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A Procedure to Validate Industrial Symbiosis Indicators Combining Conceptual and Empirical Validation Methods

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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 (EIP) and requires continuous monitoring of the professionals involved. Performance indicators for the measurement and monitoring of industrial symbiosis have been proposed and identified in the literature, however there is no consolidate indicator that is widely used in practice. These indicators require validation in order to evaluate and choose which options are able to measure the industrial symbiosis. There are two types of indicators validation, the conceptual validation and the empirical validation. This study investigates the integration of the conceptual validation and the empirical validation in the evaluation of the industrial symbiosis indicators. It is proposed the combined use of an indicator validation methodology based on expert judgment, the 3S Methodology, and a simulation technique, the Agent-Based Modeling (ABM). The proposed procedure aims to validate any indicator of industrial symbiosis, providing specific criteria to the evaluation.

Keywords. Industrial Symbiosis, Performance Indicator, Indicator Validation, Agent-Based Modeling.

Introduction

Industrial Symbiosis is characterized by a better use of by-products and waste. It is an essential part for the formation of Eco-Industrial Parks (EIP) [1, 2].

EIP is a concept of industrial arrangement created in the early 90's, where companies seek sustainable development through mutual cooperation [3, 4]. According to Lowe [4] and Veiga and Magrini [5], the concept has spread to several countries through applied projects and publications.

The industrial symbiosis monitoring and measurement in this type of park are imperative. Performance indicators have been proposed for this purpose. However, as noted by Rigby *et al*. [6], while is employed great interest in developing new performance indicators, little effort is intended to their validation. This is also observed with regard to the indicators for industrial symbiosis measurement, because none of the

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identified articles [7, 8, 9, 10, 11, 12, 13, 14] deals with the validation, but with their proposition or use.

Performance indicator validation is important because, according to Bockstaller and Girardin [15], it aims to verify if an indicator is scientifically designed, if it provides relevant information and if it is useful to its users. The validation provides greater accuracy to the indicator.

The indicator validation process can be dived into two stages: the conceptual validation and the empirical validation [15]. The first is based on the indicator data, information and description, where the validation through expert judgment is always possible [15].

Empirical validation is the indicator evaluation through visual or statistical procedures [15]. The indicator application is required, which can be accomplished through a real case or with simulated data [15].

The article proposes a procedure that incorporates aspects of both validation stages, comprising a validation methodology based on the expert judgment and a simulation through Agent-Based Modeling (ABM) technique.

1. EIP and Industrial Symbiosis

The Eco-Industrial Park concept was created in 1992 by the Indigo Development institute [4]:

> (...) a community of manufacturing and service businesses located together on a common property. Member businesses seek enhanced environmental, economic, and social performance through collaboration in managing environmental and resource issues. By working together, the community of businesses seeks a collective benefit that is greater than the sum of individual benefits each company would realize by only optimizing its individual performance [3].

According to Chertow and Ehrenfeld [16], an EIP should be considered as a dynamic system, where the park is a complex and adaptive environment, being influenced by external factors (*e.g.* market conditions) and internal factors (*e.g.* business strategies), and the system has the self-organizing ability. The industrial symbiosis is one of the ways by which an EIP can self-organize and achieve an equilibrium state [16].

The industrial symbiosis concept is presented by Chertow [17] as a metaphor where the industrial ecosystem mimics a natural ecosystem. It is responsible for the cooperation between different companies through the exchange of material, energy, water and by-products, achieving competitive advantages [17].

According to Chertow *et al.* [18], there are three types of symbiotic transactions: (i) utilities and infrastructure sharing; (ii) use of common services; (iii) by-product exchanges, where a company uses waste from another company as raw material.

Chertow [17] points out that geographical proximity is a key factor for the industrial symbiosis development, because it is through this proximity that the synergic cooperation possibilities arise. Finally, Felicio *et al.* [14] comment that the perfect symbiosis is impossible to reach, it can always be increased.

2. Indicators Validation

As already defined in the Introduction, the purpose of a performance indicator validation is to verify if the indicator is scientifically designed, if it provides relevant information and if it is useful to its users [15].

2.1. 3S Methodology

The 3S Methodology, by Cloquell-Ballester *et al.* [19], is an indicator conceptual validation methodology that aims to ensure quality, reliability and objectivity for indicators. It is based on expert judgment.

Criteria in the form of questions are used in the evaluation procedure. These criteria are separated into three classes (Conceptual coherence; Operational coherence; Utility) [19]. These criteria are presented in Table 1.

Table 1. 3S Methodology Evaluation Criteria.

Questionnaire to evaluate the indicators to be validated
Conceptual coherence
1.The definition of the indicator and the concepts that comprise it up is suitable
2.There is a biunivocal correspondence between the indicator and the factor to be quantified
3.The interpretation and meaning of the indicator are suitable
Operational coherence
1.The mathematical formulation of the indicator is suitable with regard to the concept which is to be quantified
2.The data used to establish the indicator and its units are suitable
3.The proposed measurement procedures to obtain the indicator are suitable, allowing for its reproduction and comparison
4.The indicator accuracy is suitable to quantify the factor and it is sensitive to changes in the latter
Utility
1.The indicator reliability is suitable
2.The reliability of the source of data which the indicator is made up of is suitable
3.The accessibility to the data and the applicability of the indicator are suitable
4.The information provided by the indicator may be catalogued as reliable
5.The cost of the information offered by the indicator can be considered acceptable

Source. Cloquell-Ballester *et al*. [19], p. 87.

The criteria classes are designed to satisfy the three conditions proposed by Bockstaller and Girardin [15]. The conceptual coherence aims to verify if the indicator is scientifically designed; while the operational coherence verifies whether the indicators provides relevant information; and the utility verifies whether the indicator is useful to users.

Experts are responsible for answering the questions, assigning scores 1 to 5 (Likert Scale), totally disagreeing or totally agreeing respectively [19]. An Indicator Report must be prepared so that the evaluators can access more easily the indicator's information [19].

The final score of each criterion is the average of evaluators' scores for that criterion. The criteria's scores are aggregated to form the classes' scores, which are aggregated to obtain the final score for the indicator. According to Cloquell-Ballester *et al*. [19], the indicator can be classified according to the Table 2.

Table 2. Indicator Classification.

Final sore	**Classification**
More than 4.5	Validated
Between 3.5 and 4.5	A brief review is required
Between 2.5 and 3.5	A thorough review is required
Less than 2.5	Unacceptable. Redefine

Source. Adapted from Cloquell-Ballester *et al*. [19].

The 3S Methodology consists of three stages, differentiated by the type of evaluator [19]: (i) Self-validation – Executed by the working team that developed the indicator; (ii) Scientific validation – Conducted through independent expert judgment; (iii) Social validation – Includes public participation.

2.2. Simulation in the Indicators Validation

According to Bockstaller and Girardin [15], a way to proceed with the empirical validation of an indicator is evaluating its behavior through simulation.

Among the various techniques employed to produce a simulation, Agent-Based Modeling emerges as the main option for an EIP. It has, as one of its main advantages, the no need to represent the system completely, but only its individual agents, so it is possible to understand the dynamics that results from the interaction of agents with each other and with the environment. This makes the modeling process simpler.

Furthermore, there are studies that used the ABM to represent an EIP. The model proposed by Bichraoui *et al*. [20] focuses on understand the cooperation and learning conditions that permeate the park. While the model proposed by Romero and Ruiz [21] has the aim to evaluate the influence of the symbiotic relationships in the global operation of the EIP.

3. Proposal of a procedure to validate industrial symbiosis indicators combining simulation and the 3S Methodology

The proposal of the new procedure to validate industrial symbiosis indicators is divided into three phases. At first, the 3S Methodology is adapted with regard to the evaluation criteria in order to be applied in industrial symbiosis indicators. Second, a simulation model of an EIP, that considers its symbiotic relationships, is proposed. Finally the integration between the two previous phases is described, resulting in the new validation procedure of industrial symbiosis indicators.

3.1. Adapting 3S Methodology

There are no specific criteria for the evaluation of industrial symbiosis indicators in the literature. Furthermore, the criteria proposed by Cloquell-Ballester *et al*. [19] were considered superficial, too much embracing, and even repetitive.

The first adaptation of 3S Methodology identified as necessary is the adaptation of the criteria proposed by Cloquell-Ballester *et al*. [19]. Table 3 presents the new criteria, specifics for the application on industrial symbiosis indicators.

Table 3. Evaluation criteria adapted for the application on industrial symbiosis indicators.

Questionnaire to evaluate the indicators of industrial symbiosis to be validated
Conceptual coherence
1. The indicator measures the exchange of water, energy and by-products between companies in a eco-industrial park eco industrial, correct representing the industrial symbiosis
2. The indicator classifies the different by-products in accordance with appropriate criteria
3. The indicator considers amounts of by-product reused. In a direct way*
4. The indicator considers amounts of by-product discarded
Operational coherence
1. The mathematical formulation is suitable for measuring industrial symbiosis, taking into account the aspects that must be quantified
2. The data needed to calculate the indicator are relevant, while there are no data that are relevant and are not considered
3. The measurement procedures for obtaining the data are adequate, allowing their reproduction and comparison
4. The indicator is able to indicate trends
5. The numerical result has no limit, meaning that the industrial symbiosis can always be improved
6. The indicator allows comparison with other parks
Utility
1. The indicator calculation and its procedures do not require excessive effort
2. Data sources are reliable
3. Data sources are easy to access
4. The indicator final result has meaning
5. The costs required for data collection and indicator application are acceptable

*The indicator is able to record directly the by-products that are reused, rather than, for example, quantify them by the decrease in the use of virgin raw material.

The criteria classes was not changed, because they are in accordance with the presented by Bockstaller and Girardin [15] in the indicators validation theory. The criteria adaptations were based on the EIP and industrial symbiosis theory, presented in Section 1. In addition, the studies containing the symbiosis indicators [7, 8, 9, 10, 11, 12, 13, 14] were also studied. However, due to space limitation, details of these indicators are not presented.

Another adjustment made in 3S Methodology concerns the three stages differentiated by the type of evaluator. The 3S Methodology authors, Bockstaller and Girardin [19], argue that, with this differentiation, the indicator credibility increases with the passage through the three stages. We do not disagree with the authors, however, we believe that this restricts the use of the 3S Methodology to the indicator creators. And the intention is that the procedure proposed here be used both by the indicator creator and by who wish to use the indicator or by who just wish to validate it. The proposed adaptation is to extinguish this differentiation of evaluators.

3.2. EIP Simulation through ABM

There is no study that uses an agent-based model in the representation of an EIP that aims to apply performance indicators. So we developed a simulation model of an EIP through ABM technique, using the NetLogo [22] platform, which has the purpose of representing the interactions between the companies that compose the EIP with regard to by-products flow, and allows the calculation of industrial symbiosis indicators.

In summary, the model allows:

- Entrance and exit of companies in the EIP;
- Creation of by-products exchange links between companies;
- Variation in the amounts of by-products traded between companies;
- Variation in the amounts of by-products generate by each company;
- Dispatch of by-products not used to the landfill.

The model behavior depends on input data provided by the user, which can calibrate the model in different scenarios. To consider the calculation of the indicators it is necessary to modify the source code of the model in order to include the calculation of the desired indicators. This requires additional effort, however, because it was used the ABM technique, this effort is not excessive. Furthermore, the most complex part of the source code is already written. However, due to space limitations, the model will not be described in detail.

3.3. Integrated Validation Procedure

3S Methodology, according to Section 2.1, proposes that an Indicator Record should be created, so the evaluators have access more easily to the information about the indicator to be validated. The integration between conceptual and empirical validations happens at this point. We propose that simulations complement the Indicator Report. More than theoretical information about the indicator and its construction, the report will also contain simulations of the indicator behavior, demonstrating its evolution in different scenarios.

The one interested in validating the indicator must establish the preconditions to guide the construction of scenarios. These conditions can be grounded by aspects that differentiate the indicator or by a set of typical events in an EIP. The one responsible for designing the Indicator Report is the right person to perform the simulations through the model and, eventually, by inserting the indicator calculation in the source code.

4. Result

The result is the validation process of industrial symbiosis indicators, named "Integrated Validation Procedure for Industrial Symbiosis Indicators". Figure 1 presents the process of this new procedure.

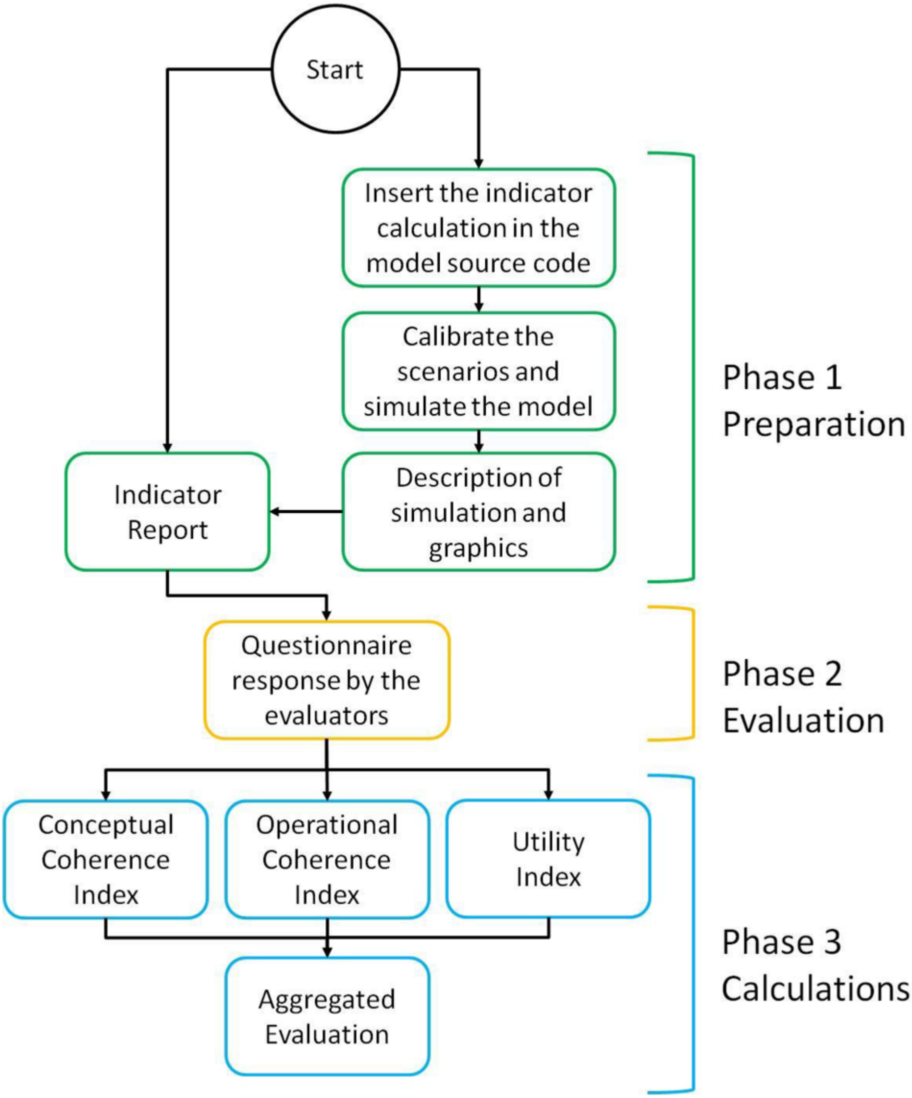


Figure 1. Integrated Validation Procedure for Industrial Symbiosis Indicators.

The process is divided into three phases: (i) Preparation; (ii) Evaluation; (iii) Calculations. Although the Evaluation phase is the "core", because it is in this phase that the experts assign scores to the criteria, the Preparation phase is the most laborious and has great importance, because it is in this phase the documents that will guide the whole evaluation are created. Any errors or omissions may jeopardize the entire process.

The Evaluation phase comprises only the questionnaire response by the evaluators, the questionnaire is presented in Table 3. The last phase, Calculation, is where the evaluators' responses are compiled and the scores of each of the three indices (Conceptual coherence; Operational coherence; Utility) and the Aggregated Evaluation are obtained. For the final decision, whether the indicator is validated, we followed the recommendation of Cloquell-Ballester *et al*. [19] presented in Table 2.

With regard to Indicator Report, we took the suggestion of minimum content, by Cloquell-Ballester *et al*. [19], and added the description of the simulations. Table 4 shows what these information are.

Table 4. Minimum content of Indicator Report.

Guide for indicator report	
1. Indicator	Name of the proposed indicator
2. Aspect	2.1. Name of the environmental or social aspect (system component) to be quantified through the indicator 2.2. Description: description of the environmental or social characteristic that represents the aspect
3. Description	3.1. Conceptual definition: definition of the indicator and of the concepts and characteristics that it is made up of 3.2. Description of data and units: description of the data and units used to quantify the environmental aspect 3.3. Operational definition: definition of the mathematical expression used to quantify the environmental aspect 3.4. Measuring method: details about sampling and/or measuring procedures followed by the indicator to be obtained. Possibility to reproduce and compare the measurement
4. Justification	4.1. Interpretation/meaning: Description of its interpretation and meaning through explanation of its operation 4.2. Accuracy: explanation of the indicator's accuracy and sensitivity to changes in the factor and security of both information and data 4.3. Relevancy: explanation of the indicator's relevancy to represent the characteristic that is to be quantified (aspect)
5. Sources	Availability of data sources. Name of the documents and/or files where the data comes from
6. Simulations	6.1. Scenarios description: description of the scenarios calibrated to simulate the indicator 6.2. Simulations: graphics and numerical results of the indicator during the simulated period 6.3. Behavior: description of the indicator behavior in each scenario

Source. Adapted from Cloquell-Ballester *et al*. [19].

Figure 2 presents an example on how the part that explains the simulations in the Indicator Report should be provided to the evaluators. We choose to present only this part because this is the innovative part of the report. It should be created as many scenarios as it deems necessary to represent the behavior of the indicator that is being validated.

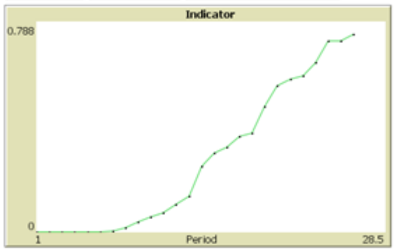
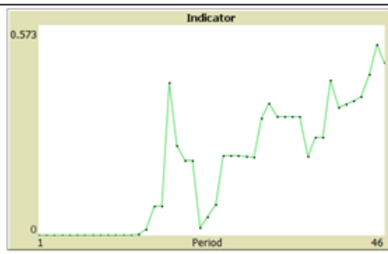
<table>
<tr><th></th><th>6.1. Scenario description</th><th>6.2. Simulation</th><th>6.3. Behavior</th></tr>
<tr><td>Scenario 1</td><td>The scenario describes an optimal situation for the development of the industrial symbiosis, where the companies in the EIP are willingness to exchange by-products...</td><td>
</td><td>In the simulation was observed increase at every period, the indicators behavior is explained because...</td></tr>
<tr><td>⋮</td><td>⋮</td><td>⋮</td><td>⋮</td></tr>
<tr><td>Scenario n</td><td>Description of the scenario.</td><td>
</td><td>Description of the indicator behavior.</td></tr>
</table>

Figure 2. The Simulation part in the Indicator Report.

5. Conclusion

The procedure proposed combines aspects of both conceptual and empirical validations to validate any indicators of industrial symbiosis. The gain in insert the simulation in a validation through the expert judgment is the provision of more information of different kinds to the evaluator, which will have more knowledge on the indicator.

The adaptation of the evaluation criteria for the specific application in industrial symbiosis indicators is another positive aspect of the procedure. Due to the possibility to simulate more than one indicator at the same time, this procedure also allows the evaluators to compare the indicators during the process of assigning scores to the evaluation criteria.

The need of great effort in the Preparation phase, particularly with regard to the simulation, is considered the main difficulty in applying the procedure.

This paper provides only the proposal of this new procedure, the practical application has not yet been held. As a next step, we will apply the procedure, verifying its applicability and possibly improving and proposing a final version.

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