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Comparison of industrial symbiosis indicators through agent-based modeling

Gabriel Couto Mantese*, Daniel Capaldo Amaral

Department of Production Engineering, University of São Paulo, São Carlos, SP, Brazil

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ABSTRACT

The validation of environmental impact indicators is a prerequisite for professionals and brokers in charge of Eco-Industrial Parks (EIPs). In the specific case of industrial symbiosis indicators, this task is particularly challenging owing to the inherent difficulty in obtaining series of real data of consequence for the small number of EIPs and large number of organizations. Agent-Based Modeling (ABM) emerges as a technique to support EIP simulations. This work endorses the use of the ABM technique to validate indicators of industrial symbiosis through the construction of a model that simulates an EIP, which is then evaluated by applying three indicators: the Industrial Symbiosis Indicator (ISI) of Felicio *et al.* (2016) and the Eco-Connectance and By-product and Waste Recycling Rate indicators of Tiejun (2010). The model was able to calculate the three indicators and identify conditions where their performances are equal or with misleading information regarding industrial symbiosis evolution. It supports the validation of industrial symbiosis indicators and demonstrates that the indicator by Felicio *et al.* (2016) is more robust for turbulent periods of industrial ecosystem environments.

1. Introduction

The use of performance indicators is one of the main approaches to support sustainable development (Ramos and Caeiro, 2010). Through this instrument, business professionals, representatives of regulatory protection agencies, and governments can diagnose, manage, and make decisions favoring the reduction of environmental impacts.

Industrial ecology has access to a new category of indicators: the so-called indicators of industrial symbiosis. Industrial symbiosis is a key concept for the development of an Eco-Industrial Park (EIP) (Agarwal and Strachan, 2006; Chertow, 1998). Managers and business professionals participating in an EIP make decisions that have a direct impact on the level of symbiosis. A number of indicators are available in literature, such as those introduced in the works of Tiejun (2010), Felicio et al. (2016), Park and Behera (2014), and Zhou et al. (2012).

According to Meul et al. (2009), the validation of a performance indicator considers two aspects of the indicator: its accuracy and credibility. The accuracy is related to the consistency the indicator has to its application, while credibility expresses the confidence the user has in the indicator and in the information provided by it as well as the willingness to effectively use the indicator (Meul et al., 2009). Accordingly, the validation process for an indicator can be separated into two stages: conceptual validation, which is based on data, information, and a description of the indicator, and empirical validation, the analysis of the behavior of the indicator outputs for which either visual or statistical procedures can be used.

According to Cloquell-Ballester et al. (2006), an ever possible way to proceed with the conceptual validation is through the expert judgment. The empirical validation of indicators for industrial symbiosis relies on data collected by various organizations and on the monitoring of a park for a significant period of time. This task is further impaired by the lack of real data owing to the scarceness of consolidated parks. A potential solution proposed by Bockstaller and Girardin (2003) is the use of simulated data.

The simulation technique known as Agent-Based Modeling (ABM) has been highlighted by Romero and Ruiz (2014) for the representation of an EIP, through which understanding the dynamics resulting from the interaction of the individuals of a system between themselves and the environment is possible (Railsback and Grimm, 2011).

The utilization of ABM as an instrument for validating symbiosis indicators is investigated in this work. Three indicators were

* Corresponding author.
E-mail addresses: gabriel_mantese@outlook.com (G. Couto Mantese), amaral@sc.usp.br (D. Capaldo Amaral).

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selected as a case study: the Industrial Symbiosis Indicator (ISI) of Felicio et al. (2016) and indicators of Eco-Connectance and By-product and Waste Recycling Rate of Tiejun (2010). According to the bibliographical review performed by Felicio et al. (2016), the indicators of connectance are recommended for brokers and professionals involved with managing and controlling EIPs. And the ISI allows for consideration of the dynamic perspective of these parks as described by Chertow and Ehrenfeld (2012).

The indicators of Tiejun (2010) are the most widespread in literature. Other studies mention its use in the evaluation of industrial symbiosis networks. These studies include Gao et al. (2013) and Hardy and Graedel (2002). The ISI (Felicio et al., 2016) is a recent indicator and needs to be evaluated before being made available to professionals. The comparison between them could reveal strengths and weaknesses for those interested in real applications. The challenge is performing both evaluation and comparison. Is the ABM simulation appropriate to answer these questions?

This study has two main objectives. The first one is to propose the application of the ABM technique for empirical validation of the cited industrial symbiosis indicators and constructing a simulation model. The second objective is to use the model to perform a comparison between three indicators to validate the model, demonstrate its use, and identify improvements in the indicators evaluated.

2. Indicators of industrial symbiosis

The EIP concept was created by the Indigo Development Institute in 1992 (Lowe, 2001) and has spread to several countries (Veiga and Magrini, 2009). It is defined as a community of industries located within the same property that seeks to improve environmental, economic, and social performance through mutual cooperation, thus generating a greater collective benefit than the sum of the individual benefits companies would gain if they do not cooperate with each other (Indigo Development, 2006).

Industrial symbiosis is fundamental to the establishment of EIPs (Agarwal and Strachan, 2006; Chertow, 1998). It has been defined by Chertow et al. (2008), who identified three types of symbiotic transactions: (i) sharing of infrastructure and utilities, (ii) provision of common resources, and (iii) by-product exchange between companies, where materials that would be discarded are used as raw materials.

The encouragement of this type of cooperation relies on the action of facilitators who can monitor and promote industrial symbiosis. Indicators of industrial symbiosis are among the tools available by these managers and Felicio et al. (2016) analyzed the relevant literature. They identified three approaches (Felicio et al., 2016): eco-industrial indicators, material flow analysis (MFA) indicators, and life cycle assessment (LCA) indicators. The research identified papers that proposed a combination of these techniques and papers using network analysis. Felicio et al. (2016) concluded that the best indicators were those proposed by Hardy and Graedel (2002) and Tiejun (2010), because they consider an indicator of connectance.

Felicio et al. (2016) analyzed the indicators and proposed a new indicator entitled Industrial Symbiosis Indicator (ISI) that differs from that of Tiejun (2010) and was elaborated to capture the dynamic behavior of an EIP. According to Felicio et al. (2016), these indicators evaluate industrial symbiosis better according to the needs of managers and brokers interested in managing and controlling EIPs. The next sections describe each one separately.

Felicio et al. (2016) did not mention the paper of Park and Behera (2014) that proposes another approach to measure the industrial symbiosis, an indicator of Eco-Efficiency. The indicator of Eco-Efficiency also seems to be a promising indicator, but we consider that a comparison between the ISI and the indicators proposed by Tiejun (2010) is yet a challenger process.

2.1. Industrial symbiosis indicator (ISI)

The objective of ISI is to monitor the evolution of industrial symbiosis in an EIP. It can be used as a decision-making tool (Felicio et al., 2016) and is useful in the management of EIPs as dynamic systems. The formula expressing ISI is shown as Equation (1) (Felicio et al., 2016):

$$ISI = \frac{EIMi}{1 + EIMo} = \frac{\sum_{w=1}^{n}(AiP_w \times DiP_w)}{1 + \sum_{w=1}^{n}(AoP_w \times DoP_w)} \quad (1)$$

Where,

n: Number and type of by-products 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

The AiP variable represents the amount of by-products exchanged between EIP companies, while AoP represents the amount that leaves the park boundaries without being used. These quantities are measured in tons (Felicio et al., 2016).

The DiP and DoP variables, however, classify the degree of each by-product. The degree is a qualitative evaluation of the environmental impact of the by-products (Felicio et al., 2016). An example presented by the authors (Felicio et al., 2016) explains the importance of classifying the by-products according to their environmental impact. For example, 100 kg of cardboard cannot be compared to 100 kg of batteries owing to their different level of toxicity to the environment. Therefore, an indicator for measuring industrial symbiosis must consider not only the quantities of the by-products but also their environmental impact. The DiP and DoP variables through the ISI accomplish that goal. For that purpose, a qualitative assessment of environmental impact within certain criteria is used. Table 1 presents the criteria used, as well as the possible evaluations for each criterion.

In the case of the inbound by-product, only the criterion "destination of by-product" is not used, while for the outbound by-product the criterion "use of by-product" is not used (Felicio et al., 2016).

Equation (2) is used to calculate the "degree of inbound by-product" and "degree of outbound by-product" (DiP and DoP), for which the weight of the criterion is assigned by the indicator user.

$$DP = evaluation\ of\ the\ criterion \times weight\ of\ the\ criterion \quad (2)$$

Where,

DP: Degree of by-product (inbound and outbound)
Evaluation of the criterion: Can assume values of 1, 3, or 5
Weight of the criterion: Calculated through the Analytic Hierarchy Process

The ISI is composed of the relationship between the amount of by-product reused as raw material and amount of by-product that leaves the EIP, while considering the potential environmental impact of each material. It increases with increase in the amount of