enterprise/department A and enterprise/department B is asymmetric and mutually beneficial symbiosis. In fact, whether the symbiotic relationship between Enterprise/department A and Enterprise/department B is symmetrical or asymmetrical symbiotic, there are many symbiotic modes, and the corresponding contribution coefficients θ_{ab} and θ_{ba} are also different.

The emergy X_i of increasing input refers to the total emergy value added by each enterprise/department in the symbiotic system to establish a symbiotic relationship with each other. For example, in order to achieve the recycling of waste under the symbiotic mode, waste recycling, sorting, increased investment in technology and process transformation, the corresponding increase in human resources costs, the new transmission pipeline lines for material symbiotic utilization or energy cascade utilization in the symbiotic system, and so on.

$$X = \sum_{i=1}^{n} X_i = X_1 + X_2 + \cdots + X_i + \cdots + X_{n-1} + X_n \tag{8}$$

In this way, Formula (1) is expressed as Formula (9):

$$SEBR = Y / X = \sum_{i=1}^{n} Y_i / \sum_{i=1}^{n} X_i \tag{9}$$

The calculated efficiency of symbiotic emergy can be used for decision analysis before investment and operation evaluation after establishment of symbiotic enterprises. For the symbiotic enterprises in planning and construction, if the result of prediction analysis is SEBR > 1, the investment in construction can be considered. If SEBR = 1, it shows that the economic and environmental benefits of the scheme have not increased much, and the plan should be further adjusted. If SEBR < 1, it indicates that the construction plan should be abandoned. For established symbiotic enterprises, if the actual effect of operation is SEBR > 1, it shows that the symbiotic relationship is sustainable, and can continue to operate and continuously improve efficiency. If SEBR = 1, at least it's good for the environment. If SEBR < 1, the operation mode of the symbiotic system is failed and must be adjusted and perfected immediately.

3. Case of study

The input-output emergy analysis of the symbiosis system between thermal power plant and cement production enterprise is shown in Table 1.

Table.1. Emergy inputs and outputs of symbiotic systems

Raw material	Unit	input (output)	Transformity (Sej/Unit)	References	Emergy (Sej) 1.00E+18
Coal	g	1.76E+11	1.17E+09	[5]	205
Limestone	g	2.01 E+11	1.00E+09	[7]	201.00
Clay	g	9.44 E+09	1.70E+09	[5]	16.41
Iron ore powder	g	3.84 E+09	8.55E+08	[5]	3.28
Gypsum	g	1.00 E+10	3.29E+09	[8]	32.90
Other minerals	g	7.66 E+09	1.00E+09	[8]	7.66
Fly ash	g	3.51 E+09	1.40E+10	[6]	49.14
Fuel	g	6.74E+09	1.17E+09	[5]	7.89
Natural gas	j	1.52E+14	4.40E+04	[9]	6.73
Electricity	j	9.86E+13	1.59E+05	[5]	15.68
Traffic	t×m	2.19 E+08	1.68 E+11	[6]	36.79
Recovery	$	1.82E+06	8.67E+12	[9]	15.77
Labour services	$	7.53E+06	8.67E+12	[9]	65.29
Cement (annual output)	g	2.31E+11	1.98E+09	[9]	458.54

Obviously, the symbiotic system composed of thermal power plants and cement production enterprises belongs to the asymmetric symbiotic system. The contribution coefficient of thermal power plants is larger, while the influence of cement production enterprises on thermal power plants is relatively small. The data in the table are brought into the formula (9):

$$Y = \sum_{i=1}^{n} Y_i = (458.54 - 380.62) \times (1.00\text{E+18})\text{sej} = 77.92\text{E+18sej}$$

$$X = \sum_{i=1}^{n} X_i = 15.77 + (36.79 - 21.84) \times (1.00\text{E+18})\text{sej} = 30.72\text{E+18sej}$$

$$SEBR = Y / X = \sum_{i=1}^{n} Y_i / \sum_{i=1}^{n} X_i = 2.54$$

Symbiotic emergy efficiency SEBR = 2.54 > 1. Therefore, using the symbiotic model and using fly ash as raw material for cement production from thermal power plants not only saves resources, but also reduces pollution. From the perspective of ecology and economy, it is more conducive to the coordinated development of the ecological environment and human society.

4. Conclusion

The composition of the symbiotic system is analyzed, the symbiotic units, the corresponding symbiotic interfaces and contents of the elements of the symbiotic system are defined, the symbiotic relationship of the symbiotic units of the system is summarized, and the Contribution Coefficients of the symbiotic units are determined. Through the analysis of industrial symbiotic emergy, the efficiency index of industrial symbiotic emergy is designed, i.e. the efficiency of symbiotic emergy (SEBR). In order to obtain the comparative results, the contribution coefficient of emergy increment is also proposed. If SEBR > 1, the symbiotic system is better than the single-yield system. If SEBR < 1, the symbiotic model should not be adopted. The emergy analysis of the symbiotic system composed of thermal power plant and cement production enterprise verifies that the symbiotic emergy benefit rate (SEBR) can effectively analyze the benefit rate of the symbiotic system.

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