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RESEARCH ARTICLE

Pilot testing model to uncover industrial symbiosis in Brazilian industrial clusters

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Abstract The main objective of this study was to create a pilot model to uncover industrial symbiosis practices in Brazilian industrial clusters. For this purpose, a systematic revision was conducted in journals selected from two categories of the ISI Web of Knowledge: Engineering, Environmental and Engineering, Industrial. After an in-depth revision of literature, results allowed the creation of an analysis structure. A methodology based on fuzzy logic was applied and used to attribute the weights of industrial symbiosis variables. It was thus possible to extract the intensity indicators of the interrelations required to analyse the development level of each correlation between the variables. Determination of variables and their weights initially resulted in a framework for the theory of industrial symbiosis assessments. Research results allowed the creation of a pilot model that could precisely identify the loopholes or development levels in each sphere. Ontology charts for data analysis were also generated. This study contributes to science by presenting the foundations for building an instrument that enables application and compilation of the pilot model, in order to identify opportunity to symbiotic development, which derives from "uncovering" existing symbioses.

Keywords Industrial symbiosis · Sustainable development · Industrial cluster · Fuzzy logic

Introduction

One of the new conceptions of industrialization started to be formed in 1989, when Robert Ayres coined the concept of industrial metabolism. By creating an analogy between industries and living organisms, industrial metabolism includes all material and energy flows through an industrial system (Erkman 1997). The first studies on industrial symbiosis were based on technical and financial perspectives. This led to the pursuit of a solid understanding on how industrial networks and human resources work (Sopha et al. 2009). There are several definitions of the concept of industrial symbiosis (IS), but it is basically defined as a synergy of by-products and waste between companies, with industrial ecology as the key tool (Vachon and Klassen 2008); Giannetti et al. 2008; Sopha et al. 2009; Mattila et al. 2010; Yang and Feng 2008).

Sharing material resources, energy, water and by-products between co-located companies is one of the main characteristics of industrial symbiosis (Chertow 2000; Yang and Feng 2008; Eckelman and Chertow 2009; Sopha et al. 2009; Jensen et al. 2011), which is being increasingly pinpointed as a way to

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reduce the environmental impact caused by industrial productions (Eckelman and Chertow 2009).

The practices of symbiotic relationships may occur at different levels, whether between companies in nearby locations or at national level. IS practices can evolve in a planned or spontaneous manner, such as the industrial symbiosis of Kalundborg, in Denmark, which is the most classical example of IS addressed by literature in the eco-industrial park (EIP). Industrial symbiosis is commonly characterized by the physical exchange between collaborating companies (Sopha et al. 2009). However, an important aspect of industrial symbiosis can also be the establishment of agreements between otherwise unrelated companies that leads to resource efficiency (Mattila et al. 2010; Jensen et al. 2011).

The development and operationalization of industrial symbiosis depend on several factors in different domains. According to Heeres and Vermeulen (2004) and Sopha et al. (2009), for industrial symbiosis to occur, relations must be aligned with the technical, financial, political, informational and organizational domains. In summary, the basic concept of industrial symbiosis is an attempt for man to learn and apply the principles of the natural ecosystem to the industrial system (Sopha et al. 2009).

However, any discussions on the environmental benefits seem to refer to existing symbioses in case studies with little analysis of variables or focus on modelling the process to implement industrial symbiosis in new industrial environments. The question on the existing potential for new symbiotic relationships and the extent of the full potential of obtaining environmental benefits through industrial symbiosis is a continuous study topic in scientific research (Eckelman and Chertow 2009). Literature addresses the principles to make industrial processes increasingly sustainable, but there is a lack of information on how to apply these principles. This leads to the evident absence of a methodology that can provide guidelines on how to uncover industrial symbiosis.

Discussions on environmental benefits mostly focus on existing exchanges. Studies on the existing potential for new symbiotic relationships and measuring the environmental effect are less common (Eckelman and Chertow 2009). Literature does not provide much information on finding methods that define and evaluate sustainability in complex systems, as most studies and data in literature on industrial symbiosis are derived from already established and known cases and practices (Eckelman and Chertow 2009).

Chertow (2007) offers an important theoretical contribution in exploring what symbiotic relationships look like before they are broadly known and at what point they are "uncovered" in industrial ecosystems. This also raises perspective for future studies suggesting that self-organizing symbiosis projects are not known until there has been some success and an uncovering event occurs. As Professor Chertow's research has shown, even when several exchanges had been implemented across firms based on self-organization, the participants and neighbours generally had not recognized or described these phenomena in environmental terms, until some sort of uncovering event had occurred, either during the initial period or later on when exchanges were more deeply rooted (Chertow 2007).

In Brazil, development of industrial clusters is of great importance in the country scenario as IPEA-Consolidated Report (2006). Furthermore, there are country programs such as "Mineiro" Industrial Symbiosis Programme, a Brazilian version of NISP (National Industrial Symbiosis Programme) UK and as the National Policy on Solid Waste (PNRS), Law 12.305/10. Despite these initiatives, not many results associated with these attempts have been observed.

Although there are pre-existing locational advantages, cooperation and physical exchanges in Brazil, besides of those specific programs mentioned, self-organizing symbiosis projects are not known in any of these clusters and they are not attempting to follow a symbiosis model. Besides, in developing countries where industrial symbiosis concept is brand new and not well known by small enterprises of industrial clusters, several potential aspects and actions similar to industrial symbioses might be happening. But maybe, they have not been uncovered yet.

Therefore, an opportunity to symbiotic development derives from "uncovering" existing symbioses because it has led to more sustainable industrial development than attempts to design and build eco-industrial parks (Chertow 2007). In this sense, this research aims to answer the question: *How to uncover industrial symbioses in Brazilian industrial clusters?*

For that, this study presents the development of a conceptual qualitative and quantitative pilot model that helps to diagnose industrial symbiosis practices through the systematic revision of aspects that form the concept of industrial symbiosis. Moreover, "although there are various international efforts on measuring sustainability, only few of them have an integral approach taking into account environmental, economic and social aspects. In most cases the focus is on one of the three aspects" (Singh et al. 2012).

This study takes into account all three aspects matching them on a method to assess the existence of industrial symbiosis practices. Also, the conceptual pilot model covers the qualitative basis on which to develop the quantitative component of indicator identification by using the fuzzy logic as multicriteria decision analysis (MCDA) method to attribute variable importance. The originality of this study lies in the development of a pilot model for industrial symbiosis and its correlations, which can be empirically applied to guide the initial stages of industrial symbiosis—and potential development aspects—especially for environments in which practices can be implicit. By creating a pilot model that can assess the presence of industrial symbiosis practices, this study seeks to promote the concrete development of industrial symbiosis.

Research methodology

This exploratory study comprises two key stages:

1. Identify basic interrelations of industrial symbiosis
2. Apply a methodology to attribute variable weights

In the first stage, the basic interrelations of industrial symbiosis were identified using a systematic criterion at ISI Web of Knowledge website, where the 2010 JCR was obtained in the categories Engineering, Environmental and Engineering, Industrial. The search criteria for each journal were defined as "industrial ecology" and "industrial cluster", and the time limit was articles published since 2008.

In the second stage, a questionnaire based on the interrelations identified in literature was created to attribute importance, followed by the selection of two groups of specialists. The fuzzy set methodology was used to attribute the weights of variable interrelation.

Identification of industrial symbiosis variables

In the Engineering, Environmental category of the ISI Web of Knowledge website, there are 45 journals with IF ranging from 9.333 to 0.261. For this study, the adopted criterion was all articles that match the percentile rank of 70 (IF > 1.032), totalling 32 journals. Of the 32 journals with the greatest factor impact in the Engineering, Environmental category, five were not available. Therefore, 27 journals of the Engineering, Environmental category were selected.

In the Engineering, Industrial category, there were 38 journals with an IF ranging from 2.993 to 0.062. Based on the same selection criterion, journals with a percentile rank of 70 (IF ≥ 0.655) were selected, totalling 27 journals. Of the 27 journals in the Engineering, Industrial category, four were not available. Therefore, 23 journals of the Engineering, Environmental category were selected.

Filtering articles in those journals consisted of reading title and abstract, summarizing and excluding repeated articles, and the remaining articles were read in their entirety to then build the tool. After filtering and exclusion of repeated articles, the resulting articles were fully read, as shown in Table 1.

An in-depth study was conducted on each article selected in journal of the Engineering, Environmental and Engineering, Industrial categories, with keywords Industrial Cluster and Industrial Ecology. Based on the in-depth study of the 55 articles and confrontation of their ideas and concepts, it was possible to identify the main citations and references of a given aspect. At this stage, with a systematic and detailed study of each article, it was also possible to extract the key factors considered fundamental for industrial symbiosis to occur. With this theoretical contribution, according to literature, the main basic relationships—symbiotic transactions—needed in all activities of industrial symbiosis are by-product exchange, sharing of utilities and/or services and cooperative management. The synthesis of each of these concepts is shown in Table 2.

Table 1 Total selected articles for full reading. Source: Authors

Journal categories/ keywords	Engineering, Environmental	Engineering, Industrial	Total
Industrial ecology	34	14	48
Industrial cluster	4	3	7
Total	38	17	55

Although Table 2 represents the synthesis of the main citations of symbiotic transactions by the authors listed above, it does not mean that each author addressed the three spheres; any mention by an author on any of the three spheres was considered. Literature evidently emphasizes the exchange of waster or by-products as the key characteristic of industrial symbiosis. This is unquestionably an important element. However, if the aim is sustainability—the foundation of industrial symbiosis—an all-encompassing outlook that involves financial, social and ecological aspects is required (Veiga and Magrini 2009). Therefore, a tool that helps to diagnose industrial symbiosis must be aligned with the key domains of sustainable development and its pillars.

Industrial symbiosis operation domains

Literature on sustainability indicates some variables that extrapolate the environmental pillar and are essential for sustainable development to occur, such as the need for technique and financial resources, the organizational aspect of the nature of the decision-making process, awareness on the aspects related to information and know-how and attitudes of the actors (Ehrenfeld and Gertler 1997; Korhonen 2002; Heeres and Vermeulen 2004; Sopha et al. 2009). Some approaches denominate these variables as domains, sometimes considered barriers to industrial symbiosis. In others, they are considered success factors.

Approaches that address the sustainability of productive systems and determining aspects in this context, whether considered barriers or success factors, were used to identify the operation domains of industrial symbiosis. Thus, Table 3 shows definition and domains of operation for symbiotic transactions.

A systematized bibliographical revision allowed the identification of the key domains and revealed the relevant approaches that were included. During article analysis, the mention of any of the domains in the context of sustainable development was considered. Again, those that mentioned domains previously presented by other authors in the assembly of Table 3 were not excluded.

Table 2 Spheres of industrial symbiosis relationships. Source: Authors

Definition		
The definition of industrial symbiosis is based on three symbiotic transactions:		
By-product exchange	Sharing of utilities and/or services	Cooperative management
Use of waste of other companies as raw material	Such as water treatment for re-use, power and waste treatment	Cooperation in topics of mutual interest, such as planning, training or management of sustainability

Authors: Chertow (2007); Schmidt and Schwegler (2008); Bailey et al. (2008); Yang and Feng (2008); Zhang et al. (2008); Eckelman; Chertow et al. (2008); Chertow (2009); Geng et al. (2009); Veiga and Magrini (2009); Heidrich et al. (2009); Li (2009); Liwarska-Bizukojc et al. (2009); Kovanda et al. (2009); Schönsleben et al. (2010); Mattila et al. (2010); Bain et al. (2010); Pakarinen et al. (2010); Tiejun (2010); Sopha et al. (2010); Anh et al. (2011); Taskhiri et al. (2011); Coli et al. (2011); Schoenherr (2011); Goldstein et al. (2011); Jensen et al. (2011); Lehtoranta et al. (2011); Rodríguez et al. (2011); Mu et al. (2011); Zhang et al. (2011); Coelho et al. (2012); Despeisse et al. (2012); Ohnishi et al. (2012); Smith and Ball (2012); Zhu et al. (2012)

Once the main necessary relationships were identified to characterize industrial symbiosis, a theoretical pilot model was created. After establishing the spheres and domains, the most important aspects for a cluster of companies to be considered industrial symbiosis are easily comprehended. Withal, the creation of a pilot model is quite complex. Models are simplified and intelligible representations of the world that help to reveal the essential characteristics of a domain or field of study (Sayão 2001). A model "is a cultural creation used to represent a reality, or some of its aspects, to make it qualitatively and quantitatively describable and, sometimes, observable" (Sayão 2001, p. 83).

The components can be endogenous variables (control), exogenous variables (non-controllable) and parameters. Endogenous variables express the consequences of exogenous variables. Exogenous variables are considered non-controllable and introduce external information needed for the tool (Leite 2000). Parameters are stable and generally constant values.

A conceptual framework was created taking into account the essential components required to build a model and the complexity of aspects of industrial symbiosis extracted from literature. The mechanism consolidated in the developed pilot model is graphically represented in Fig. 1.

"Endogenous" and "exogenous" variables are aspects that were identified in literature as being necessary for industrial symbiosis to occur. The correlation of these variables occurs in the "black box" shown in Fig. 1 (black box that cannot be opened). It is assumed that exogenous variables influence the behaviour of endogenous variables considering that, for example, for *by-product exchanges* to occur, some technical

Table 3 Industrial symbiosis operation domains. Source: Authors

Domains	Definition	Factors
Technical	The relationship is technically feasible in chemical, physical and spatial terms between exchange flows, compatible between needs and capacities, and with accessible technology costs.	Labour; Physical structure; Logistic structure
Financial	The relationship must be financially feasible or not present financial risks in terms of virgin input costs, value of waste and by-product flow, transaction and costs of opportunity, size of capital investment and discount rates.	Investments; Financial return; Competitiveness
Policy	Caused by several legal aspects and environmental regulations, such as international policies, fiscal and tax elements, rates, fines, subsidies and credit.	Fiscal elements; Fines; Credit lines; Policies
Informational	The right people need the right information at the right time. Access and availability of relevant information between areas and with the correct orientation, and continuous information management.	Information management actions
Organizational and institutional	The goal must be aligned with the organizational structure of the company at several levels, in terms of trust, opening, environmental maturity, level of social interaction and proximity, local availability when making decisions, company history, nature of interaction between the industries, policy formulators and organization culture (familiarity).	Mission statement; Vision; Strategic planning

Authors**:** Ehrenfeld and Gertler (1997); Korhonen (2002); Heeres and Vermeulen (2004); Chertow (2007); Yang and Feng (2008); Sopha et al. (2009); Kovanda et al. (2009); Bain et al. (2010); Schönsleben et al. (2010); Schönsleben et al. (2010); Taskhiri et al. (2011); Coelho et al. (2012); Despeisse et al. (2012); Chertow and Lifset (2013)

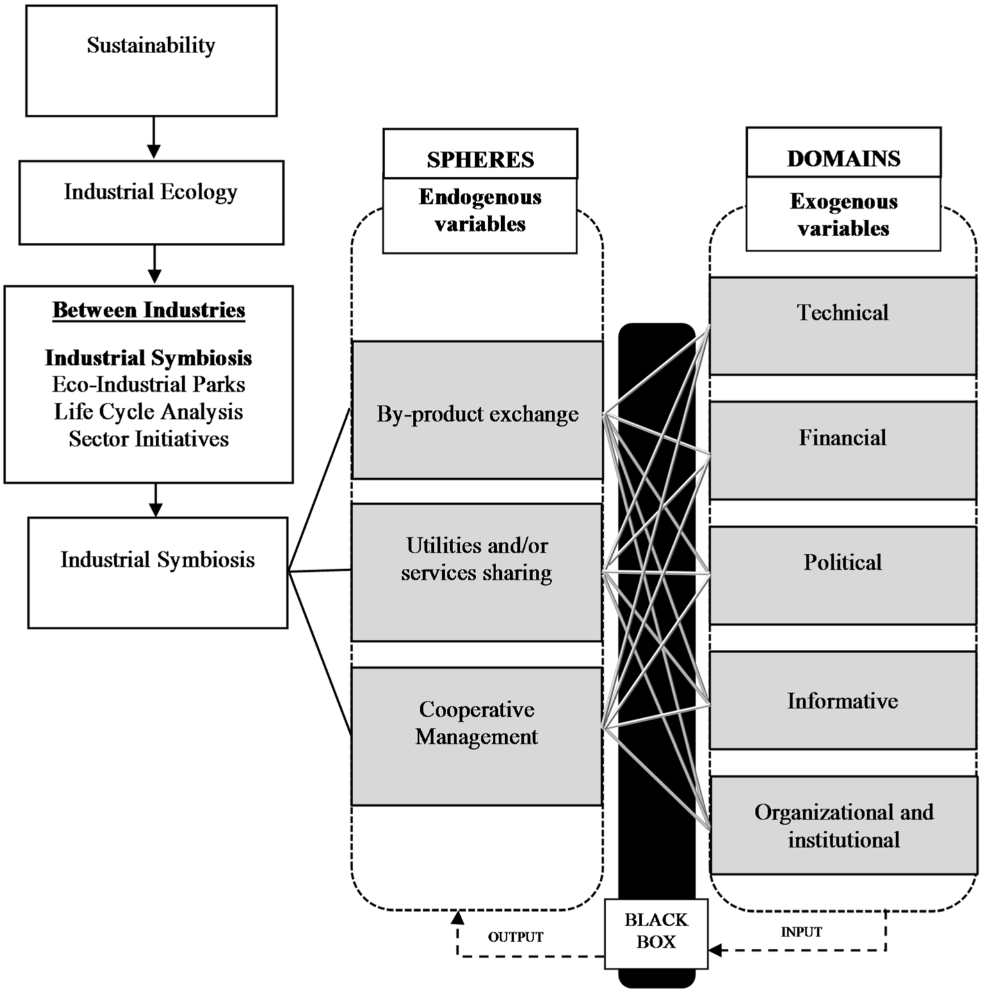

Fig. 1 Analysis structure of industrial symbiosis interactions: spheres and domains. Source: Authors

condition is required, and some financial capacity; some public incentive policy or internal policy of companies that reinforces this vision will influence the exchange; the informative aspect to know the supply and demand of by-products will influence the exchange; the *organization and institutional structure* of companies and of the cluster may aid by-product exchanges. These influences occur in parallel to the other variables, as shown in Fig. 1.

Furthermore, the observation of consolidated phenomena in the model shows that correlations between endogenous and exogenous variables result in industrial symbiosis. Some of these phenomena require greater control from companies, such as cooperative management. Others suffer the influence of several external factors, such as those that result from the behaviour of individuals or from the national and international macroeconomic environment. Withal, the levels of importance of these correlations are unknown. Literature addresses each of these correlations as necessary for industrial symbiosis to occur. However, the level at which each of the correlations influences industrial symbiosis activities has not been established.

Therefore, to precisely evaluate the development level of industrial symbiosis in an industrial cluster, or the precursor of activities, these attributions are fundamental. Thus, after substantiating the structure, it was also possible to identify the level of importance of each consolidated correlation in this pilot model. A tool was created for this purpose, in the form of a questionnaire containing the basic variables of the main relationships presented in the figure. This tool and its questions were created by researchers and members of the ISIE—International Society for Industrial Ecology, by means of several support and adjustment meetings.

After all the recommended adjustments were made to the questions, a multicriteria decision analysis (MCDA) was used to calculate the weight of the variables. "MCDA is a set of methods that can be used to support the process of decision making by taking into consideration multiple criteria in a flexible manner, by means of a structured and intelligible framework" (Cinelli et al. 2014).

The selected MCDA method to attribute the weights of variable interrelation was fuzzy logic. The Fuzzy Set Theory was created by mathematician Lotfi Zadeh and the bases of this theory were published in 1965 in the *Information and Control Journal* (Oliveira 2006; Oliveira 2012). In summary, fuzzy sets help researchers conceptualize social and political phenomena as a set of imprecise limits that vary from "full pertinence" to "total exclusion" (Klir and Yuan 1995).

According to Zadeh (1988), a central point of fuzzy logic is that it seeks to model imprecise modes of reasoning that play an important role in the capacity to make rational decisions in an uncertain or imprecise environment. In turn, this capacity depends on the human capacity to infer an approximate answer to a question based on a knowledge base that is inexact, incomplete or not fully reliable. The fuzzy set method is very diversified, with a wide range of possible applications (Ragin and Pennings 2005).

Fuzzy pertinence scores define the level at which each variable pertains to a set—which is different from multivariate analysis with the AHP method that uses a hierarchical structure of problem evaluation criteria for the decision-making process (Gomes et al. 2004). Fuzzy sets identify qualitative states, while also evaluating different levels of association between full inclusion and total exclusion. In this sense, a fuzzy set can be considered a continuous variable intentionally calibrated to indicate the pertinence level of a given set (Ragin and Pennings 2005).

According to Oliveira (2012, p. 32), fuzzy logic "is capable of absorbing vague information that is normally described in natural language and of converting it to a number format that can be easily managed in a computer, in order to model the imprecise mode of human reasoning and aid human decision-making skills". In the first stage, in order to make a pilot test, all the results from the questionnaires answered by the specialists were collected to obtain a better understanding of the dynamics of industrial symbiosis.

In the context of analysing industrial symbiosis variables, it is therefore necessary to identify the pertinence level of the answers of specialists to then identify the pertinence of each variable. The answer scores were 1 (No importance), 2 (Little importance), 3 (Moderate importance), 4 (Important) and 5 (Very important) and the level of certainty was between 0.00 (full denial of the alternative) and 0.10 (full acceptance of the alternative). An answer of 3.85, for example, ranged between moderate and important with a strong tendency to be important. Then, specialists on the topic were asked to answer the questionnaire. These experts were selected to attribute the level of importance of correlations. Two groups were selected:

Kalundborg symbiosis Located in Denmark, the Kalundborg Eco-Industrial Park started its activities in 1963. It is an industrial ecosystem where waste from one company is used as a resource by another company, in a closed cycle, resulting in mutual financial and environmental benefits.

Industrial symbiosis LinkedIn group LinkedIn is a professional tool. The industrial symbiosis group in LinkedIn was created on March 13, 2009, and has more than 600 members, including students, professors and specialists on the subject from several parts of the world. The group is committed to promoting discussion and information on this subject. Participants hold daily debates on related topics (IS LINKED IN 2013).

The selected group of specialists portrays knowledge and experiences related to industrial symbiosis in various parts of the world. From the two groups of specialists to which the questionnaires were submitted, 12 (twelve) completed questionnaires were returned. When data consistency was tested, one generated fuzzy set was non-convex and another was inconsistent and they were both discarded. This resulted in 10 (ten) valid questionnaires.

The pertinence level of the answers of specialists was first identified to then identify the pertinence of each variable. The answer scores were 1 (No importance), 2 (Little importance), 3 (Moderate importance), 4 (Important) and 5 (Very important) and the level of certainty was between 0.00 (full denial of the alternative) and 0.10 (full acceptance of the alternative). An answer of 3.85, for example, ranged between moderate and important with a strong tendency to be important.

Results were checked based on fuzzy logic and separated by the country of each respondent; all of which belong to the industrial symbiosis LinkedIn group. The "Kalundborg" line shows the answer of specialists of the Kalundborg Symbiosis Eco-Industrial Park, in Denmark. Results of the by-product exchange sphere are shown in Table 4.

Results represent a valuable scenario, as they agree with the literature review approach in which the exchanging of by-products is considered a key factor of industrial symbiosis and show the importance in the cooperation sphere, which has the force to make the other spheres effectively occur.

Result analysis and assessment structure

Analysing those results, in the three key spheres of Exchange, Sharing and Management, standard deviation was relatively lower than when the interrelations with the domains were analysed. This shows a uniformity in the responses of the specialists and that regardless of the country or field of knowledge of the specialist, the importance of the "Spheres" variables also shows uniformity.

In relation to the interrelations of the spheres with the domains, considering they are subject to external interference—such as business culture of the country and macroeconomic scenario—and considering that the sample comprised respondents from all over the world, uniformity of the answers was lower, which justifies a greater standard deviation in some of the analysed domains.

Table 4 Results of level of importance: exchange sphere/sharing sphere/cooperative management sphere

Exchange sphere	Specialists		1	1.1	1.2	1.3	1.4	1.5
	Sphere-domain		Exchange	Technique	Financial	Policy	Informational	Organizational
	IS LinkedIn	USA	5	5	5	2	5	1
		Germany	3.43	4.56	4.56	3.15	3.71	3.54
		UK	3.50	3.33	2.60	3.50	3.25	3.40
		Sweden	3.86	4.00	3.71	3.76	3.72	3.95
		Portugal	4	5	5	5	3	3
		Holland	4.17	4.17	4.17	1.00	2.58	2.58
		Taiwan	4.00	4.00	3.83	4.17	3.83	4.00
		Denmark	4.04	4.04	3.96	4.00	4.00	2.04
		Spain	2.36	3.18	3.26	3.33	3.29	3.40
	Kalundborg symbiosis	Kalundborg	4.04	4.14	4.09	4.04	4.04	4.04
		Average	3.84	4.14	4.02	3.40	3.64	3.10
		Standev	0.67	0.60	0.74	1.15	0.67	0.98
Utilities and/or services sharing sphere	Specialists		2	2.1	2.2	2.3	2.4	2.5
	Sphere-domain		Sharing	Technique	Financial	Policy	Informational	Organizational
	IS LinkedIn	USA	3	5	5	1	5	1
		Germany	2.71	2.48	4.42	2.00	2.29	3.88
		UK	3.33	3.29	3.67	3.40	3.40	2.60
		Sweden	3.58	3.64	3.83	3.88	3.81	3.92
		Portugal	4	5	5	5	4	3
		Holland	3.62	4.17	4.17	1.40	4.06	4.22
		Taiwan	4.17	4.17	4.17	4.17	3.83	4.17
		Denmark	3.00	3.40	3.40	2.60	3.96	3.96
		Spain	2.84	3.47	3.46	3.00	3.00	0.00
	Kalundborg symbiosis	Kalundborg	4.04	4.04	4.04	4.09	4.09	4.09
		Average	3.43	3.87	4.12	3.05	3.74	3.08
		Standev	0.53	0.78	0.57	1.30	0.72	1.48
Cooperative management sphere	Specialists		3	3.1	3.2	3.3	3.4	3.5
	Sphere-domain		Cooperation	Technique	Financial	Policy	Informational	Organizational
	IS LinkedIn	USA	3	4	5	3	4	5
		Germany	4.50	4.50	4.53	3.63	4.42	4.43
		UK	3.40	3.40	3.33	3.33	3.29	3.29
		Sweden	3.96	4.00	3.79	3.92	3.91	3.88
		Portugal	5	4	5	5	3	3
		Holland	4.17	4.17	4.17	1.09	4.17	4.22
		Taiwan	4.17	4.17	3.83	4.17	4.17	4.17
		Denmark	4.04	3.00	3.40	3.40	3.40	3.29
		Spain	3.50	3.40	3.00	3.30	3.33	3.00
	Kalundborg symbiosis	Kalundborg	4.04	4.09	4.09	4.04	4.09	4.04
		Average	3.98	3.87	4.01	3.49	3.78	3.83
		Standev	0.57	0.46	0.68	1.02	0.48	0.67

Source: Authors

For a better subsequent graphic representation, the answer scores 1 (No importance), 2 (Little importance), 3 (Moderate), 4 (Important) and 5 (Very important) that the specialists used to attribute weight were transformed into decimals. The score 1 (one) therefore corresponds to the highest level of company responses and, in each sphere and domain, the value that corresponds to the value attributed by the specialist in order to be considered industrial symbiosis is shown in Table 5.

Table 5 Sphere/domain intensity indicators

1. Intensity indicator in by-product exchange—IIIS	1.1 Intensity indicator of technical factors—$\mathrm{FT}_{\mathrm{IIIS}}$	1.2 Intensity indicator of financial factors—$\mathrm{FE}_{\mathrm{IIIS}}$	1. 3 Intensity indicator of policy factors—$\mathrm{FP}_{\mathrm{IIIS}}$	1.4 Intensity indicator of informational factors—$\mathrm{FI}_{\mathrm{IIIS}}$	1.5 Intensity indicator of organizational factors—$\mathrm{FO}_{\mathrm{IIIS}}$	Average domains
1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.80	0.80	0.80	0.60	0.80	0.60	0.72
2. Intensity indicator in sharing utilities and/or services—IICU	2.1 Intensity indicator of technical factors—$\mathrm{FT}_{\mathrm{IICU}}$	2.2 Intensity indicator of financial factors—$\mathrm{FE}_{\mathrm{IICU}}$	2.3 Intensity indicator of policy factors—$\mathrm{FP}_{\mathrm{IICU}}$	2. 4 Intensity indicator of informational factors—$\mathrm{FI}_{\mathrm{IICU}}$	2.5 Intensity indicator of organizational factors—$\mathrm{FO}_{\mathrm{IICU}}$	Average domains
1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.60	0.80	0.80	0.60	0.80	0.60	0.72
3. Intensity indicator in cooperative management—IICG	3.1 Intensity indicator of technical factors—$\mathrm{FT}_{\mathrm{IICG}}$	3.2 Intensity indicator of financial factors—$\mathrm{FE}_{\mathrm{IICG}}$	3.3 Intensity indicator of policy factors—$\mathrm{FP}_{\mathrm{IICG}}$	3.4 Intensity indicator of informational factors—$\mathrm{FI}_{\mathrm{IICG}}$	3.5 Intensity indicator of organizational factors—$\mathrm{FO}_{\mathrm{IICG}}$	Average domains
1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.80	0.80	0.80	0.60	0.80	0.80	0.76

Source: Authors

It was thus possible to create the industrial symbiosis assessment—ISA graph, shown in Fig. 2, in which the maximum value in each sphere 1 (one) and the minimum value are the result of the importance levels attributed by the specialists.

The methodology was adjusted considering the standard deviation in the answers of the specialists. An interval was established based on the average of total domains and between the intensity values attributed in each sphere. This interval was called "Relative Interval" as it suffered the influence of the qualitative view of the researchers. Withal, between the relative interval and minimum attributed level, it is already possible to infer the pre-existence of symbiotic relationships.

Charts for each of the three spheres were also developed: ontology chart in the By-product Exchange sphere, comprising analysis of the vertexes of each domain with maximum values of 1 (one) and minimum values resulting from the levels of importance attributed by the specialists; ontology chart in the Utilities and/or Services Sharing sphere, comprising analysis of the vertexes of each domain with maximum values of 1 (one) and minimum values resulting from the levels of importance attributed by the specialists; and ontology chart in the Cooperative Management sphere, comprising analysis of the vertexes of each domain with maximum values of 1 (one) and minimum values resulting from the levels of importance attributed by the specialists.

Once the level of importance of relationships and the ontology charts for the analysis structure of industrial symbiosis relationships were determined, the following step is creating the instrument for diagnostics. Thus, creating a model to easily identify potential aspects of industrial symbiosis is an attempt to find what symbiotic relationships look like before they are broadly known and at what point they may be "uncovered" in industrial ecosystems. The pilot model presented here helps to find self-organizing symbiosis projects not known until there has been some success and an uncovering event occurs. Moreover, according to Chertow (2007), even when several exchanges had been implemented across firms based on self-organization, the participants and neighbours generally had not recognized or described these phenomena in environmental terms, until some sort of uncovering event had occurred, either during the initial period or later on when exchanges were more deeply rooted.

However, identifying more potential industrial symbiosis opportunities is not an easy task specially in developing countries.

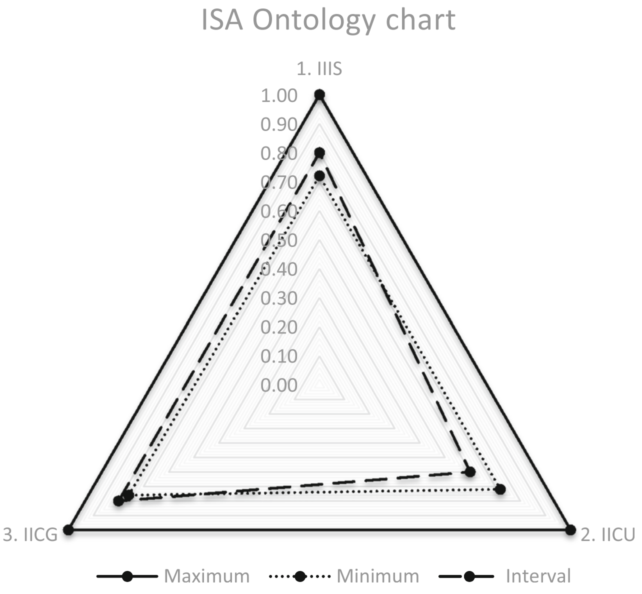

Fig. 2 ISA ontology chart. Source: Authors

There is a lack in the literature to be filled, suggesting the need of identifying more potential industrial symbiosis opportunities, optimizing energy structure, increasing industrial efficiency and recovering local ecosystems (Geng et al. 2014).

In developing countries where industrial symbiosis concept is new and not well known by small enterprises (majority of industrial clusters/networks), several potential aspects and actions that might lead to industrial symbioses may be happening without being recognized or described. The pilot model makes it easily.

Furthermore, most existing methods for sustainability assessment including those based on life cycle thinking employ biophysical approaches to quantify the resource flows and environmental impact of products and processes (Chopra and Khanna 2014). Nevertheless, none of those methods brings direction on how to easily uncover cases of industrial symbiosis and of how to easily uncover potential aspects in conventional industrial networks.

The study developed by Zhang et al. (2016) through the combination of the two metrics divided the networks into one type of weak completeness and two forms of strong completeness. Results of their work revealed how different structures influenced the exchanges among members of a system, thereby providing insights into threats that may destabilize the network. Most threats happen when weak degree of completeness was sparse with few connections (Zhang et al. 2016). Such results also reinforce the importance of uncovering industrial symbiosis cases in initial stages.

Grouping various types of industrial activities in symbiosis network brings many benefits from economies of scale in many ways such as of land development and common facilities (Geng et al. 2014; Park and Behera 2014; Bain et al. 2010).

Industrial ecology and industrial symbiosis were generated to alleviate the environmental pressure and determine the appropriate way to develop the environment and the economy, providing environmental and economic benefits (Wang et al. 2016; Yu et al. 2015; Leigh and Li 2015; Park and Behera 2014; Bain et al. 2010). Thus, many benefits arise from industrial symbiosis and a large number of research especially focus on economic gains (Li et al. 2015).

Higher industrial diversity, in terms of population equitability (resource movement, how diversity affects industrial ecosystem productivity), would allow synergy replication and thus promote higher instances of industrial symbiosis in general (Jensen 2016). Industrial diversity may be a fragility when trying to identify potential symbiotic aspects in industrial cluster when the industry homogeneity prevails. Notwithstanding, a large amount of industrial clusters have heterogeneous nature (Giuliani 2006).

Thus, the model presented in this study is a start to identify emerging cases, uncovering unknown practices and by that, new directions can be provided for effectiveness of cases that could be in imperfect form of industrial symbioses. “In actual production chains, two forms of imperfect industrial symbiosis can occur: excess or scarcity of waste. In the first case, a specific waste is produced in greater quantity than it is required, and a fraction of its total amount has to be disposed of to the landfill, or sent to a chain outside the network. In case of scarcity, a specific waste is produced in less quantity than it is required, and part of the required substitutable primary resources has to be purchased from outside the network” (Yazan et al. 2016, p. 4). So, if imperfect symbiosis occurs but is found in the beginning, new directions can be provided from early stages, fostering effectiveness. Thus, effective solutions in actual production chains may emerge by uncovering new cases, providing solutions to upgrade the system to a perfect industrial symbiosis state.

The concept of symbiosis network provides a useful theoretical perspective for studying the relationship among enterprises in an ecosystem. However, Wang et al. (2016) reinforce that there is lack of specific quantitative examination. Eckelman and Chertow (2009) corroborate in the same way, reinforcing that the question on the existing potential for new symbiotic relationships and the extent of the full potential of obtaining environmental benefits through industrial symbiosis is a continuous study topic in scientific research.

Therefore, the originality of this study lies on the development of a pilot model to uncover industrial symbiosis and its correlations, that can be empirically applied and then will help to guide the initial stages of IS—and potential development aspects—especially for environments in which practices can be implicit. The pilot model to uncover industrial symbiosis is a simple and fast method to identify emerging opportunities to symbiotic development and comes to filling the lack pointed in the literature by “uncovering” potential of industrial symbiosis in Brazilian industrial clusters. The pilot model can also be a help for other countries with similar needs.

Final considerations

It is important to acknowledge that the number of specialists to attribute the level of importance of correlations was small. However, both selected groups hold great knowledge of the theme. Hereby, they are of great importance and, as a pilot test, this research opens possibilities to extend this study, validating the methodology with a greater amount of experts.

Hence, it was possible to reach the general objective of this study, which was creating a pilot model that helps to diagnose industrial symbiosis, answering the question: How to uncover industrial symbioses in Brazilian industrial clusters? As mentioned before, especially in developing countries, the diagnosis is of great importance once such phenomena had not been recognized or described until some sort of uncovering event had occurred, either during the initial period or later on when exchanges were more deeply rooted.

The research was conducted in several stages following the specific goals of conducting a systematic review to create a bibliographical portfolio of industrial ecology and industrial symbiosis concepts. In turn, it provided the fundaments to extraction of the main conceptual aspects that compose industrial symbiosis practices. Also, by identifying industrial symbiosis practices and their correlations was the base to develop a theoretical model to then establish a method to attribute weights to the spheres and domains needed to promote the methodology in the tool.

By developing an assessment model of industrial symbiosis, the results reflected a pilot testing that provided a basic and flexible structure for improvements that can be adapted to different scenarios. This flexibility and improvement potential significantly contribute to studies of industrial symbiosis in networks.

Once the theoretical model was determined, the following step is creating the instrument for diagnostics. Of course that, in order to apply the theoretical model, under the variation of different variables, it is possible that correlations between endogenous and exogenous variables may change. For that reason, we recommend that any empirical application of the model to uncover industrial symbiosis gets strict with the spheres and domains but has the flexibility to consider the current scenario. The model is a guide for further studies on uncovering industrial symbiosis considering spheres and domains that are interrelated.

For future studies, the empirical application of the model can be developed according to the researcher’s needs, which may be questionnaires, interviews, among others, as long as it matures the spheres and domains developed in the model as a guidance to find self-organizing symbiosis projects not known until there has been some success.

The benefits of creating an industrial symbiosis project cover the financial, social and environmental foundations of the network. Thus, the importance of identifying the pre-existence of industrial symbiosis in the initial stages and its potential aspects and level of intensity of interrelations corroborates the benefits of its development.

Moreover, the depth of analysis of this pilot model targets the diagnosis of industrial symbiosis aspects, of its existence. An in-depth analysis of the effectiveness of existing interrelations will lead to a maturing of the pilot model’s assessment capacity.

This study can also be extended. The weight attributed to the interrelations, resulting in indicator values of the developed pilot model, is based on the assessment of a specific and previously selected group of researchers on the topic. Application of the fuzzy method to identify the pertinence level of the specialist’s answers—to later identify the pertinence of each variable—models the imprecise manner of human reasoning and converts it into an objective number format to ensure lesser subjectivity.

Withal, the intensity indicator values need periodical updating, as the importance of interrelations is directly related to the evolution of industrial symbiosis success cases and of the research in these cases. In addition, to validate the model would be necessary to increase the number of expert groups and respondents.

This study will help to create future studies in relation to this need. It also contributes to future studies that lead to the empirical application of the model. Application of this tool in an eco-industrial park with pre-established and acknowledged industrial symbiosis practices will enable the evaluation of this tool, by mapping different points, and the advantages and disadvantages in relation to its applicability and the obtained results.

Considerable evolutions resulted from the conduction of this study, providing opportunities for new studies. In this sense, this study also creates a starting point for new studies that seek to identify the potential of industrial symbiosis, thus validating the applicability of the pilot-testing model.

The originality of this study lies in the development of a pilot model that helps to diagnose industrial symbiosis, aligned with the key domains of sustainable development and its pillars. The pilot model can be empirically applied to guide the initial stages of industrial symbiosis—and potential development aspects—especially for environments in which practices can be implicit.

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