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Agent-based simulation to evaluate and categorize industrial symbiosis indicators

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ABSTRACT

There is a research effort towards the understanding of industrial symbiosis and part of it is directed to the development of performance indicators. The result is a variety of indicators, which hinders the evaluation, comparison, and decision by researchers and practitioners. This paper presents a comparative evaluation of the industrial symbiosis indicators available in the literature. The indicators were simulated through an agent-based model in two distinct scenarios, in a stable environment and in one with significant changes. The behaviors of the indicators were compared and the results allowed the classification of the indicators into three groups: (i) those related to the amount of by-products reused; (ii) those that behave according to the percentage of by-products reused; (iii) those influenced by the number of links. Considering the differences in performance and complexity, amount of information for calculation, it is concluded that the best alternative is to combine indicators from different groups. The indicators Connectance & Eco-Connectance (simplicity), Eco-Efficiency (overall park impact), and Industrial Symbiosis Indicator (flexibility) stood out. The simulation proved to be a platform that can be used for the study and development of these indicators.

1. Introduction

Industrial symbiosis aims to draw together separate companies in a collective approach to the physical exchange of materials, water, energy and by-products, in an attempt to achieve competitive advantages (Chertow, 2000). The seminal example is the Kalundborg industrial complex, Denmark, where companies, in the 1970's, started to exchange energy and materials in a self-organized way (Chertow, 2000, 2007; Ehrenfeld and Chertow, 2002; Jacobsen, 2006; Valentine, 2016).

After Kalundborg, great effort was employed in attempts to replicate the phenomenon in other localities and, as Chertow and Ehrenfeld (2012) observed, most of these attempts were unsuccessful because industrial ecosystems resemble complex adaptive systems, subjected to changes that discourage the maintenance of industrial symbiosis relationships among the actors.

The current challenge is to consider this complexity. One of the efforts has been the proposal of performance indicators for industrial symbiosis measurement and monitoring (Hardy and Graedel, 2002; Dai, 2010; Zhou et al., 2012; Gao et al., 2013; Park and Behera, 2014; Wen and Meng, 2015; Trokanas et al., 2015; Felicio et al., 2016). It is understood that these indicators could be useful tools for managers to create initiatives for monitoring, evaluation, and an incentive to maintain the bonds of industrial symbiosis.

As identified by Mantese et al. (2016), these efforts are mainly devoted to proposals for new indicators, while the efforts towards evaluation and comparison of the proposed indicators are not in the same proportion. Especially regarding the direct comparison between the indicators in order to identify which one would be most suitable for each situation.

The authors who mostly considered this topic were Mantese and Amaral (2017), who presented a simulation model capable of representing an Eco-Industrial Park (EIP) and its symbiotic interactions to calculate the behavior of industrial symbiosis indicators. The indicators could be applied through different scenarios and without the need for actual data. The model was successfully tested, allowing the evaluation of the indicators proposed by Dai (2010) and Felicio et al. (2016).

The model proposed by Mantese and Amaral (2017) has certain limitations; it does not consider the amounts of final products produced and sold to other companies in the park, the energy consumption, the emissions of CO_2 in the atmosphere, and the

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financial value of symbiotic and non-symbiotic transactions between the companies of the park. The model considers only the amount of by-products, generated by the companies, that are reused by other companies or that are discarded.

Despite its limitations, this research showed that simulations allow the comparison between indicators. Would it be possible to improve the model proposed by the authors and then submit all the industrial symbiosis indicators to a comparison of their behavior in predefined scenarios? If so, could we identify similarities, differences, advantages, and disadvantages for each indicator in a comparative way and thus establish guidelines for the decisions of professionals and researchers?

This paper describes a comparative evaluation of the industrial symbiosis indicators. It presents the adaptations and advances introduced into the model proposed by Mantese and Amaral (2017), named *EIPSymb*, and the results of a comparison between the indicators proposed in eight studies, which were identified through a systematic literature review. This paper demonstrates their strengths, weaknesses and an indication for the combination of use and paths to make them more robust from a scientific point of view.

The method used in this paper was developed from the simulation model proposed by Mantese and Amaral (2017), the *EIPSymb*. It was necessary to make advances in the model to adapt it to the objective of a comparative evaluation and create a more sophisticated scenario, capable of challenging the limits of the indicators' behavior.

Section 2 presents the literature review. Section 3 describes the problem statement and the model that generated the simulations. Section 4 describes the requirements used to define the simulation scenarios and their parameterization. describe and discuss the results of the simulations, and Section 7, the conclusions.

2. Literature review

2.1. Industrial symbiosis indicators

Lombardi and Laybourn (2012) updated the industrial symbiosis definition provided by Chertow (2000), defining it as:

"Industrial Symbiosis engages diverse organizations in a network to foster eco innovation and long-term culture change. Creating and sharing knowledge through the network yields mutually profitable transactions for novel sourcing of required inputs, value-added destinations for non-product outputs, and improved business and technical processes" (Lombardi and Laybourn 2012, p. 29).

Industrial symbiosis can be observed through the cooperation of different entities through three transaction types: utility sharing, services joint provision, and exchanges of by-products to be reused as inputs (Chertow et al., 2008; Wu et al., 2006).

The definition of by-product is “something that is produced as a result of making something else” (Cambridge Dictionary, 2017). When we refer to a by-product, we are considering any kind of material in any state, except CO_2, energy and water, which were the result of the production process and are not the final product.

The evaluation of the industrial symbiosis level through indicators is one of the important challenges in the field. Mantese and Amaral (2016) performed a systematic literature review to identify the performance indicators for the measurement of industrial symbiosis in EIPs and identified eight papers, presented in Table 1. The indicators proposed by Gao et al. (2013) are identical to the indicators proposed by Dai (2010), with different names.

In addition to identifying the indicators proposed in the literature, Mantese and Amaral (2016) presented a brief description and a qualitative comparison, discussing the indicators' properties and differences. Despite the progress, their effort was not an systematic evaluation.

2.2. Validation of indicators

In the field of environmental science, the validation of indicators is a fundamental process before their use for decision-making. According to Bockstaller and Girardin (2003), it consists of verifying whether the indicator was scientifically designed, if the information provided is relevant, and if it is useful to the users.

Furthermore, they considered that validation could be divided into two stages, conceptual validation and empirical validation (Bockstaller and Girardin, 2003). The first is based on the evaluation of the indicator's conceptual data, such as information about its construction, where an always possible way is through the judgment of experts (Bockstaller and Girardin, 2003). The empirical validation takes place through statistical or visual procedures, where the indicator must be applied in a real situation or within simulated data (Bockstaller and Girardin, 2003).

Among the available methodologies for the validation of indicators, is the 3 S Methodology, by Cloquell-Ballester et al. (2006) based on expert judgment, which assigns grades to the indicator that is being validated based on established criteria.

Mantese et al. (2016) adapted the evaluation criteria of the 3 S Methodology for the specific validation of industrial symbiosis indicators. Furthermore, they suggested the use of indicator simulations in order to provide experts not only information on the indicator's construction, but also on its behavior in different scenarios (Mantese et al., 2016).

Another effort in this field was made by Mantese and Amaral (2017), who proposed a model, developed through the Agent-Based Modeling (ABM) technique, for the simulation of industrial symbiosis indicators. Initially the model was applied in the simulation of the indicators proposed by Dai (2010) and Felicio et al. (2016), with the potential to be extended to other indicators (Mantese and Amaral, 2017).

The number of proposals for indicators, however, is greater than the number of papers presenting applications or evaluations of these indicators. In the case of the evaluations, there are still no objective comparisons between the proposed indicators. Regarding the industrial symbiosis indicators identified in the literature by Mantese and Amaral (2016), and presented in Table 1, there are some arising questions:

- Are indicators different from each other?
- Which is the degree of similarity or differentiation between the indicators?
- In which environmental conditions are they advantageous?
- Which indicator to apply?

2.3. Agent-based modeling

The ABM is defined by Gilbert (2008) as a method for the creation of simulation models that are composed of agents that can interact with each other and with the environment. According Ghali et al. (2017), through ABM it is possible to verify the behavior of a complex system by modeling the individuals that compose it, that is, its agents. Similarly, Railsback and Grimm (2011) highlighted as an advantage of the ABM that it is only necessary to represent the state of the agents and not of the system as a whole.

The possibility of representing complex models is an aspect that approximates this technique to the study of industrial symbiosis, a phenomenon that involves several actors, decisions and interactions. Romero and Ruiz (2014) compared ABM with System Dynamics as alternatives for the simulation of symbiotic networks