Methodological aspects of applying eco-efficiency indicators to industrial symbiosis networks

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ABSTRACT

In this study, we proposed eco-efficiency indicator as an integral parameter for simultaneously quantifying the economic and environmental performance of industrial symbiosis (IS) networks. Based on the World Business Council for Sustainable Development definition of eco-efficiency, the eco-efficiency indicators proposed include one economic indicator, and three generally applicable simplified environmental indicators (raw material consumption, energy consumption, and CO2 emission). Three eco-efficiencies corresponding to three environmental indicators are assessed using seven IS networks that were developed between 2007 and 2012, which are currently operational in Ulsan Eco-Industrial Park (EIP), South Korea. Our results indicate that the eco-efficiency of individual IS networks improved up to 28.7%. Besides, the evolution of seven IS networks comprising 21 companies resulted in an overall eco-efficiency enhancement of about 10%. The proposed eco-efficiency indicators for IS networks can be easily utilized to communicate with decision makers at any level to assist in transforming conventional industrial complexes to EIP. The implications of the study and limitations of the methodology are delineated.

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1. Introduction

Rapid economic growth has resulted in unsustainable patterns of consumption of consumer goods and natural resources, especially in the Asia Pacific region (Chiu and Geng, 2004). To maximize resource efficiency while minimizing pollutant emissions, countries such as China, Taiwan, Korea, and Japan in the Asia Pacific region have recently initiated national eco-industrial park (EIP) demonstration programs (Shi et al., 2010; EPA, 2008; Park et al., 2008; van Berkel et al., 2009). EIPs optimize the use of resources through interactions between companies that exchange waste and by-products, and through integrated resource recovery systems (Lowe and Koenig, 2006). Industrial symbiosis (IS), based on the concept of industrial ecology, has gained prominence for improving the sustainability of industrial regions with both public and private benefits (Bain et al., 2010). According to Chertow et al. (2008), three types of symbiotic transactions can occur: (i) utilizing waste from others as raw material (by-product exchanges), (ii) sharing utilities or access to services such as energy or waste treatment, and (iii) cooperating on issues of common interest such as emergency planning, training, or sustainability planning. Among these symbiotic transactions, bilateral exchanges among firms are among the more conspicuous occurrences, and are referred to as the ‘kernel’ of symbiosis (Chertow, 2007), green twinning, or by-product synergies (Ehrenfeld and Chertow, 2002).

With regard to EIP initiative in South Korea, Ulsan was selected as one of the five demonstration regions (Park et al., 2008). IS networks were existing in Ulsan before 2005, but were unplanned and spontaneous in nature. Starting in 2005, systematic design and development of new networks began through the research and development into business’ framework devised by the Ulsan EIP center (Behera et al., 2012). The IS networks existing in the national industrial complexes in Ulsan before and after the Korean EIP initiative are shown in Fig. 1.

From eco-industrial development (EID) perspective, the development of a framework to evaluate the effectiveness of IS networks is greatly needed, and is broadly facilitated by two approaches, (i) a triple bottom line (TBL) approach and (ii) a life cycle approach (Kurup et al., 2005). Unlike the life cycle approach, effectiveness evaluation of IS networks by the TBL approach is simple and
Fig. 1. Symbioses existing in Ulsan EIP (Dashed-lined and solid-lined boxes refer to companies involved in symbioses before and after EIP initiative, respectively. Numbers within bracket along the arrows indicate the analyzed networks. MWWTF: Municipal wastewater treatment facility; FWTF: Food waste treatment facility; MWLF: Municipal waste landfill facility).
convenient. Through the TBL approach, effectiveness can either be measured in terms of sole indicators such as economic, environmental, and social benefits or by means of integrated indicators such as socio-economic benefits or eco-efficiency. However, eco-efficiency for symbiotic transactions has recently attracted attention since eco-efficiency is one of the key issues and challenges for EID, along with sustainable consumption and production (Chiu et al., 2009).

Eco-efficiency encourages business opportunities and allows companies to become more environmentally responsible and profitable (WBCSD, 1993). In similar perspective, IS brings together companies from diverse business sectors with the aim of improving resource efficiency through the cascaded use of materials, energy and water, sharing assets, logistics, and expertise. Thus, eco-efficiency concept provided by the World Business Council for Sustainable Development (WBCSD) can be adopted to evaluate the performance of IS networks.

There are reports on the eco-efficiency evaluation of particular industries (Kharel and Charmondusit, 2008) or groups of industries in particular industrial complexes (Charmondusit and Keartpakpraek, 2011). However, despite a growing interest in EID activities worldwide, limited tools and techniques are available for evaluating and reporting the performance of IS networks, which can be utilized to communicate with decision makers to adopt as a policy goal.

The overall objective of this research is to present eco-efficiency as a framework to evaluate the performance of IS networks in an EIP. Based on the WBCSD definition of eco-efficiency, three clear, simplified and generally applicable environmental indicators (raw material consumption, energy consumption, and CO2 emissions) are proposed. First, the methodology for eco-efficiency assessment is described and, then applied to the symbiotic transactions in Ulsan EIP to elucidate the same. Second, the implication of this research is discussed in the light of its contributions to eco-efficiency concept and indicators have also been applied to various products and processes (Korhonen and Luptack, 2004; Park et al., 2007; Aoe, 2007; Syyrakou et al., 2006). In addition to products and processes, the eco-efficiency concept and indicators have also been applied to the design of industrial parks by using process re-engineering (Grant, 1997). The eco-efficiency of single industries or groups of industries in particular industrial complexes has also been evaluated, but there exists no universally accepted method to evaluate the performance of IS networks. The EIP depicted in Fig. 2 shows an IS network among three companies. Each company obtains resources from both external sources and other tenants in the EIP. Each company has two types of waste, waste that is discharged outside of the EIP and waste that is exchanged with other companies in the EIP. The waste discharged from Company 1 is equal to the resource for Company 2, which is traded within EIP system boundaries. In this study, the system boundary of IS covers all the companies involved in a single symbiotic transaction.

3. Brief description of industrial symbioses in Ulsan

A brief description of the seven symbiotic transactions (Fig. 1) currently operational in the Ulsan EIP is given below. A detailed description of the symbiotic transactions in Ulsan EIP can be found elsewhere (Behera et al., 2012).

(1) Industrial waste incineration facility supplying steam to a paper mill

Before the development of symbiosis, the heat generated due to the incineration of industrial waste was not utilized for any beneficial purposes. However, steam is presently being generated via this waste heat and is supplied to a nearby paper mill. Steam, in the amount of 23.5 ton/hr, is generated through the incineration of 80 ton/day of industrial waste, of which 12 ton/hr is supplied to the paper mill. Before the development of synergy, the paper mill was using 343.63 lit/hr of B–C oil to generate 10 ton/hr of steam.

(2) Reuse of effluent as a carbon source from a petrochemical company in a municipal wastewater treatment plant

A petrochemical company generates 16.8 ton/day of wastewater containing 1, 4-butanediol of which 15.1 ton/day is supplied to a municipal wastewater treatment plant, to be used as a carbon source for nutrient removal. Prior to the development of this synergy, the municipal wastewater treatment plant was consuming methanol as a carbon source at an average rate of 7.92 ton/day.
16 kgf/cm²) was produced by utilizing the heat generated as a result of incinerating municipal solid waste (300 ton/day). Of 45 ton/hr of steam, 23 ton/hr was used to generate electricity (1500 kWh), 11 ton/hr was utilized to make hot water, and the rest was condensed to water. However, with the development of synergy, all steam (45 ton/hr) is supplied to a TPA manufacturing company. Before the development of synergy, the TPA manufacturing company was consuming 67 ton/hr of B-C oil to generate 7 ton/hr of steam.

(4) Chemical plants supplying steam to another chemical manufacturing company

Two chemical plants use process heat to produce steam at a rate of 229.2 ton/hr and 77 ton/hr. They supply 30 ton/hr of steam to another nearby chemical plant, which was previously consuming B-C oil to generate steam.

(5) Supply of zinc powder from a zinc waste processing company to a paint manufacturing company

Zinc powder (558 ton/yr) in the form of flake, dross and ash was collected from three industries and processed after which it was supplied to two other companies for the production of zinc-rich paints. A total of 1676 ton/yr of zinc waste was produced prior to the development of this symbiotic network, of which about 35% is utilized for the production of zinc-rich paints.

(6) Zinc manufacturing company supplying steam and CO₂ to a paper mill

Excess steam (70 ton/hr) from a zinc manufacturing company, which consumes coal to generate steam, is supplied to a nearby paper mill. Consequently, the reduction in fuel (B-C oil) consumed for steam production in the paper mill reduces stack gas emissions. Moreover, flue gas from the zinc manufacturing company can be used as a consistent and concentrated source of CO₂ and is now being used to supply 8 ton/hr of CO₂ required for the paper mill.

(7) Chemical plant supplying steam to another chemical manufacturing company

The chemical plant, which utilizes process heat to produce 310 ton/hr of steam, is supplying 80 ton/hr of steam to a TPA manufacturing company that was consuming B-C oil to generate steam, before the synergy network.

4. Methodology

4.1 Identification of eco-efficiency indicators

The eco-efficiency concept originally developed for the business sector that focuses on creation of more goods and services can also be applied to evaluate the performance of symbiotic transactions. The concept, as developed by WBCSD, is not restricted to any type of company, for example, small and medium – size enterprises or international companies. The WBCSD has identified a range of possibilities that encourage eco-efficiency in the business sector: (i) reducing material requirements for goods and services, (ii) reducing the energy intensity of goods and services, (iii) reducing toxic dispersion, (iv) enhancing material recyclability, (v) maximizing the sustainable use of renewable resources, (vi) extending product durability, and (vii) increasing the service intensity of goods and services. Most eco-efficiency measures or indicators focus on the consumption of energy, materials, and water, and the emissions of greenhouse gases (GHGs), wastewater, and pollution. In this study, we selected four indicators, based on their data availability and relevance to IS.

4.1.1 Economic indicator

WBCSD has proposed costs as a possible indicator of product or service value for companies (Verfaillie and Bidwell, 2000). However, while evaluating the benefits achieved through the substitution of waste and by-products for virgin materials, the net value added by the symbiotic transactions is shared by the participating companies. Thus, we recommend applying net economic benefit as a generally applicable economic indicator for IS networks.

4.1.2 Environmental indicators

4.1.2.1 Raw material consumption indicator. In the framework of the WBCSD, material consumption is the total weight of all materials that the company purchases or obtains from other sources, including raw materials for conversion, other process materials, and pre-or semi-manufactured goods and parts (Verfaillie and Bidwell, 2000). For a symbiotic network, such indicators are very important, as total material consumption can be reduced through exchanges of by-products. Thus, we propose the use of material consumption as one of the generally applicable environmental indicators for IS networks.

4.1.2.2 Energy consumption indicator. Energy consumption is a global environmental issue and is relevant to all businesses. It is a very important parameter for evaluating the effectiveness of IS networks, since some transactions deal with an enormous amount of energy during exchanges. A large amount of energy may be saved when a particular material from the system serves as an alternative to virgin materials that normally require large amounts of energy to extract. Correspondingly, if incineration with energy recovery is
part of the treatment of waste, the energy produced can substitute for other energy sources. Thus, we propose the use of energy consumption as one of the generally applicable environmental indicators for IS networks.

4.1.2.3. CO2 emission indicator. This indicator is an important element of GHG emissions resulting from fuel combustion, process reactions, and treatment processes. Climate change related to increasing emissions of GHGs is a major issue. In the process of synergy development, there can be a net reduction in GHG-emissions. A large amount of GHG-emissions can be reduced when waste or by-products from a system can be substituted for virgin material in another system. For example, if incineration with energy recovery is a part of the system, the energy produced can substitute for other energy sources, which in many cases contribute to GHG-emissions. Thus, we propose the use of GHG as a generally applicable environmental indicator for IS networks.

4.2. Eco-efficiency evaluation of symbiotic transactions

Evaluation of eco-efficiency values in this research was based on the WBCSD approach (WBCSD, 2000). The mathematic notations of eco-efficiency, as a combination of economic and ecological performance, are expressed by the ratio Equation (2):

$$\text{Eco-efficiency} = \frac{\text{EI}}{\sum \text{EN}_m} \quad (2)$$

where EI is an economic performance indicator expressed in US$, and the environmental performance indicator is noted by EN. \( \sum \text{EN}_m \) implies the total environmental influence as a function of \( m \) type of independent categories (indicators), such as resource consumption, energy consumption, and CO2 emission. The representation of multiple indicators as a single indicator was made using Equation (3):

$$R = \frac{1}{m} \sum_{i=1}^{m} \alpha S_i \quad (3)$$

where \( R \) is the environmental impact reduction that collectively accounts for the impact reduction in each category, \( m \) is the number of indicators, \( \alpha \) is the weightage for each indicator, and \( S_i \) is the impact reduction due to each indicator. In this study, equal weightage (\( \alpha = 1 \)) have been allocated to each selected indicator.

The following assumptions were made during eco-efficiency evaluation: (i) the total economic benefits of the companies involved in Ulsan were assumed to be equal before and after the establishment of the symbiotic transactions despite the fact that all these transactions have resulted in economic benefit. The increase in economic benefit following these transactions is almost negligible as compared to the financial performances of the individual companies, (ii) the eco-efficiency of the companies involved before symbiotic transactions was assumed to be 1.0, which was considered as a baseline for evaluating the increment in eco-efficiency.

The enhancement in eco-efficiency of the symbiotic transactions was calculated based on Equation (4):

$$\Delta \text{Eco-efficiency enhancement} = \text{EE}_b - \text{EE}_a$$

$$= \left( \frac{P_b}{I_b} \right) - \left( \frac{P_a}{I_a} \right) = \frac{P_a}{I_a} \left( \frac{I_a}{I_b} - 1 \right) = \frac{P_a}{I_a} \left( \frac{R}{1-R} \right) \quad (4)$$

where \( \Delta \text{EE} \) is eco-efficiency of the network, \( P \) is the economic benefit, \( I \) is the environmental impact, \( a \) denotes before network development, and \( b \) denotes after network development, \( R = [1 - (I_b/I_a)] \), \( P_b = P_a \) and \( P_a/I_a \) denotes the baseline eco-efficiency value.
Evolution of eco-efficiency due to ‘n’ number of symbiotic transactions can be expressed as:

\[
\Delta EE_i = \sum_{i=1}^{n} \left( \frac{P_b - P_a}{P_b - \sum_{i=1}^{n} I_a} \right) = \sum_{i=1}^{n} \left( \frac{P_b}{P_a} \right) \left( \frac{\sum_{i=1}^{n} I_b}{\sum_{i=1}^{n} I_a} - 1 \right)
\]

\[
= \left( \frac{\sum_{i=1}^{n} I_b - \sum_{i=1}^{n} I_a (1 - R_i)}{\sum_{i=1}^{n} I_a (1 - R_i)} \right) = \frac{\sum_{i=1}^{n} R_i}{\sum_{i=1}^{n} (1 - R_i)}
\]

(5)

5. Results and discussion

5.1. Eco-efficiency assessment of industrial symbioses

Eco-efficiency is a measure that can be increased in two ways: either the numerator in Equation (1), that is, economic value can be increased, or the denominator, that is, environmental impact can be decreased. In this study we emphasized the eco-efficiency enhancement of IS networks by the reduction of environmental impact in each eco-efficiency indicator. As mentioned earlier, even though there is an increase in economic benefits after the participating companies are engaged in symbiotic transactions, we assumed the total economic benefit to be same before and after network development, primarily due to negligible increase in the financial performance and difficulties associated with data collection.

Table 1 presents the types of exchanges, selected environmental indicators and their values in each symbiotic transaction. Based on the data presented in this table, eco-efficiency assessment for network 1 is as given below:

Environmental impact reduction due to energy consumption,
\[ S_1 = \{(143.5 - 131.5) \text{ ton/hr}/143.5 \text{ ton/hr} \} = 0.0836 \]

Environmental impact reduction due to CO2 emission,
\[ S_2 = \{(29.6 - 27.3) \text{ ton/hr}/29.6 \text{ ton/hr} \} = 0.0777 \]

Consequently, \[ R = (1/m) \sum_{i=1}^{m} \alpha_S i = 0.05376 \]
and, \[ \Delta EE = 0.0568 = 5.68\% \]

As shown in Fig. 3, networks 2 and 7 have the highest eco-efficiency enhancements, 14.9% and 28.7%, respectively, followed by networks 6, 5, 4, 3, and 1. For networks dealing with similar types of exchanges, eco-efficiency enhancement values were found to differ. For example, the eco-efficiency enhancement of network 7 was 2.5 and 5 times higher than that of networks 6 and 1, respectively. This indicated that irrespective of the type of exchange, the eco-efficiency enhancement value is dependent on the quantity of waste materials that are substituted for virgin raw material, the amount of energy saved, and pollution reduction in terms of CO2 and other air pollutants. Most importantly, the type of energy used to replace the virgin raw materials plays a vital role. For instance, among all five synergy networks involving steam, the highest overall eco-efficiency enhancement of network 7 is attributed to the utilization of process heat (142 gJ/hr), resulting from the exothermic reaction during TPA manufacture, to produce steam used by another participating company in the network. Consequently, the exchange resulted in significant enhancement of CO2 (99.9%) and overall eco-efficiency (28.7%). The observed eco-efficiency enhancement of network 2 is purely due to reduction in raw material consumption, wherein about 90% of 1, 4-butadiol containing wastewater is supplied to a municipal wastewater treatment plant as a replacement for commercially available methanol.

Fig. 4 shows the relative progress and overview of eco-efficiency improvement based on Equation (5). This figure represents the eco-efficiency enhancement of a total of 21 companies connected through seven networks. In the industrial complexes in Ulsan, two IS networks including five companies started functioning in 2007. Subsequent addition of networks until the year 2011 resulted in relatively similar eco-efficiency improvement. However, the addition of seventh network involving three companies is predicted to enhance eco-efficiency up to 0.12. Taking into account all the seven networks, the eco-efficiency enhancement is predicted to fluctuate between 0.09 and 0.12, with an average of about 0.1, for example, a 10% improvement. The 10% improvement is an average figure, wherein the networks with lower improvement potential are compensated for by greater improvement in others.

5.2. Discussion

In order to retrofit a traditional industrial complex to EIP, the park infrastructure requires renovation to include means for moving by-products from one plant to another, warehousing by-products for supply to external customers, and common facilities for waste processing. As a result, economic and environmental benefits to the companies, such as production costs (due to purchasing unwanted by-products from others at negotiable prices and selling by-products) decrease, energy consumption decreases, demand on natural resources decreases, and waste emissions and waste management requirements on the site decreases. These objectives can be achieved through the development of symbioses among companies in an industrial complex. Recently, successful cases of such symbioses have been observed in the Asia Pacific regions that were carried out through various national EIP initiatives (Behera et al., 2012; Shi et al., 2010; van Berkel et al., 2009). Governments play a crucial role in devising and supporting these EIP initiatives. For instance, in South Korea, while the government support the stakeholders for network identification and feasibility analysis, the EIP centers assist in different stages of symbiosis development, especially during the implementation stage (in terms of arranging the finance through various public and private funding mechanisms). However, compared to the classical evaluation of IS networks through separate estimates of economic and environmental benefits, inclusion of an integrated indicator incorporating both of these benefits could serve in a better way attracting stakeholders including companies and civic societies to promote symbiotic transactions and, persuading policy makers for regional development through the EIP initiatives.

This research provides a framework for application of the eco-efficiency concept as an evaluation tool for IS networks in order to translate the eco-efficiency ideas into reality. The study emphasizes on widely accepted, quantifiable, and transparent indicators for the calculation of eco-efficiency. The methodology adopted for calculating and reporting eco-efficiency can assist the participating companies in IS networks to set new eco-efficiency improvement targets. In order to help them to assess their eco-efficiency improvements, companies participating in IS networks are required to collect their own data and calculate their own eco-efficiency performances. Subsequently, the companies can reengineer their processes to reduce the consumption of resources
and pollution, while reducing costs. Good cooperation among companies can enhance the value of by-products, which eventually helps companies to become more eco-efficient (WBCSD, 2000).

The main advantage of the eco-efficiency concept is that it allows companies participating in symbiotic transactions to monitor their performances with regard to eco-efficiency trends. Fig. 5 explains the overall process of the Ulsan EIP initiative starting with the development of a strategy to encourage the participation of stakeholders and finally evaluating the eco-efficiency of the networks that are developed. The eco-efficiency indicators selected in this study are used to evaluate the eco-efficiency of each network to help decision makers to retrofit conventional industrial parks into EIPs. Thus, continuous monitoring and assessment of eco-efficiency is critically important for developing cost-effective measures of reducing environmental pressures through the development of symbiotic transactions among companies. These results reflect the contributions of newly developed synergies for eco-efficiency enhancement in EIPs, which may help governments at various levels to further improve eco-efficiency.

5.3. Implication

The major implications of this study lie in the development of empirically based and testable frameworks that combine the simple and widely applicable environmental indicators to recognize their relative impacts on network performance. This is significant, most extant research does not discuss the eco-efficiency of IS networks. The concepts applied in this study can also be easily applied to IS initiatives elsewhere.

Eco-efficiency has not yet been used as a framework for assessing the performance of IS networks. However, it was recently implemented in Australian minerals processing and metals production operations for cleaner production (van Berkel, 2007). Eco-efficiency can be extended to eco-innovation by means of three innovation platforms: (i) eco-efficient operations, (ii) eco-efficient process design, and (iii) eco-efficient technology. Therefore, it is apparent that eco-efficiency can also be extended to EIP projects due to their potential for significant contribution to eco-innovation.

Eco-innovation is defined as innovation that results in a reduction of environmental impact of products, or processes. So far, the promotion of eco-innovation has mainly focused on the development and application of environmental technologies (OECD, 2009). However, as a step forward, many companies are presently eco-innovating on their own by making their production processes more resource efficient via adopting waste minimization methods, using pollution control technologies, and other such initiatives. In this context, the adoption of IS helps accelerate the innovation process through enhanced resource/energy efficiency, and the reduction of carbon and other pollutant emissions, which are considered to be important drivers for eco-innovation at the industrial park level. The application of eco-efficiency to eco-innovation projects is a promising route towards true sustainability since eco-efficiency indicators support incremental innovation in products and processes, and may potentially facilitate radical innovation when applied at the company level (OECD, 2009). Therefore, it is important for industrial park managers, EIP centers, and concerned agencies to integrate and apply the concept in a holistic way. Each measurement approach may have its own strengths and weaknesses, and no single method or indicator can comprehensively describe eco-innovation.

5.4. Limitations

Eco-efficiency has the ability to combine performances along two of the three axes of sustainable development, namely, environment and economics (Ehrenfeld, 2005). In order to explain the direction of progress toward the goal of sustainable development, the social dimension of symbiosis implementation should be included in future research. For instance, the selection of economic and environmental indicators as components of eco-efficiency indicators should be in line with social issues such as job creation and enhanced community image.

Second, for the sake of eco-efficiency calculation, economic benefits were assumed to be the same both before and after network development. This was mainly due to either negligible economic benefit as compared to the total financial performance of the companies involved, or shortcomings in data, as company managers are often reluctant to disclose such information. Thus, the calculated eco-efficiency values may not be accurate, but should be considered to be conservative estimates. Nevertheless, if exact information is available on economic benefits, eco-efficiency enhancement can equally be calculated using Equation (4) without simplifying it to \[ R/(1-R) \].

Third, allocation of equal weightage to each environmental indicator \( (a = 1) \) should be further fine-tuned to calculate the eco-efficiency enhancement precisely. Besides, environmental impact can be represented through various categories such as abiotic depletion, eutrophication, global warming, acidification, or phototoxicity. This could help to account for all of the significant impacts of industries or services linked to the established networks.

Finally, the most significant limitation of the eco-efficiency evaluation is the availability and quality of the data required for calculations. Since our estimates are based on raw material and energy consumption and statistical conversion factors (IPCC, 2006), in some cases, they may not represent industrial reality. Despite the eco-efficiency increases offered by the symbiotic transactions in Ulsan, there is also a need to compare IS with that of upstream pollution prevention together with traditional end-of-pipe technologies (Salmi, 2007) to persuade the critics of IS and at the same time identify the most efficient and attractive options.

6. Conclusions

Considering the importance of EIP initiatives worldwide, the development of a framework to evaluate the effectiveness of IS networks is highly needed. Towards this, our study is a starting point that have attempted to present an indicator integrating both economic and environmental benefits of IS networks. A methodology is, thus, proposed that includes one economic indicator, and three commonly used environmental indicators (raw material consumption, energy consumption, and CO2 emission). Application of the methodology to the IS networks in Ulsan EIP shows that the eco-efficiency of individual IS networks has improved up to 28.7%. Besides, the evolution of all the seven IS networks (comprising 21 companies) has resulted in an overall eco-efficiency enhancement of 10%, which may be considered as an example of eco-innovation. The proposed framework could serve in attracting companies and civic societies to promote symbiotic transactions and also persuade decision makers such as governmental authority managers and policy makers for regional development through EIP initiatives. Continuous monitoring and assessment of eco-efficiency should be conducted over time and further research is warranted to address the limitations of this study.

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Note

Terminology in the research literature is somewhat inconsistent. In this article, we use eco-industrial development (EID) to refer to the application of industrial ecology principle to industry. Eco-industrial park (EIP) is used to indicate formally constituted industrial parks that pursue activities to maximize the resource efficiency. IS networks or symbiotic transactions refer to, in a broader sense, the exchanges in which at least three different entities are involved in exchanging at least two different resources (Chertow, 2007) and/or bi-lateral exchanges including by-product synergy, green-twinning and kernels, and utility sharing systems.

References