PRODUÇÃO ONLINE
REVISTA CIENTÍFICA ELETRÔNICA DE ENGENHARIA DE PRODUÇÃO
ABEPRO
ISSN 1676-1901

IDENTIFICATION AND QUALITATIVE COMPARISON OF PERFORMANCE INDICATORS OF INDUSTRIAL SYMBIOSIS

IDENTIFICAÇÃO E COMPARAÇÃO QUALITATIVA DE INDICADORES DE DESEMPENHO DE SIMBIOSE INDUSTRIAL

Gabriel Couto Mantese* E-mail: gabriel_mantese@outlook.com
Daniel Capaldo Amaral* Email: amaral@sc.usp.br
*Department of Production Engineering, University of São Paulo (USP), São Carlos,SP, Brazil

Abstract: Industrial symbiosis is the exchange of by-products, energy and water between industries, centered on a collective approach, and in order to achieve competitive advantages. It is central to the concept of eco-industrial park and requires continuous monitoring by the professionals involved. Indicators have been proposed and the objective of this work is to identify and describe the indicators present in the literature, and then make a conceptual comparison. In a total of seven indicators, the ISI (Industrial Symbiosis Indicator), from Felicio *et al*. (2016), stands out due to the amount of its positive features, bigger than the others, and for facilitating the indication of trends. The Environmental Impact indicator, from Trokanas *et al*. (2015), also stands out, but for considering the financial and energy consumption aspects, inherent in the industrial symbiosis networks. The others indicators have serious problems, including superficiality and difficulty of application. A combination of both would be the best alternative, but further research is recommended with more robust assessments, based on cases or simulations.

Keywords: Industrial Symbiosis. Eco-Industrial Park. Performance Indicator. Indicators Evaluation. Comparison between Indicators.

Resumo: A simbiose industrial é o intercâmbio de subprodutos, energia e água entre indústrias, centradas em uma abordagem coletiva, e com vistas a atingir vantagens competitivas. Ela é um elemento central para o conceito de parque eco-industrial e necessita de contínuo monitoramento pelos profissionais envolvidos. Há propostas de indicadores e o objetivo deste trabalho é identificar e descrever os indicadores de desempenho existentes na literatura para, em seguida, proceder a uma avaliação e comparação conceitual. De um total de sete indicadores, o ISI (Indicador de Simbiose Industrial), de Felicio *et al*. (2016), se destacou pela quantidade de características positivas, maior que os demais, e por facilitar a indicação de tendência. E o indicador de Impacto Ambiental, de Trokanas *et al*. (2015), por considerar os aspectos financeiros e de consumo energético inerentes às redes de simbiose industrial. Os demais apresentam sérios problemas, desde a superficialidade até a dificuldade de aplicação. Uma combinação de ambos seria a melhor alternativa, mas recomendam-se novas pesquisas com avaliações mais robustas, baseadas em casos ou simulações.

Palavras-chave: Simbiose Industrial. Parque Eco-Industrial. Indicador de Desempenho. Avaliação de Indicadores. Comparação entre Indicadores.

1 INTRODUCTION

The Eco-industrial Park (EIP) concept was created by Indigo Development Institute in late 1992 and presented to US-EPA (United State Environmental Protection Agency) in 1993 (INDIGO DEVELOPMENT, 2006; LOWE, 2001).

The interest in this type of industrial community is growing, which can be confirmed by Veiga and Magrini (2009) that show how the EIP concept has been spread to several countries as a new industrial arrangement model. Furthermore, Lowe (2001), at the beginning of 2001, identified that at least 100 eco-industrial projects had been initiated around the world and, since then, it is published regularly about the outcomes of these experiences or about the research methods and tools to support the EIPs establishment and development.

The EIP subject brings up the Industrial Symbiosis term, because, as noted by Chertow (1998), using data from 13 projects over two years, the industrial symbiosis is a key element for the EIP characterization. Agarwal and Strachan (2006) agree that an EIP is the grouping of industrial symbiosis networks. Therefore, the process of industrial symbiosis is essential to the EIP formation, and need to be measured, monitored and evaluated.

According to Agarwal and Strachan (2006), the industrial symbiosis development is limited because of the lack of comprehensive evaluation methods. Park and Behera (2014) reinforce this argument, the authors found that there is no method universally accepted to evaluate the performance of industrial symbiosis networks. One challenge is to improve the symbiosis networks evaluation and the first step is to ensure its maintenance and promotion.

There are papers dedicated to evaluate industrial symbiosis networks in industrial clusters, for example, Sokka *et al*. (2008), Bain *et al*. (2010), Wang *et al*. (2013; 2014) and Geng *et al*. (2014). Most of them use analysis based on the Life Cycle Assessment and Material Flow Analysis techniques to describe the networks, which does not necessarily characterize the symbiosis network.

Following the trend of the environmental and sustainable areas, where the sustainable development analysis and measurement are pursued through the proposition and utilization of performance indicators, as can be seen in Tachizawa (2009), Vianna *et al*. (2010), Rodrigues *et al*. (2015) and Rollano *et al*. (2015), recently emerged authors interested in creating performance indicators that measure specifically the industrial symbiosis.

Authors like Hardy and Graedel (2002), Tiejun (2010) and Felicio *et al*. (2016) use a performance indicator, or a set of indicators, to measure the industrial symbiosis in industrial parks. However, through a search in Web of Science databases, it was not found any paper compiling these indicators and comparing them with each other.

This paper has three objectives. The first is to list and present the performance indicators, or set of indicators, identified in the literature that have the aim to measure the industrial symbiosis. The second objective is to compare the indicators and evaluate them qualitatively. Finally, the third objective is to select the best indicator, or set of indicators, for measuring the industrial symbiosis in EIPs.

2 ECO-INDUSTRIAL PARKS AND THE INDUSTRIAL SYMBIOSIS

An EIP is an industrial community, where its members pursue the environmental, social and economic performance improvement through cooperation, obtaining a collective benefit greater than the sum of individual benefits that would be obtained without cooperation (INDIGO DEVELOPMENT, 2006).

The industrial symbiosis is an analogy to the term already known from biology, but inserted into business reality. According to Chertow *et al*. (2008), there are three types of symbiotic transactions that may occur: (i) infrastructure and utilities sharing; (ii) provision of common services; (iii) by-product exchanges, where a company uses the disposal/waste from another company as raw material.

The industrial symbiosis process, by improving the environmental issues, can also achieve social and economic advantages within an industrial cluster of companies that cooperate with each other synergistically.

In this context, the definition of instruments that contribute to the management of the professionals responsible for the EIP, known as brokers, becomes essential, as their role is stimulate the expansion of industrial symbiosis.

3 EVALUATING INDUSTRIAL SYMBIOSIS INDICATORS

According to Neely *et al*. (1995), the performance measurement is the process of quantifying the effectiveness and/or the efficiency of an action. A performance indicator, or a set of indicators, is able to play this role. For Ramos and Caeiro (2010), the performance indicators are the mostly widely used approach for the evaluation of sustainable performance.

A performance indicator, or set of indicators, to measure industrial symbiosis and its evolution is a necessary tool for the EIP's brokers.

Neely *et al*. (1997) is one of the research groups that more developed and systematized the indicators literature. The authors presented a form of performance indicators description, *The Performance Measure Record Sheet*, and general criteria that serve to indicators in the Operations Management area. Franceschini *et al*. (2006) updated these general criteria.

In addition to the general criteria, it was also identified a set of specific works for the evaluation of environmental and sustainability indicators. They are the works of Bockstaller and Girardin (2003), Cloquell-Ballester *et al*. (2006) and Kurtz *et al*. (2001).

The most complete is the Bockstaller and Girardin (2003), which proposed a classification and a procedure, based on a decision tree, indicating how to proceed the validation of environmental performance indicators. This structure was used by Cloquell-Ballester *et al*. (2006) to create a specific methodology of indicators validation, based on expert judgment.

An indicator validation can be divided into two stages, the conceptual validation and the empirical validation (BOCKSTALLER; GIRARDIN, 2003). The first is based on the indicator data, information and description, as well on the perception of experts. The second stage is the evaluation with visual or statistical procedures, involving simulated or real data. This paper deals with the evaluation of indicators through the conceptual validation recommendations proposed by these authors.

4.1 RESEARCH METHOD

The research method involves two stages: (i) Indicators identification; (ii) Conceptual evaluation.

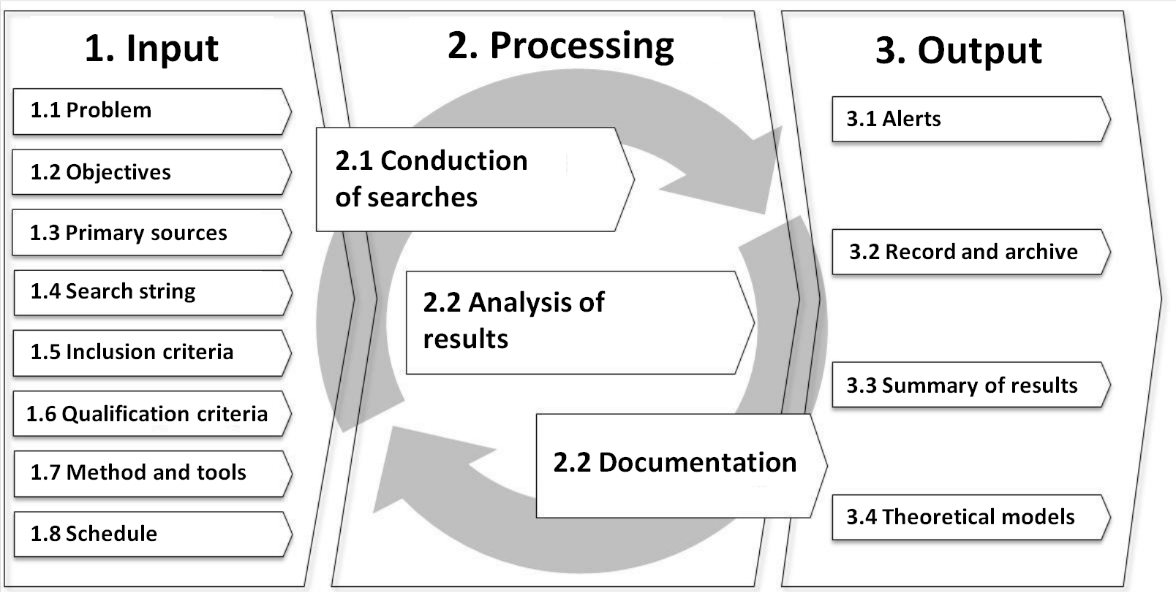
4.1 Indicators Identification

The first stage is the identification of the industrial symbiosis indicators that are available in the literature. A systematic literature review was conducted. The *RBS Roadmap* guide, by Conforto *et al*. (2011), was selected, because it is a systematic procedure of systematic literature review and can be used to conduct literature researches with greater scientific rigor (CONFORTO *et al*., 2011).

The guide was proposed with a primary focus on researches in the operations management field, specifically in product development and project management (CONFORTO *et al*., 2011). However, it can be applied in other areas, and was identified as a useful method for this research in particular.

The *RBS Roadmap* guide consists of three phases, containing a set of steps within each of them, as can be seen in Figure 1.

Figure 1 – Phases of *RBS Roadmap*



Source: Conforto *et al*., (2011, p. 7)

In Phase 1 (Input) the guidelines are defined, *i.e*., the systematic literature review is planned. In Phase 2 (Processing) is where the systematic literature review is performed, as the search string is conducted and the filters, for the papers inclusion, are applied. Finally, the Phase 3 (Output) is where the selected items are included in the research repository and the results are synthesized.

There are 3 filters to be applied at the papers founded by the search. In the first filter only the title, the keywords and the abstract are read. The second filter consists of reading the introduction and the conclusion of the papers. And in the last filter the remaining papers are read completely (CONFORTO *et al*., 2011).

4.2 Conceptual Evaluation

In the second stage, the conceptual evaluation of the selected indicators is performed. This evaluation is made through a comparison of the indicators, highlighting their qualities and weaknesses.

In order to find a common language for this comparison it was applied a set of criteria and elements to describe each indicator. The source was the theory about "good indicators", *i. e.*, the general and specific criteria to describe the performance indicators. These criteria were identified on performance indicator theory cited in Section 3 and are summarized in Table 1.

Table 1 – Set of criteria identified

Reference	Criteria
Neely *et al*. (1997)	Derived from strategy; Simple to understand; Accurate; Relevant; Clearly defined; Visual impact; Consistent; Fast feedback; Explicit purpose; Explicitly defined formula and source of data; Simple consistent format; Based on trends; Precise; Objective.
Franceschini *et al*. (2006)	Properly operationalise the representation-target; Should not provide more than the required information; Should be defined considering the expenses to collect the needed information; Be easy to be understood and to be used.
Bockstaller and Girardin (2003)	Well founded; Supplying reliable information; Useful.
Cloquell-Ballester *et al*. (2006)	Conceptual coherence; Operational coherence; Utility.
Kurtz *et al*. (2001)	Conceptual relevance; Feasibility of implementation; Response variability; Interpretation and utility.

Source: the Authors

It can be seen that some criteria from different authors are equal or very similar, which reinforce these findings.

The comparative evaluation between indicators is not intended to check if the indicators have adherence to the criteria, or if a particular indicator has adherence with more criteria than others. Table 1 was built only to systematize the contribution of some of the principal authors in the performance indicators and indicators validation areas, serving as a theoretical basis for the qualitative evaluation, which is accomplished through a comparison.

5 SYSTEMATIC LITERATURE REVIEW

To conduct the systematic literature review, the first step was the definition of the Input Phase of *RBS Roadmap*:

a) **Problem.** There are performance indicators for measuring industrial symbiosis? If so, which are?
b) **Objective.** Identify performance indicators for measuring industrial symbiosis in eco-industrial parks that are available in the literature.
c) **Primary sources.** Initially, the works of Felicio *et al*. (2016), Hardy and Graedel (2002) and Tiejun (2010) had already been identified through previous studies about industrial symbiosis and eco-industrial parks. From these works, which propose indicators for measuring industrial symbiosis, the keywords for the search were identified.
d) **Search string.** All the databases from Web of Science (THOMSON REUTERS, 2015) were used and the search was applied in Topic (Title, Abstract and Keywords). The search was conducted in January 2016 and includes papers published up to 2015. It was used the search string: *ts=("industrial symbiosis" OR "industrial ecology") AND ts=(indicator* OR index OR indice* OR connectance).*
e) **Inclusion criteria.** Only works that present one or more indicators for measuring the industrial symbiosis were included. Works that present methods as, for example, the work of Bain *et al*. (2010), which proposes the use of the Material Flow Analysis method for checking the industrial symbiosis, were excluded.
f) **Qualification criteria.** The selected works were classified in three ways: (i) Presents only a specific indicator for measuring the industrial symbiosis in EIPs; (ii) Presents a specific indicator composed of sub-indicators for measuring the industrial symbiosis in EIPs; (iii) Presents a set of indicators that together measure the industrial symbiosis in EIPs.
g) **Method and tools.** For the application of the search, as stated above, it was used the Web of Science (THOMSON REUTERS, 2015) databases.

The second phase of *RBS Roadmap* was initiated by the search string application in the selected database. The result yielded a total of 200 papers. After applying the first filter, *i.e.*, reading of title, abstract and keywords, 34 papers were selected. With the second filter, reading of introduction and conclusion, 14 papers were selected. Finally, with the application of the third filter, where the paper is read completely, 7 papers were selected. Although the work of Felicio *et al*. (2016) still being in the *in press* condition, and out of range of the systematic literature review (after 2015), it was included because it is one of the primary sources and is adherent to the research problem.

The result of systematic literature review, *i.e.*, the 8 works identified, is presented in Table 2.

Table 2 – Selected works

Reference	Work Title	Periodical or Event	Qualification criterion
Hardy and Graedel (2002)	Industrial ecosystems as food webs	Journal of Industrial Ecology	Set of indicators
Tiejun (2010)	Two quantitative indices for the planning and evaluation of eco-industrial parks	Resources, Conservation and Recycling	Set of indicators
Zhou *et al*. (2012)	Modeling and Optimization of a Coal-Chemical Eco-industrial System in China	Journal of Industrial Ecology	Set of indicators
Gao *et al*. (2013)	Study on Byproducts Recycling in Eco-industrial Parks	Advanced Research on Material Engineering, Chemistry and Environment	Set of indicators
Park and Behera (2014)	Methodological aspects of applying eco-efficiency indicators to industrial symbiosis networks	Journal of Cleaner Production	Specific indicator composed by sub-indicators
Wen and Meng (2015)	Quantitative assessment of industrial symbiosis for the promotion of circular economy: a case study of the printed circuit boards industry in China's Suzhou New District	Journal of Cleaner Production	Specific indicator
Trokanas *et al*. (2015)	Semantic approach for pre-assessment of environmental indicators in Industrial Symbiosis	Journal of Cleaner Production	Specific indicator composed by sub-indicators
Felicio *et al*. (2016)	Industrial symbiosis indicators to manage eco-industrial parks as dynamic systems	Journal of Cleaner Production	Specific indicator

Source: the Authors

The third phase of the *RBS Roadmap* consists only of the summary of results, where the identified indicators are described in detail.

6 INDICATORS DESCRIPTION

The indicators description is made through an adaptation of *The Performance Measure Record Sheet*, by Neely *et al*. (1997). This method provides a summary and a simple report from each indicator, and highlights the main aspects for comparisons (NEELY *et al*., 1997).

6.1 Connectance and Symbiotic Utilization

Hardy and Graedel (2002), based on the Food Webs theory, proposed the use of two indicators simultaneously. Both are described in Table 3.

Table 3 – Connectance and Symbiotic Utilization

Indicator title	a. Connectance b. Symbiotic Utilization
Purpose	a. Define the degree of association between the EIP companies b. Measure the magnitude and hazardousness of symbiotic relations
Related to which business goal?	a. Cooperation between companies b. By-products exchange incentive. Greater incentive to exchange of hazardous by-products
Minimum and maximum value	a. Ranges from 0 to 1. The higher the better b. Ranges from 0 to infinity. The higher the better
Formula	a. $C = \frac{2L}{S(S-1)}$ Where, L: number of links S: number of companies in the EIP b. $U = \sum_{i=1}^{n} M_i H_i$ Where, M: mass flow H: potential hazard for each material stream n: number of links
Source of data	Wastes/by-products flows of each company. Hazard level of each waste/by-product.

Source: structure adapted from Neely *et al*. (1997) and content adapted from Hardy and Graedel (2002)

6.2 Eco-Connectance and By-product and Waste Recycling Rate

These two indicators were proposed by Tiejun (2010) to be used together. The indicators can be seen in Table 4.

Table 4 – Eco-Connectance and By-product and Waste Recycling Rate

Indicator title	a. Eco-Connectance b. By-product and Waste Recycling Rate
Purpose	a. Define the degree of association between the EIP companies b. Define the degree of by-products and waste recycling in the EIP
Related to which business goal?	a. Business cooperation b. Waste reduction
Minimum and maximum value	a. Ranges from 0 to 1. The higher the better b. Ranges from 0 to 1. The higher the better
Formula	a. $C_e = \frac{L_e}{S(S-1)/2}$ Where, L_e: linkage of observable (as opposed to potential) by-products and waste flow S: number of companies present in the park b. $C_R = C_e r_L$ Where, C_e: Eco-Connectance r_L: average of the by-product and waste recycling percentage among any two enterprises in the EIP
Source of data	Waste and by-product flow of each company

Source: structure adapted from Neely *et al*. (1997) and content adapted from Tiejun (2010)

The work of Gao *et al*. (2013) proposed the same indicators, only changing part of their names. The indicator of Eco-connectance is called Ecological Correlation Degree among Enterprises. And the By-product and Waste Recycling Rate is named Rate of Byproducts Recycling in EIPs.

6.3 Industrial Symbiosis Index and Link Density

These indicators are presented by Zhou *et al*. (2012). Table 5 shows the two indicators.

Table 5 – Industrial Symbiosis Index and Link Density

Indicator title	a. Industrial Symbiosis Index b. Link Density
Purpose	a. Check the intensity of resource utilization in the industrial symbiosis system b. Check the association density between the EIP companies
Related to which business goal?	a. Increase the waste/by-product exchange between EIP companies b. Cooperation between the park companies
Minimum and maximum value	a. Ranges from 0 to 1. The higher the better b. Ranges from 0 to (n – 1)/2, where n is the number of companies. The higher the better
Formula	a. $Industrial\ Symbiosis\ Index = \frac{Symbiosis\ links}{Total\ links}$ b. $Link\ Density = \frac{Total\ links}{Number\ of\ companies}$ Where, Total links: Symbiotic links added to the final products flow links between EIP companies
Source of data	Local of origin and destination of waste/by-products and of products of each company

Source: structure adapted from Neely *et al*. (1997) and content adapted from Zhou *et al.* (2012)

6.4 Eco-efficiency

Park and Behera (2014) proposed an Eco-efficiency indicator to evaluate the performance of symbiotic networks in an EIP. This indicator is composed by other four indicators, an economic indicator and three environmental indicators. Table 6 shows a summary of the indicators.

Table 6 – Eco-efficiency

Indicator title	Eco-efficiency
Sub-indicators	a. Net Economic Benefit b. Raw Material Consumption c. Energy Consumption d. CO_2 Emission
Purpose	Evaluate the eco-efficiency of symbiotic transactions Encouraging the expansion of symbiotic relationships and increasing eco-efficiency
Related to which business goal?	a. Reduce costs b. Consuming wastes/by-products from other EIP companies c. Reduce energy consumption d. Reduce emission of greenhouse gases
Minimum and maximum value	Assumes any real value. The higher the better
Formula	$Eco-efficiency = \frac{EI}{EN}$ Where, EI: Net economic benefit achieved through the exchange of by-products EN: Representation of environmental influence, represented by the formula: $EN = \sum_{i=1}^{3} \propto S_i$ Where, S_i: impact due to each environmental indicator α: Weight of each environmental indicator (sum of weights must be equal to 1)
Source of data	a. Monetary amount saved due to industrial symbiosis links b. Quantity of raw material consumed by each company c. Amount of energy consumed by each company d. Amount of CO_2 emission of each company

Source: structure adapted from Neely *et al*. (1997) and content adapted from Park and Behera (2014)

6.5 Resource Productivity Index

The Resource Productivity Index emerged from the combination between the Substance Flow Analysis (SFA) approach and the Resource Productivity (RP) indicator. It was proposed by Wen and Meng (2015). Table 7 summarizes this indicator.

Table 7 – Resource Productivity Index

Indicator title	Resource Productivity Index
Purpose	Evaluate the contribution of industrial symbiosis in the development of circular economy
Related to which business goal?	Productivity enhancement Use of wastes/by-products as raw material
Minimum and maximum value	Assumes any real value. The higher the better
Formula	$RP = \frac{\sum IAV}{\sum DMI}$ Where, RP: Resource Productivity ∑IAV: Industrial added value ∑DMI: Direct material input in the system (amount) The variable ∑DMI is only about the direct material used, *i.e.*, only the virgin raw material. The indirect material is the reused raw material, *i.e.*, wastes/by-products that are reused as raw materials. Thus the indicator increases with the substitution of direct material by indirect material. Due to the use of the SFA approach, the Resource Productivity Index considers only one type of substance in its calculation. This means that for every production chain, a new value of the indicator must be calculated. On the other hand, the substance may be energy or water, and thus, the indicator value for the use of water and energy can be calculated.
Source of data	Amount of direct material used Industrial value added by company

Source: structure adapted from Neely *et al*. (1997) and content adapted from Wen and Meng (2015)

6.6 Environmental Impact

The Environmental Impact indicator was proposed by Trokanas *et al*. (2015). It consists of five sub-indicators. Table 8 shows them all.

Table 8 – Environmental Impact

Indicator title	Environmental Impact (ENVI)
Sub-indicators	a. Embodied Carbon Cost (ECC) b. Virgin Materials Financial Saving (VMFS) c. Landfill Diversion Financial Saving (LDFS) d. Transportation Financial Impact (TFI) e. Energy Consumption Financial Impact (ECFI)
Purpose	Assess the financial impact due to the environmental impact of symbiotic transactions a. Assess the embodied carbon cost of materials exchanged between the companies b. Assess the financial savings achieved through the replacing of virgin materials by by-products c. Assess the financial savings achieved by not sending the reused by-products to landfill d. Assess the financial impact of the reused by-products transportation between companies e. Assess the energy cost consumed in the processing of reused by-products
Related to which business goal?	Reduction of environmental impact
Minimum and maximum value	Assumes any real value. The lower the better.
Formula	$ENVI = \sum_{i=0}^{pairs} \frac{(w_{ECC} * ECC) - (w_{VMFS} * VMFS) - (w_{LDFS} * LDFS) + (w_{TFI} * TFI) + (w_{ECFI} * ECFI)}{\sum w_i}$ Where, pairs: amount of symbiotic transactions w: weight of sub-indicators The sub-indicators are calculated according to the formulas: a. $ECC = \left(\sum_{ij}^{n_{res}} Q_{ij} * EC_{R(ij)}\right) * CO_2^P$ b. $VMFS = \sum_{ij}^{n_{in}} C_{ij} * (FP_{ij} - RP_{ij})$ c. $LDFS = \sum_{ij}^{n_{res}} Q_{ij} * (DC_{ij} + RP_{ij} + LT)$ d. $TIF = \left(\sum_{ij}^{n_{sym}} TF_{ij} * l_{ij} * Q_{ij}\right) * CO_2^P$ e. $ECFI = \left(\sum_{ij}^{n_{en}} Q_{ij} * CC_{ij}\right) * CO_2^P$ Where, Q_{ij}: Quantity of by-product exchanged between industries i and j $EC_{R(ij)}$: Embodied carbon of by-product exchanged between industries i and j CO_2^P: Price of CO_2 as formed in the boundaries of carbon exchange scheme C_{ij}: Capacity of industry j satisfied by industry i FP_{ij}: Price of the feedstock that is replaced by a by-product between industries i and j RP_{ij}: Price of by-product exchanged between industries i and j DC_{ij}: Disposal cost for by-product exchanged between industries i and j LT: Landfill tax for region TF_{ij}: Transportation factor between industries i and j l_{ij}: The physical distance between industries i and j CCij: Carbon content of energy type n_{res}: Number of by-products exchanged in the symbiotic network n_{in}: Number of inputs involved in the symbiotic network n_{syn}: Number of pairwise exchanges in the symbiotic network n_{en}: number of different types of energy required in a symbiotic network
Source of data	Amount of exchanged by-products Amount of energy used in processing by-products Geographical location of industries Price of the replaced raw materials and by-products

Source: structure adapted from Neely *et al*. (1997) and content adapted from Trokanas *et al*. (2015)

6.7 Industrial Symbiosis Indicator (ISI)

The ISI was proposed by Felicio *et al*. (2016) and is described in Table 9.

Table 9 – Industrial Symbiosis Indicator

Indicator title	Industrial Symbiosis Indicator (ISI)
Purpose	Indicate the evolution of the performance of symbiotic relationships between companies of an EIP
Related to which business goal?	Encourage the expansion of symbiotic relationships
Minimum and maximum value	Ranges from 0 to infinity. The higher the better
Formula	$ISI = \frac{EIMi}{1 + EIMo} = \frac{\sum_{w=1}^{n}(AiP_w \times DiP_w)}{1 + \sum_{w=1}^{n}(AoP_w \times DoP_w)}$ Where, n: number of by-product types involved in the calculation w: type of by-product EIMi: Environment impact momentum inbound EIMo: Environment impact momentum outbound AiP: Amount of inbound by-product DiP: Degree of inbound by-product AoP: Amount of outbound by-product DoP: Degree of outbound by-product To calculate DiP and DoP the following formula is used: $DP = evaluation\ of\ the\ criterion \times weight\ of\ the\ criterion$ The weigh and evaluation of the criterion must be provided by the indicator user. Table 9.1 shows the criteria and the evaluation for the by-products exchanged. (Table 9.1 below) **Source**: Felicio *et al*. (2016) DiP does not consider the criterion "Destination of Waste", while DoP does not use the criterion "Use of Waste".
Source of data	Wastes and by-products flows of each company. Waste legislation. Class of waste. Problems/risks with regard to waste.

Table 9.1 – Evaluation criteria of waste degree

CRITERIA	EVALUATION
Legislation	1. Good Practices 3. General Requirement 5. Specific Legal Requirement
Class of Waste	1. Non-hazardous – Inert 3. Non-hazardous – Non-inert 5. Hazardous
Use of Waste	1. Waste is treated at both the donor and recipient company 3. Waste is treated at the recipient company 5. Waste treatment is not required at either of the companies
Destination of Waste	1.Another EIP with pretreatment 3. Another EIP without pretreatment 5. Industrial Landfill (Class I and II)
Problems/Risks	1. Nonexistent 3. Possible/isolated 5. Frequent

Source: Structure adapted from Neely *et al*. (1997) and content adapted from Felicio *et al*. (2016)

7 EVALUATION OF INDICATORS

Using the criteria presented in Section 4.2 and the formula and characteristics of each indicator, described in Section 6, the main aspects that an industrial symbiosis indicator should cover were identified: (i) Correct representation of industrial symbiosis; (ii) Waste/by-product classification; (iii) Quantification of reused and discarded wastes/by-products; (iv) Difficulty of data access and collection; (v) Indication of trend; (vi) Existence of a reference value (for comparison); (vii) Coverage value (minimum and maximum values).

The indicators evaluation is summarized in Table 10, which, due to its size, is divided into two parts (10.A and 10.B).

Table 10.A – Comparative evaluation of indicators (first part)

Indicator(s)	Positive aspects and strengths	Negative aspects and weaknesses
Connectance and Symbiotic Utilization (HARDY; GRAEDEL, 2002)	1- Wastes receive different classifications according to their hazardousness 2- Consider the amount of reused waste 3- Data of amount of waste are not difficult to obtain 4- Symbiotic Utilization do not have maximum value, meaning that the industrial symbiosis can always be increased	1- The hazardousness classification of wastes does not follow a rule 2- Values of different EIPs cannot be compared because the hazardousness classification may be different 3- Do not consider the amount of discarded waste
Eco-Connectance and By-product and Waste Recycling Rate (TIEJUN, 2010; GAO *et al.*, 2013)	1- Consider both quantity of used and discarded waste 2- Data of amount of waste are not difficult to obtain	1- Do not classify the different types of waste 2- The formula of the By-product and Waste Recycling Rate indicator is inconsistent, because a company can send 50% of the generated waste to another company and the remaining 50% to a third company. This results in a r_L equal to 50%. But in another scenario, the same company is sending 100% of the generated waste to only one company, which would result in a r_L equal to 100% 3- Do not consider the absolute value of amount of waste, only the percentage
Industrial Symbiosis Index and Link Density (ZHOU *et al.*, 2012)	1- The data are very easy to be obtained	1- Only verify if the companies have some kind of connection, but do not consider the waste amount or its classification 2- These indicators do not represent the industrial symbiosis as defined by Chertow *et al*. (2008)

Source: the Authors

Table 10.B – Comparative evaluation of indicators (second part)

Indicator(s)	Positive aspects and strengths	Negative aspects and weaknesses
Eco-efficiency (PARK; BEHERA, 2014)	1- Considers financial aspects 2- Considers energy consumption 3- Data of amount of raw material are not difficult to obtain	1- Financial data are difficult to obtain 2- Does not classify the different types of material 3- Values of different EIPs cannot be compared, because the weight of environmental sub-indicators may be different 4- Does not consider the amount of discarded waste 5- The data of amount of waste are not used directly, because data of amount of virgin raw material consumed are used. This suggests that the less virgin materials are being used, the more by-products and wastes are being used as raw material. That is an indirect measure of waste use as input
Resource Productivity Index (WEN; MENG, 2015)	1- Although the classification of materials is not considered, it is used the Substance Flow Analysis approach to quantify the materials in an equivalent way 2- It has no maximum value, meaning that the industrial symbiosis can always be increased 3- Considers financial aspects	1- Financial data are difficult to obtain 2- Does not consider the amount of discarded waste 3- The data of amount of waste are not used directly, because data of amount of virgin raw material consumed are used. This suggests that the less virgin materials are being used, the more by-products and wastes are being used as raw material. That is an indirect measure of waste use as input 4- It is not calculated just one value for the whole EIP. It is necessary to calculate the indicator for each chain of each substance type
Environmental Impact (TROKANAS *et al*., 2015)	1- Considers the amount of reused waste 2- Although the classification of waste is not considered, it is used the Embodied Carbon approach to quantify the waste in an equivalent way 3- Considers financial aspects 4- Considers energy consumption	1- Financial data are difficult to obtain 2- Involves the use of many data for the indicator calculation, which difficult the use at the beginning of the application 3- Does not consider the amount of discarded waste 4- Values of different EIPs cannot be compared because the sub-indicators weights may be different
Industrial Symbiosis Indicator (ISI) (FELICIO *et al*., 2016)	1- Classifies the wastes based on various criteria 2- Considers both quantity of used and discarded waste 3- It has no maximum value, meaning that the industrial symbiosis can always be increased 4- Data of amount of waste are not difficult to obtain 5- Indicates trend	1- In the formula was necessary to add 1 in the denominator. This causes different effects depending on the magnitude of exchanged waste amounts 2- It is necessary to be always aware to changes in the criteria classifications of each waste at each period. Can be hard-working 3- Values of different EIPs cannot be compared because the criteria weights may be different

Source: the Authors

Table 10 indicates the set of positive and negative aspects of each indicator. Both indicators from Zhou *et al*. (2012) can be considered superficial compared to the others. They are reductionists in the scope of the industrial symbiosis information and dimensions.

The indicators from Felicio *et al*. (2016) and Hardy and Graedel (2002) stand out positively because they consider the waste classification. Hardy and Graedel (2002), however, only consider the hazardousness in the classification. Felicio *et al*. (2016) suggest five criteria and rules to classify each waste. In addition, the indicators from Hardy and Graedel (2002) do not consider the amount of discarded waste, which is considered by the indicator from Felicio *et al*. (2016).

Although the indicators proposed by Wen and Meng (2015) and by Trokanas *et al*. (2015) do not consider the waste classification, they stand out because this aspect is overcame through the use of Substance Flow Analysis and Embodied Carbon approaches respectively, being able to compare equivalently the different materials. However, the indicator from Wen and Meng (2015) does not consider the direct use of exchanged by-products and waste, it considers the amount of virgin raw material used. That also occurs with the indicator from Park and Behera (2014). In addition, the indicator from Wen and Meng (2015) should be calculated for each chain of each substance type, it does not provide a unique value for the park as a whole.

The indicators from Felicio *et al*. (2016) and Tiejun (2010) are the only ones to consider the amount of discarded waste. However, the indicators from Tiejun (2010) do not use absolute values, only percentages of the reused waste. Furthermore, the indicators from Tiejun (2010) do not consider the classification of waste.

The indicators proposed by Park and Behera (2014) and by Trokanas *et al*. (2015) are the only ones to consider the financial aspect and the energy consumption, while the indicator from Wen and Meng (2015) considers only the financial aspect. The disadvantage is that such data are difficult to be shared among EIP members, which can complicate the application.

8 CONCLUSIONS

The main indicators are the ISI (FELICIO *et al*., 2016) and the Environmental Impact indicator (TROKANAS *et al*., 2015). The positive characteristics of both indicators stand out, but they also have negative aspects and weaknesses that must be considered.

For the researches and industrial engineering professionals interested in measuring the industrial symbiosis, it is suggested the combined use of the ISI and the Environmental Impact indicator, or some of its sub-indicators. This work also provides the basis for researchers interested in creating new indicators, because it shows advantages and disadvantages that can serve as an inspiration for proposing new indicators.

This work did a conceptual validation and, as a next step, is suggested an empirical validation. It was impossible to be made because these indicators are at an early stage of proposition. The most appropriate is to apply the ISI and the Environmental Impact indicator in a real situation, *i.e.*, in a consolidated EIP.

However, the access to such parks is still difficult, and there are not many real cases that can be used for a test.

ACKNOWLEDGEMENTS

The authors thank FAPESP (São Paulo Research Foundation) for funding support through grants No 2014/11464-0 and No 2015/17192-5.

REFERENCES

AGARWAL, A.; STRACHAN, P. **Literature review on eco-industrial development initiatives around the world and the methods employed to evaluate their performance / effectiveness**. The Robert Gordon University. Report, 2006.

BAIN, A.; SHENOY, M.; ASHTON, W.; CHERTOW, M. Industrial symbiosis and waste recovery in an Indian industrial area. **Resources, Conservation and Recycling**, v. 54, n. 12, p. 1278-1287, 2010. http://dx.doi.org/10.1016/j.resconrec.2010.04.007.

BOCKSTALLER, C.; GIRARDIN, P. How to validate environmental indicators. **Agricultural systems**, v. 76, n. 2, p. 639-653, 2003. http://dx.doi.org/10.1016/S0308-521X(02)00053-7.

CHERTOW, M. R. The eco-industrial park model reconsidered. **Journal of Industrial Ecology**, v. 2, n. 3, p. 8-10, 1998. http://dx.doi.org/10.1162/jiec.1998.2.3.8.

CHERTOW, M.R.; ASHTON, W.; ESPINOSA, J.C. Industrial symbiosis in Puerto Rico: environmentally e related agglomeration economies. **Regional Studies**, v. 42, n. 10, p. 1299-1312, 2008. http://dx.doi.org/10.1080/00343400701874123.

CLOQUELL-BALLESTER, V-A.; CLOQUELL-BALLESTER, V-A.; MONTERDE-DÍAZ, R. SANTAMARINA-SIRUANA, M-C. Indicators validation for the improvement of environmental and social impact quantitative assessment. **Environmental Impact Assessment Review**, v. 26, n. 1, p. 79-105, 2006. http://dx.doi.org/10.1016/j.eiar.2005.06.002.

CONFORTO, E. C.; AMARAL, D. C.; SILVA, S. L. da. Roteiro para revisão bibliográfica sistemática: aplicação no desenvolvimento de produtos e gerenciamento de projetos. In: CONGRESSO BRASILEIRO DE GESTÃO DE DESENVOLVIMENTO DE PRODUTO– CBGDP, 8., 2011. **Anais...** Porto Alegre, RS. 2011.

FELICIO M., AMARAL D., ESPOSTO K., DURANY X. G., Industrial symbiosis indicators to manage eco-industrial parks as dynamic systems, **Journal of Cleaner Production**, v. 118, p. 54-64, 2016. http://dx.doi.org/10.1016/j.jclepro.2016.01.031.

FRANCESCHINI, F.; GALETTO, M.; MAISANO, D. Classification of performance and quality indicators in manufacturing, **International Journal of Services and Operations Management**, v. 2 n. 3, p. 294-311, 2006. http://dx.doi.org/10.1504/IJSOM.2006.009862.

GAO, X. L.; LI, R. Q.; LI, R. Study on Byproducts Recycling in Eco-Industrial Parks. **Advanced Materials Research**, v. 788, p. 288-292, 2013. http://dx.doi.org/10.4028/www.scientific.net/AMR.788.288.

GENG, Y.; LIU, Z.; XUE, B.; DONG, H.; FUJITA, T.; CHIU, A. Emergy-based assessment on industrial symbiosis: a case of Shenyang Economic and Technological Development Zone.

Environmental Science and Pollution Research, v. 21, n. 23, p. 13572-13587, 2014. http://dx.doi.org/10.1007/s11356-014-3287-8.

HARDY, C.; GRAEDEL, T. E. Industrial ecosystems as food webs. **Journal of Industrial Ecology**, v. 6, n. 1, p. 29-38, 2002. http://dx.doi.org/10.1162/108819802320971623.

INDIGO DEVELOPMENT. **Eco-industrial parks (EIP)**. 2006. Available in: http://www.indigodev.com/Ecoparks.html. Access in: 26 mar. 2015.

KURTZ, J. C.; JACKSON, L. E.; FISHER, W. S. Strategies for evaluating indicators based on guidelines from the Environmental Protection Agency's Office of Research and Development. **Ecological indicators**, v. 1, n. 1, p. 49-60, 2001. http://dx.doi.org/10.1016/S1470-160X(01)00004-8.

LOWE, E. A. **Eco-industrial park handbook for Asian developing countries**. A Report to Asian Development Bank, Environment Department, Indigo Development, Oakland, CA, 2001.

NEELY, A. D.; GREGORY; M.; PLATTS, K. Performance measurement systems design: a literature review and research agenda. **International Journal of Operations & Production Management**, v. 15 n. 4, p. 80-116. 1995. http://dx.doi.org/10.1108/01443579510083622.

NEELY, A. D.; RICHARDS, A. H.; MILLS, J. F.; PLATTS, K. W.; BOURNE, M. C. S. Designing performance measures: a structured approach. **International journal of operations & Production management**, v. 17, n. 11, p. 1131-1152, 1997. http://dx.doi.org/10.1108/01443579710177888.

PARK, H. S. BEHERA, S. K. Methodological aspects of applying eco-efficiency indicators to industrial symbiosis networks. **Journal of Cleaner Production**, v. 64, p. 478-485, 2014. http://dx.doi.org/10.1016/j.jclepro.2013.08.032.

RAMOS, T. B.; CAEIRO, S. Meta-performance evaluation of sustainability indicators. **Ecological Indicators**, v. 10, n. 2, p. 157-166, 2010. http://dx.doi.org/10.1016/j.ecolind.2009.04.008.

RODRIGUES, A. M.; ZEVIANI, C. H.; REBELATO, M. C.; BORGES, L. Avaliação de desempenho ambiental industrial: elaboração de um referencial metodológico. **Revista Produção Online**, v. 15, n. 1, p. 101-134, 2015. http://dx.doi.org/10.14488/1676-1901.v15i1.1719.

ROLLANO, C. R. L.; DE OLIVEIRA FONTES, C. H.; BARBOSA, A. S. Análise da evolução do desenvolvimento sustentável nas indústrias produtoras de biocombustíveis no Brasil. **Revista Produção Online**, v. 15, n. 2, p. 696-733, 2015. http://dx.doi.org/10.14488/1676-1901.v15i2.1938.

SOKKA, L.; MELANEN, M.; NISSINEN, A. How can de sustainability of industrial symbioses be measured?. **Progress in Industrial Ecology – An International Journal**, v. 5, n. 5/6, p. 518-535. 2008. p. 518. http://dx.doi.org/10.1504/PIE.2008.023414.

TACHIZAWA, T. Sustentabilidade e responsabilidade social: proposta de modelo de diagnóstico socioambiental baseada em pesquisa empírica. **Revista Produção Online**, v. 9, n. 4, p. 795-821, 2009. http://dx.doi.org/10.14488/1676-1901.v9i4.281.

THOMSON REUTERS. **Web of Science**. 2015. Available in: http://apps.webofknowledge.com/UA_GeneralSearch_input.do?product=UA&search_mode=

GeneralSearch&SID=4BQI1LwNdHBiu1hUF9O&preferencesSaved=. Access in: 22 dec. 2015.

TIEJUN, D. Two quantitative indices for the planning and evaluation of eco-industrial parks. **Resources, Conservation and Recycling**, v. 54, n. 7, p. 442-448, 2010. http://dx.doi.org/10.1016/j.resconrec.2009.09.010.

TROKANAS, N.; CECELJA, F.; RAAFAT, T. Semantic Approach for Pre-assessment of Environmental Indicators in Industrial Symbiosis. **Journal of Cleaner Production**, v. 96, n. 34, p. 9e361, 2015. http://dx.doi.org/10.1016/j.jclepro.2013.12.046.

VEIGA, L. B. E.; MAGRINI, A. Eco-industrial park development in Rio de Janeiro, Brazil: a tool for sustainable development. **Journal of Cleaner Production**, v. 17, n. 7, p. 653-661, 2009. http://dx.doi.org/10.1016/j.jclepro.2008.11.009.

VIANNA, W. B.; GIFFHORN; E.; FERREIRA, N. A. de; PALADINI, E. P. Alinhamento Estratégico e Indicadores de Desempenho: Um Estudo para a Integração de Processos de Gestão da Qualidade. **Revista Produção Online**, v. 10, n. 1, 2010. http://dx.doi.org/10.14488/1676-1901.v10i1.211.

WANG, G.; FENG, X.; CHU, K. H. A novel approach for stability analysis of industrial symbiosis systems. **Journal of Cleaner Production**, v. 39, p. 9-16, 2013. http://dx.doi.org/10.1016/j.jclepro.2012.08.031.

WANG, G.; FENG, X.; CHU, K. H. Symbiosis Analysis on Industrial Ecological System. **Chinese Journal of Chemical Engineering**, v. 22, n. 6, p. 690-698, 2014. http://dx.doi.org/10.1016/S1004-9541(14)60084-7.

WEN, Z.; MENG, X. Quantitative assessment of industrial symbiosis for the promotion of circular economy: a case study of the printed circuit boards industry in China's Suzhou New District. **Journal of Cleaner Production**, v. 90, p. 211-219, 2015. http://dx.doi.org/10.1016/j.jclepro.2014.03.041.

ZHOU, L.; HU, S.; LI, Y.; JIN, Y.; ZHANG, X. Modeling and Optimization of a Coal-Chemical Eco-industrial System in China. **Journal of Industrial Ecology**, v. 16, n. 1, p. 105-118, 2012. http://dx.doi.org/10.1111/j.1530-9290.2012.00447.x.

Artigo recebido em 12/02/2016 e aceito para publicação em 10/03/2016
DOI:http://dx.doi.org/ 10.14488/1676-1901.v16i4.2349