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Comparison of industrial symbiosis indicators through agent-based modeling

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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

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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):

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

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.

$$DP = evaluation\ of\ the\ criterion \times weight\ of\ the\ criterion \tag{2}$$

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

Table 1
By-product evaluation criteria.

Criteria	Evaluation of the criteria
Legislation	(1) Good practices (3) General requirement (5) Specific legal requirement
Class of by-product	(1) Non-hazardous, inert (3) Non-hazardous, non-inert (5) Hazardous
Use of by-product	(1) By-product is treated by both the donor and recipient company (3) By-product is treated by the recipient company (5) By-product treatment is not required by either of the companies
Destination of by-product	(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: Felicio et al. (2016), p. 59.

by-product reused as raw material and decreases with increase in the amount of discarded by-product. Its value has no specific meaning; it is an index number that provides an indication of trend. Furthermore, it has no limit, which is consistent with the concept that perfect symbiosis cannot be achieved but can always be incremented (Felicio et al., 2016).

The indicator can also be used in the decision regarding the entry of a new company into the park by verifying the extent to which this new company can help to increase the industrial symbiosis. In addition, through its calculation process, identifying the contribution of each company to the overall industrial symbiosis is also possible (Felicio et al., 2016).

2.2. Eco-connectance and by-product and waste recycling rate

The Eco-Connectance indicator establishes the degree of connectivity between the companies that constitute the EIP and is defined by Equation (3) (Tiejun, 2010):

$$C_e = \frac{L_e}{S(S-1)/2} \tag{3}$$

Where,

C_e: Eco-Connectance of the EIP
L_e: Observable (as opposed to potential) by-products and waste flow
S: Number of factories or companies in an EIP

The indicator of the By-product and Waste Recycling Rate defines the degree to which the by-products and wastes of a company are used by other companies in the EIP (Tiejun, 2010). It is defined by Equation (4) (Tiejun, 2010):

$$C_R = C_e \times r_L \tag{4}$$

Where,

C_R: By-product and Waste Recycling Rate
C_e: Eco-Connectance of the EIP
r_L: Average of by-product and waste recycling percentage between any two companies in an EIP, $0\% < r_L \leq 100\%$

Both indicators range from 0 to 1, are interdependent and inseparable, and can be used either in the planning or construction of an EIP, or even in the quantitative assessment of an existing EIP (Tiejun, 2010).

Comparing the ISI with the two indicators proposed by Tiejun (2010), the ISI has no finite value, while the indicators of Tiejun (2010) range from 0 to 1. In addition, the ISI considers the quantity of reused and discarded by-products. Conversely, the indicators of Tiejun (2010), through the By-product and Waste Recycling Rate indicator, consider the percentages of by-products reused, and, through the Eco-Connectance indicator, only the quantities of symbiotic links. Lastly, the greatest difference between the two sets of indicators is that the ISI considers the classification of the by-products through some criteria, while the indicators of Tiejun (2010) neglect this aspect.

3. Agent-based modeling

Romero and Ruiz (2014) identified the system dynamics (SD) and ABM techniques as the most likely options for modeling an EIP. After comparing both approaches, as presented in Table 2, these authors chose ABM as the most appropriate technique.

According to Gilbert (2008), ABM is “a computational method that enables a researcher to create, analyze, and experiment with models composed of agents that interact within an environment.” The interactions, which follow certain rules, create emerging patterns in the system (Page, 2005).

An advantage is that it is not necessary to represent the overall state of the system, only the status of each individual agent (Railsback and Grimm, 2011). This simplifies the modeling, since to directly model the system as a whole, more complex and sophisticated mathematical models would be required instead of dealing with smaller parts of this system, *i.e.*, their agents.

ABM has been applied to different fields including ecology (Grimm and Railsback, 2013; Wilensky and Rand, 2015) and organizational systems (Wilensky and Rand, 2015). According to Wilensky and Rand (2015), ABM has been widely used in the past two decades by scientists conducting research. In fact, two recent papers apply ABM to the modeling of EIPs, namely Romero and Ruiz (2014) and Bichraoui et al. (2013).

The work by Romero and Ruiz (2014) aimed to allow the evaluation of the potential of the symbiotic relationships between companies that comprise the park and to evaluate the overall operation of the EIP in different scenarios. In the work by Bichraoui et al. (2013), the ABM technique is used to create a model that represents an EIP, with a focus on understanding the cooperation and learning conditions.

None of the researchers, however, used this technique as a validation procedure for indicators of industrial symbiosis. This is the goal of the model introduced in the current work. As the strategy to test this idea, we created a model and perform an evaluation of the industrial symbiosis indicators that are more useful for managers and brokers in EIPs, as evaluated by Felicio et al. (2016). These professionals need references for choosing and adapting indicators as decision tools to improve the industrial symbiosis levels.

4. Description of the simulation model

The model was named *EIPSymb*, an allusion to EIP and Symbiosis terms. The ODD (Overview, Design Concepts, and Details) protocol proposed by Grimm et al. (2006) is used for its description. The ODD protocol was initially published with the purpose of standardizing the descriptions of ABM (Grimm et al., 2010). It was designed so that ABM publications would be more complete, quick and easy to understand, and organized in a manner that allows for presenting information in a consistent order (Railsback and Grimm,

Table 2
Comparison between system dynamics and agent-based modeling.

Comparative features	System dynamics	Agent-based Modeling
Modeling approach	**Deductive** (top-down). Inference from the structure to the system behavior.	**Inductive** (bottom-up). Inference from the agents' behavior to the system behavior.
Unit of analysis	**System Structure**. The behavior of the system arises from its structure.	**Agents' rules**. The behavior of the system emerges from the agents' behavior and their interactions.
Building blocks	**Feedback loops**. Representation of cause-and-effect relationships.	**Agents**. Individual entities that form the system.
Handling of time	**Continuous**. Temporal variable is continuous.	**Discrete**. Temporal variable is discrete.
Formal expression	**Algebraic equations** that define variable relationships and feedback.	**Logic sentences** that define behavioral rules of the agents.
Model representation	**Causal relationships** that nonlinearly link the observed variables, parameters, and stock accumulations, considering temporal and spatial delays between cause and effect.	**Agent population** formed by autonomous, heterogeneous, and independent entities with their own objectives, properties, and social ability to interact between them and with their surroundings.
Model representation	**Causal loop diagrams** and stock and flow structures.	**Individual representation** of agents that form the system.

Source: Adapted from Romero and Ruiz (2014), p. 396.

2011). Its computational development was performed in the NetLogo platform, a programmable modeling environment that simulates natural and social phenomena through complex system models (Netlogo, 2015).

4.1. Overview

4.1.1. Purpose

The purpose of *EIPSymb* is to represent the interactions between companies of an EIP in terms of the flow of by-products. *EIPSymb* was designed to allow the calculation of indicators of industrial symbiosis for every change in the system's state from the data of inbound and outbound by-products. The simulation includes three indicators for an initial evaluation of the model: Eco-Connectance and By-product and Waste Recycling Rate, by Tiejun (2010), and the ISI, proposed by Felicio et al. (2016).

4.1.2. State variables and scales

The global environment is divided into two local units. The first represents the EIP and contains the agents *company*, which may interact with each other through the exchange of by-products. The other unit represents the environment external to the EIP and contains the agent *landfill*, which is responsible for receiving the non-reused by-products. There is only one agent of the landfill type, which is associated with a single state variable, named *who*, which is the identification of each agent. The agents *company* are defined by the following variables:

who: Identification of each agent.
type-product: Represents the type of product produced by the company. It may assume the values 0, 1, 2, 3, or 4.
type-residue-generated: Represents the type of by-product generated in the manufacture of the product. It is directly related to the variable *type-product*. Table 3 shows the relationship between the types of products and the by-products generated.
type-residue-used: Represents the type of by-product that can be used by the company as raw material. It is directly related to the variable *type-product*. Table 3 shows the relationship between the types of products and the by-products used as raw materials.
time-in-park: Number of complete periods in the EIP.
residue-generated: Amount (in tons) of by-product generated.
residue-absorption-capacity: Capacity (in tons) of by-product that the company is able to absorb as raw material.
residue-absorbed: Amount (in tons) of by-product that the company is using as raw material.

The concept used to define the types of products and the types of by-products generated or used as raw materials was inspired by the study of Bichraoui et al. (2013).

There is yet another type of entity, the *link*, which represents the by-products' flow between *EIPSymb* agents, whether company-company or company-landfill. This entity is represented by the state variables:

end1 and *end2*: Identification of the *link*. *end1* is associated with the number of the agent's *who* variable from where the by-product is being released. *end2* is related to the number of the agent's *who* variable to which the by-product is being sent.
type-residue: Represents the type of by-product exchanged through the *link*.
time-existence: Number of periods that the *link* exists.
intensity: Amount (in tons) of by-products that are being sent by the *link*.
color: Allows for visual differentiation between the industrial symbiosis *links* and the *links* of by-products sent out of the EIP. The *link* between two companies is green, while the *link* to the landfill is red.

4.1.3. Process overview and scheduling

The *EIPSymb* must be initiated through a *Setup* command button that clears the NetLogo *world*, visually differentiates local units, and creates the agent *landfill*. After this command, the *EIPSymb* is ready to be initiated. Fig. 1 depicts a flowchart of the processes included in the model.

The *Increment* process varies the amount of by-product generated and each company's by-products absorption capacity with respect to the previous period. The process *Indicator calculation*, in addition to calculating the value of the three indicators, updates their graphs. The process *Show values* is responsible for listing the values of *companies* and *links* variables. Each process will be detailed further, in the subsection “Submodels”.

4.2. Design concepts

4.2.1. Basic principles

The concept of industrial symbiosis in EIPs is one of the basic

Table 3
Types of products and their relationships with the types of by-products generated and used as raw material.

Type-product	Type-residue-generated	Type-residue-used
0	A	E
1	B	A
2	C	B
3	D	C
4	E	D

principles used in *EIPSymb*. The others are the ISI, Eco-Connectance and By-product and Waste Recycling Rate indicators as well as their respective mathematical formulations.

4.2.2. Emergence

The numerical results of the ISI, Eco-Connectance and By-product and Waste Recycling Rate indicators represent the emerging *EIPSymb* phenomena.

4.2.3. Sensing

Companies are aware of the amount of their by-products that the other companies can still absorb. Thus, they do not send more by-products than the amount that companies with which they exchange by-products can absorb. Companies also realize when other companies with which they exchange by-products had their by-product absorption capacities reduced, thus scale down the amount of by-products they send them. They also recognize the type of by-product that each company is able to absorb. Therefore, only compatible by-products are exchanged.

4.2.4. Interaction

The interactions between agents occur through two types of links:

company-company: Dispatching of by-products from one company to another that uses the by-products as raw materials.
company-landfill: By-products that are not exchanged with other companies in the EIP and are thus sent to the landfill.

4.2.5. Stochasticity

Various *EIPSymb* processes display random behaviors in which the uniform distribution is used:

Increment: Each company's *residue-generated* and *residue-absorption-capacity* variables may increase or decrease according to a rationale that involves randomness.
New company entry: Uses a randomness-based rationale to decide whether a new company enters.
Once the company enters the EIP, another random process determines the type of product it will produce, therefore defining the type of by-product generated and the type of by-product used as raw material.
Company exit: Uses a randomness-based logic to determine the exit of a company.
Link creation: Considers a probability-based rationale to decide whether companies that do not yet exchange by-products will start this exchange.
Increased links intensity: The *intensity* variable associated with the *links* of by-products exchanged between companies depends on a randomness-based rationale to decide whether an increase will occur.
Decreased links intensity: The *intensity* variable associated with the *links* of by-products exchanged between companies depends on a randomness-based rationale to decide whether a decrease will occur.

The processes described, except for the definition of the type of product produced in each company—and, consequently, the type of by-product generated and the type of by-product used as raw material—use input values provided by the *EIPSymb* user.

4.2.6. Collectives

The collective observed in *EIPSymb* is related to the fact that the assembly of companies forms an industrial park. However, when companies interact, they do not change their behavior, acting as a collective.

4.2.7. Observation

The communication of the results of the *EIPSymb* simulation includes the visualization of the following:

NetLogo *world* in the current period.
The current period, the number of companies, existing symbiosis links and possible symbiosis links in the current period.
Values of the ISI, Eco-Connectance and By-product and Waste Recycling Rate indicators in the current period.
Graphic evolution of the ISI, Eco-Connectance and By-product and Waste Recycling Rate indicators over time.
Values of each company's residue-generated, residue-absorption-capacity, residue-absorbed, type-residue-generated, and type-residue-used variables in the current period.
Values of each *link*'s *intensity* variable in the current period.

Fig. 2 shows the *EIPSymb* output interface.

4.3. Details

4.3.1. Initialization

The initialization of the *EIPSymb* is accomplished through the *Setup* command. The command differentiates local units and creates the agent *landfill* allocating it to a local unit external to the EIP. During the simulation, companies and *links* between those companies are created. When a company is created, the *residue-generated* and *residue-absorption-capacity* variables are given the same value, which is equal to 100 t. However, when a *link* between two companies is established, the *intensity* variable is given the value of 1 t.

4.3.2. Input

According to Grimm et al. (2010), this element is reserved to

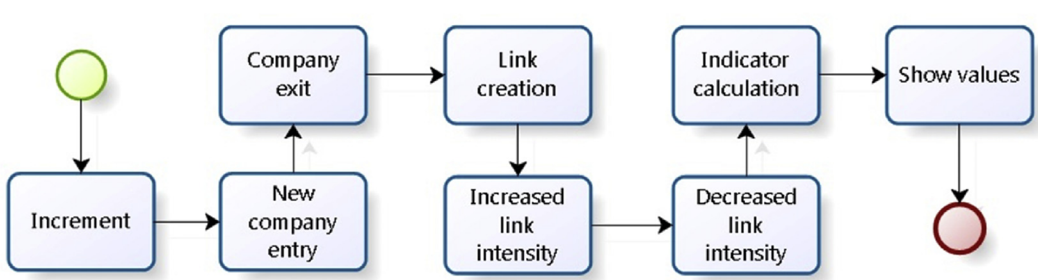

Fig. 1. Flowchart overview of *EIPSymb* processes.

describe the utilization of external data and their sources. The *EIPSymb* does not use external data; however, the element "Input" was maintained to describe the input data used in the description of the simulation scenario. Such data must be supplied by the user at the start of the simulation and at any period interval considered desirable to change their values. Input data include:

probability-of-entry-of-a-new-company: Value between 0% and 100% is used in the entry decision of a new company.
probability-of-exit-of-a-company: Value between 0% and 100% is used in the exit decision of a company
probability-of-creating-connection: Value between 0% and 100% is used in the decision to create new *links* between companies.
probability-of-increasing-connection-intensity: Value between 0% and 100% is used in the decision to increase the amount of by-products exchanged between companies through existing *links*.
probability-of-decreasing-connection-intensity: Value between 0% and 100% is used in the decision to decrease the amount of by-products exchanged between companies through existing *links*.
probability-of-increasing-production: Value between 0% and 100% is used in the decision to increase the production of each company with a direct impact on the *residue-generated* and *residue-absorption-capacity* variables.
probability-of-decreasing-production: Value between 0% and 100% is used in the decision to decrease the production of each company with a direct impact on the *residue-generated* and *residue-absorption-capacity* variables.
intensity-variation-step: This value must be greater than 1 and is used in processes that vary the *link intensity* between companies. This value represents the step in which *link intensity* is altered.
increment-production. This value must be greater than 1 and is used in the *Increment* process that changes the values of each company's *residue-generated* and *residue-absorption-capacity* variables. This value represents the step in which these variables are changed.

The evaluations of the criteria proposed by Felicio et al. (2016) for the classification of the generated by-products and for use in the calculation of the ISI are also input data. The possible classifications of each by-product are presented in Section 2.1, Table 1. Only the criterion "destination of by-product" is not classified since, in this simulation model, the only destination available when the by-products are not used is the landfill.
Fig. 3 depicts the spaces intended for input data insertion.

4.3.3. Submodels

There are ten submodels in the *EIPSymb*, eight of them are shown in Fig. 1:

Setup: The *Setup* submodel is not depicted in the overview flowchart of the *EIPSymb* processes (Fig. 1). It is already described in the subsection "Initialization". This submodel prepares the simulation environment.
Increment: Responsible for changing each company's *residue-generated* and *residue-absorption-capacity* variables. It does so by using the *increment-production* input data to adjust the variation step.
New Company Entry: Accounts for the entry of new companies into the EIP. It is also responsible for assigning values to each company's *type-product*, *type-residue-generated*, and *type-residue-used* variables.
Company Exit: Accounts for the exit of companies from the EIP.
Link Creation: Responsible for creating new symbiotic links between EIP companies.
Increased Links Intensity: This submodel aims to control the increase of the variable *intensity* of symbiotic *links*.
Decreased Links Intensity: Controls the decrease of the variable *intensity* of symbiotic *links*.
Indicator calculation: Accounts for the calculation of the numerical values of the three indicators used in the *EIPSymb*. It also updates their corresponding graphs. The values of the variable *intensity* of each *link* and the by-product classifications are used to calculate the ISI. The values of the *number of companies*, *possible links*, *existing links*, and *link intensity* variable are used to calculate the Eco-Connectance and the By-product and Waste Recycling Rate indicators.
Show values: Lists the values of each company's *residue-absorbed*, *residue-absorption-capacity*, and *residue-generated* variables. It also lists the values of the *link intensity* variable.
Residue absorption assistant: Responsible for updating the *residue-absorbed* variable. This submodel is not depicted in the overview flowchart of the *EIPSymb* processes (Fig. 1). It is activated whenever the values of the *intensity* of one or more *links* change through the action of some submodel or activity. This occurs, for example, when a *link*'s *intensity* decreases so that the receiving company will absorb fewer by-products. In that case, its *residue-absorbed* variable is updated through this submodel.

In order to better describe the *EIPSymb*, the flowcharts of some submodels are presented in Appendix A. Furthermore, the Appendix C presents how to proceed to download and use the model.

5. Simulation

In order to confirm the behavior of the indicators, the *EIPSymb* model was used to create different scenarios. These were conceived to represent potential situations occurring in a real EIP. Not all possible situations need to be represented, but only a subset that enables the evaluation of the indicators' behavior in different situations. There are four primary scenarios and two additional scenarios derived from two of these primary scenarios.

Scenario 1 represents an optimal situation for the development of industrial symbiosis. In this scenario, companies exchange by-products with all other companies that use those by-products as raw materials, as long as there is available by-product in the donor company and a need for it in the receiving company. The *links intensity* and the production of each company are always increased, but the rate at which *links intensity* grows is higher than the rate at which companies increase their production. It is initiated from zero, *i.e.*, with no company in the EIP. In order to represent an expanding park, a new company enters the EIP at every period but none leave it. The classification of the by-products, performed in agreement with Felicio et al. (2016) for the calculation of the ISI (Table 1), aims to classify by-products displaying the lowest possible environmental impact.

Scenario 1 in which only the classification of the by-products is different, was also created. These classifications are opposed to those in Scenario 1, since they aim to represent the by-products with the highest possible environmental impact. In both scenarios, 25 periods are simultaneously simulated.

Scenario 2 represents an unstable situation where it cannot be predicted what may happen in the coming periods. The entry rate for a company in the EIP is high; however, its exit rate is also high, thus generating a high turnover within the park. Input data are defined in such a way that increments of the *links intensity* and in each company's production are unpredictable, *i.e.*, increasing, decreasing, or remaining stable for distinct instances. The

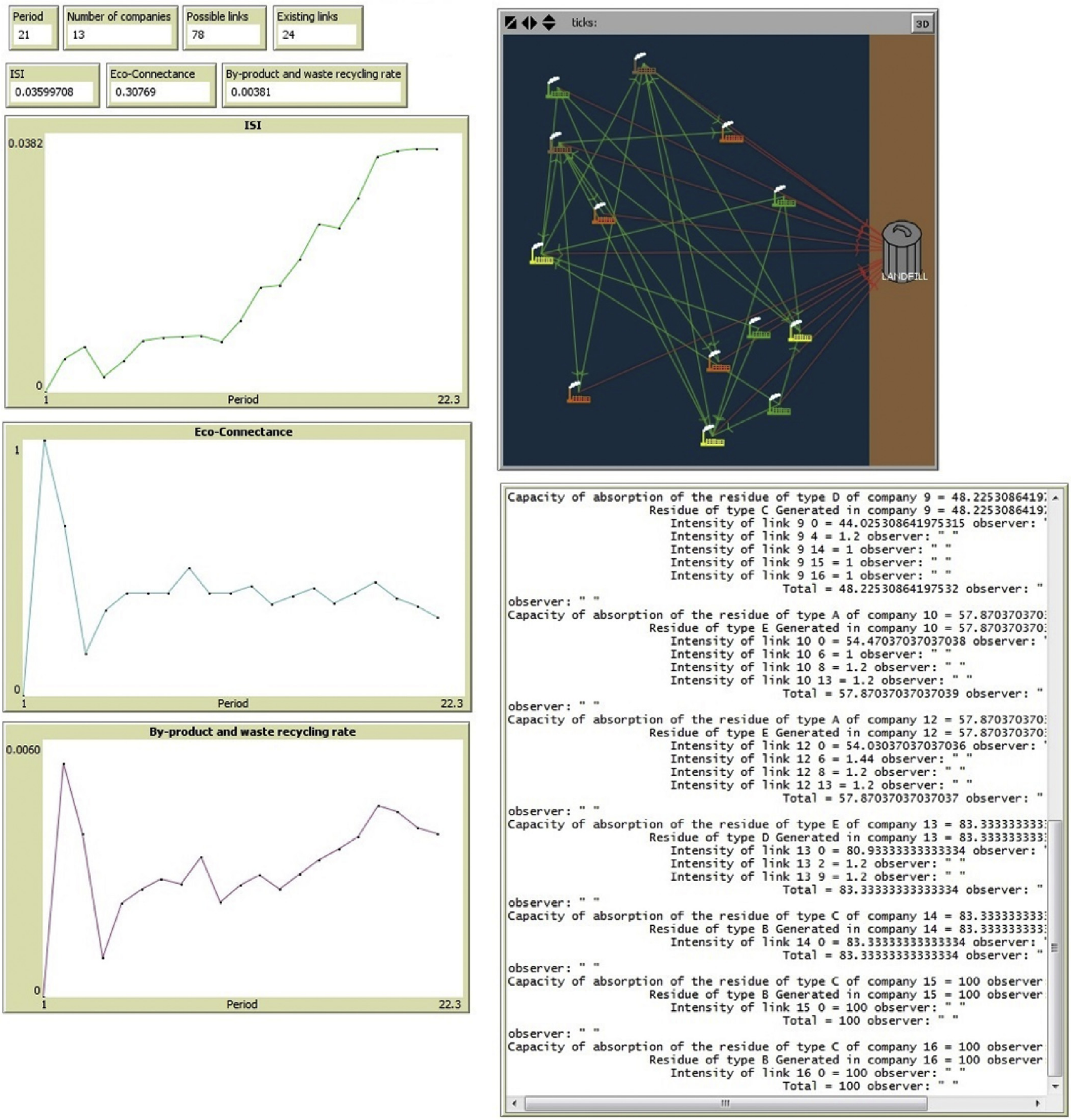

Fig. 2. Visualization of the *EIPSymb* outputs.

classification of the by-products is performed in such a way to present three by-products classified as having a high environmental impact potential and two others with low environmental impact potential.

In order to establish a similar relation to the one existing between Scenarios 1 and 1′, Scenario 2′ is created by changing the classifications of the by-products in relation to Scenario 2. By-products classified as having a high impact potential in Scenario 2 are now classified as having a low impact potential, and the reverse also occurs. In both scenarios, 35 periods are simultaneously simulated.

Before starting the simulation of Scenario 3, a maturation period is performed. This maturation period is calibrated to only entry of a single company by period, no other process is accomplished. It is simulated during 15 periods, and in the final section of this maturation period, there are 15 companies in the park. These companies do not exchange any by-products with other companies, all are sent to the landfill, so the values of the indicators are null. Scenario 3 represents a conservative situation regarding the evolution of industrial symbiosis, *i.e.*, a situation in which companies are hesitant

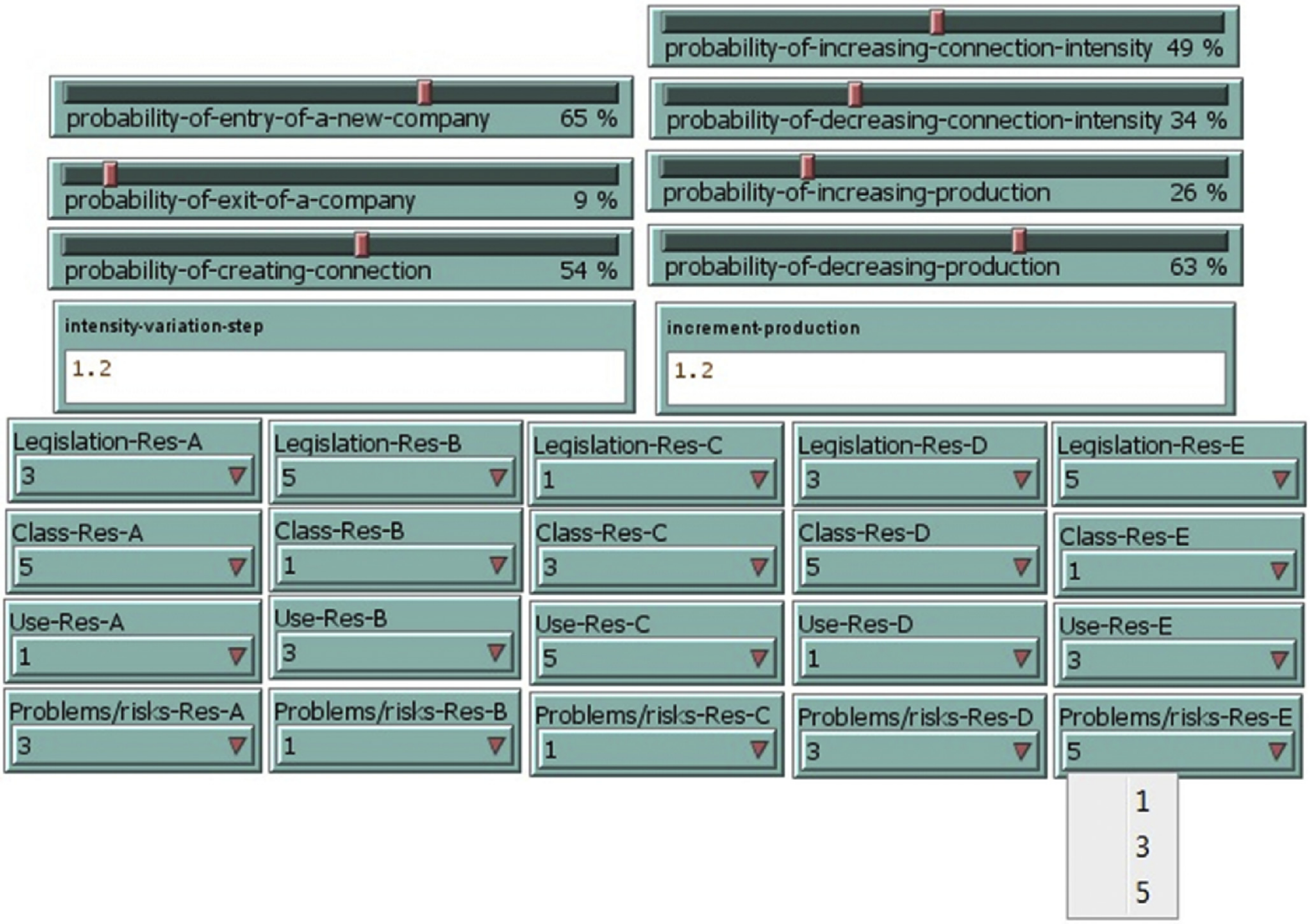

Fig. 3. Input data.

to cooperate with each other, but when cooperation between two companies is initiated it tends to increase, although at a low rate. The companies' production also increases at a low rate. In this scenario, there are no companies entering or exiting the EIP. Therefore, the companies that were created at the maturation period are the ones that comprise this scenario. The classification of the by-products is made to have all types of classifications among the by-products. This scenario is initiated after the 15 periods of the maturation period and simulated for 25 periods.

Scenario 4 represents a completely adverse situation to the development of industrial symbiosis. In this scenario, companies barely create *links* for by-product exchange, and the existing *links* tend toward lower *intensities* until extinguished. The entry probability of a company is average, while its exit probability is low. Furthermore, the companies' production volumes tend to increase, thus aggravating the result of industrial symbiosis given the increase in the amount of by-products sent to the landfill. This scenario is initiated after 25 periods simulated in Scenario 3. The classification of by-products is made to have all types of classification among the by-products. This scenario is simulated for 20 periods.

Table 4 shows the specific values of the input parameters used in each scenario.

There are two conditions that are constant in all scenarios:

By-products not reused by the companies are sent to the landfill.
The evaluation criteria proposed by Felicio et al. (2016) for the calculation of the ISI all have the same weight, *i.e.*, 0.25.

5.1. Scenario 1 and Scenario 1′

Fig. 4 shows the graphical evolution of the three indicators. The graphical evolution of the ISI is depicted by two curves. One curve represents Scenario 1 and is designated as ISI, while the other curve represents Scenario 1′ and is named ISI'. The other two indicators (Eco-Connectance and By-product and Waste Recycling Rate) assume equal values in both scenarios since the classification of the by-products has no influence over their values. To assist in the understanding and interpretation of the graphical evolution of the indicators, some outputs and details regarding the simulation is provided in Appendix B.

The Eco-Connectance indicator has a very high variation in the beginning and then remains practically stable. This occurs because at the beginning there are only a few companies, and any change, however small, in the number of symbiotic links or number of companies in the park produces a large change in the value of the indicator. Following this turbulent period, the indicator value remains stable within the same level. This value represents the equilibrium level of the Eco-Connectance indicator for the established scenario.

When comparing the ISI with the By-product and Waste Recycling Rate indicator, the existence of two distinct phases can be observed. The first phase goes up to Period 13, in which the two indicators display a marked tendency to increase in value. The second phase, following Period 13 onward, is represented by the ISI continuing to increase (though at a less pronounced rate) while the By-product and Waste Recycling Rate indicator begins to drop. This

Table 4
Values of input parameters used in the scenarios.

Entry parameter	Scenarios					
	1	1′	2	2′	3	4
Probability of entry of a new company	100%	100%	80%	80%	0%	50%
Probability of exit of a company	0%	0%	2%	2%	0%	1%
Probability of creating connection	100%	100%	40%	40%	15%	5%
Probability of increasing connection intensity	100%	100%	50%	50%	50%	5%
Probability of decreasing connection intensity	0%	0%	25%	25%	5%	50%
Probability of increasing production	100%	100%	50%	50%	50%	50%
Probability of decreasing production	0%	0%	50%	50%	5%	5%
Intensity variation step	2.0	2.0	1.5	1.5	1.05	1.2
Production increment	1.1	1.1	1.5	1.5	1.05	1.2
Legislation of by-product A	1	5	5	1	1	3
Class of by-product A	1	5	5	1	3	5
Use of by-product A	5	1	1	5	5	1
Problem/risks of by-product A	1	5	5	1	1	3
Legislation of by-product B	1	5	5	1	3	5
Class of by-product B	1	5	5	1	5	1
Use of by-product B	5	1	1	5	1	3
Problem/risks of by-product B	1	5	5	1	3	5
Legislation of by-product C	1	5	1	5	5	1
Class of by-product C	1	5	1	5	1	3
Use of by-product C	5	1	5	1	3	5
Problem/risks of by-product C	1	5	1	5	5	1
Legislation of by-product D	1	5	1	5	1	3
Class of by-product D	1	5	1	5	3	5
Use of by-product D	5	1	5	1	5	1
Problem/risks of by-product D	1	5	1	5	1	3
Legislation of by-product E	1	5	1	5	3	5
Class of by-product E	1	5	1	5	5	1
Use of by-product E	5	1	5	1	1	3
Problem/risks of by-product E	1	5	1	5	3	5

happens after some companies that are in the EIP for more time have 100% of their by-products sent to other companies, thus the symbiotic links between these companies cannot increase the percentage of exchanged by-product. On the other hand, there are new companies entering in the EIP that are still sending little-to-none by-products to other companies. Over the evaluation periods, the combination of these two events intensifies causing a negative influence on the trend of both indicators. However, there is greater rigor in the By-product and Waste Recycling Rate since the indicator considers the percentage of exchanged by-products and not the absolute quantities, as does the ISI.

This result provides an indication that the Eco-Connectance and By-product and Waste Recycling Rate indicators are not robust to changes in the quality of exchanged wastes or to changes in the volume of discarded and reused by-products. Lastly, the difference between the ISI and ISI' values can be noted. This difference is exclusively rooted in the different classifications of the by-products, thus proving that this indicator is sensitive to changes in the type of waste exchanged.

5.2. Scenario 2 and Scenario 2′

Likewise, as with Scenarios 1 and 1′, Scenarios 2 and 2′ were simulated simultaneously. Fig. 5 depicts the graphical evolution of the indicators. Appendix B also provides information on the simulation of these scenarios.

There are moments where ISI increases while ISI′ decreases. This behavior can be observed in Fig. 5, which highlights the passage of Period 30 to Period 31. This occurs as a consequence of the differences in the classifications of the by-products between Scenarios 2 and 2′. In fact, in Scenario 2, by-products A, B, and C are classified as displaying a high environmental impact, while by-products D and E are classified as displaying a low impact. In Scenario 2′, however, the reverse is true, *i.e.*, by-products A, B, and C are classified as displaying a low environmental impact, while by-products D and E are classified as displaying a high impact. From period 30 to period 31, the percentage of recycled by-products from set A, B, and C increases, while the percentage of recycled by-products of set D and E decreases. This has a positive impact on the ISI value and a negative impact on the ISI′ value. The opposite also occurs; for example, there are times when the ISI' increases while the ISI decreases.

At other instances, the ISI, ISI′ and indicator of Eco-Connectance increase, but the By-product and Waste Recycling Rate indicator decreases. This occurs when going from Period 32 to Period 33 and can also be observed in Fig. 5, in which Period 32 is highlighted. The explanation for this phenomenon is the same as in Scenarios 1 and 1′. The ISI takes into account the amounts of by-products while the By-product and Waste Recycling Rate takes into consideration the percentage of each symbiotic link with respect to those produced by the transferring company. It is thus possible that the average percentage of by-products exchanged in the *links* may decrease. This decrease may occur despite the creation of new connections that produce an increase in the value of the Eco-Connectance indicator and despite the fact that the total percentage of by-products reused in the EIP increases thereby contributing to increased ISI and ISI' values. This potential situation results from the presence of new *links* which, although newer, still exchange few by-products, thus negatively affecting the value of the By-product and Waste Recycling Rate indicator.

5.3. Scenario 3 and Scenario 4

The graphical evolution of the three indicators in both scenarios is depicted in Fig. 6. Likewise, as with the previous scenarios, some information on the simulation of both scenarios is provided in Appendix B.

As shown in Fig. 6, in Scenario 3 the three indicators display a

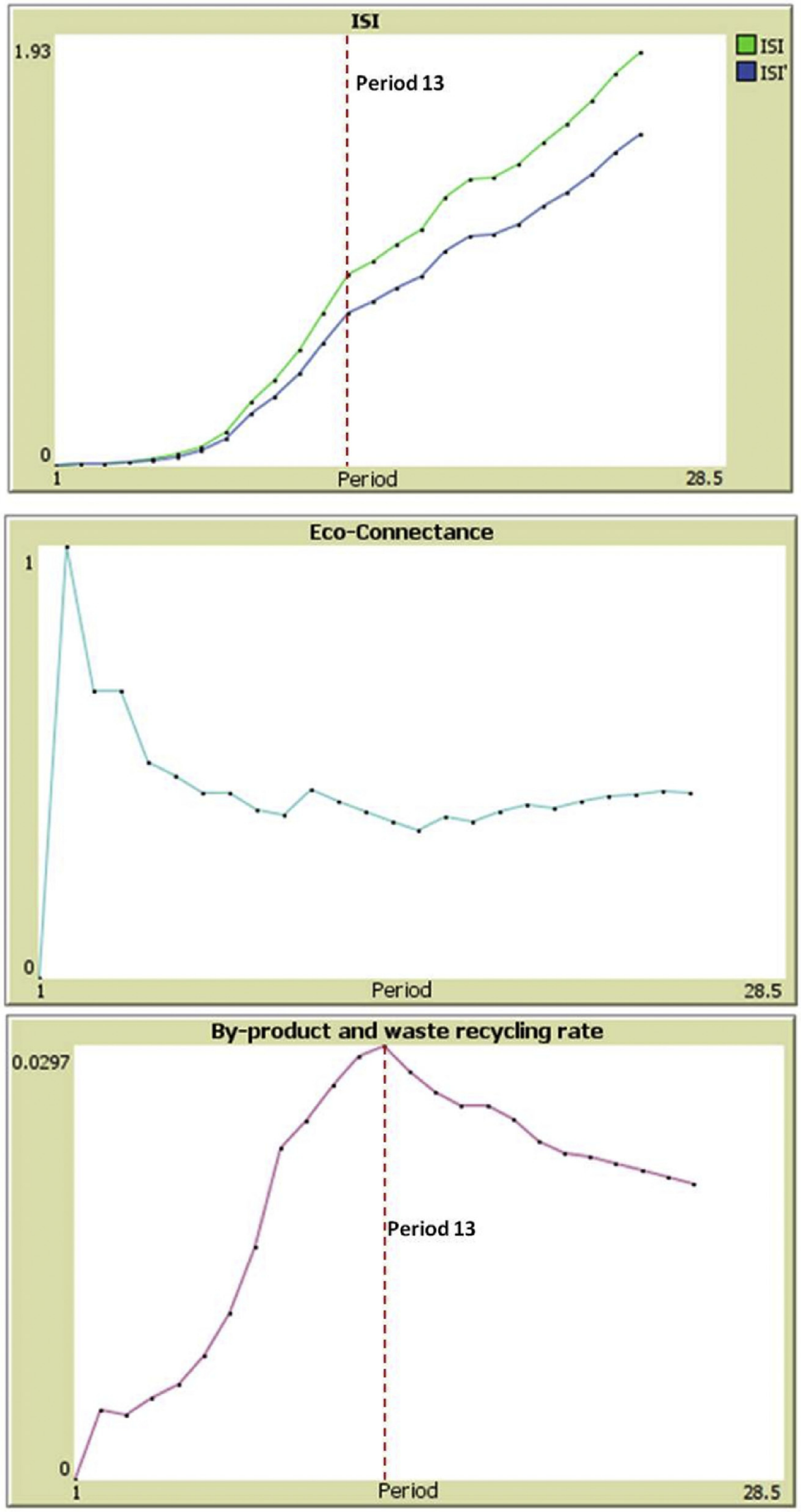

Fig. 4. Graphical evolution of indicators in Scenarios 1 and 1′.

sharp increase at the beginning of the simulation and soon reach an equilibrium. Despite this, both the ISI and By-product and Waste Recycling Rate indicator display low values owing to the conservative approach used in the calibration of the scenario. The equilibrium level of the three indicators represents the moment at which all possible industrial symbiosis links established by the 15 companies in the EIP in the given scenario are reached. Afterward, the ISI and By-product and Waste Recycling Rate indicator do not

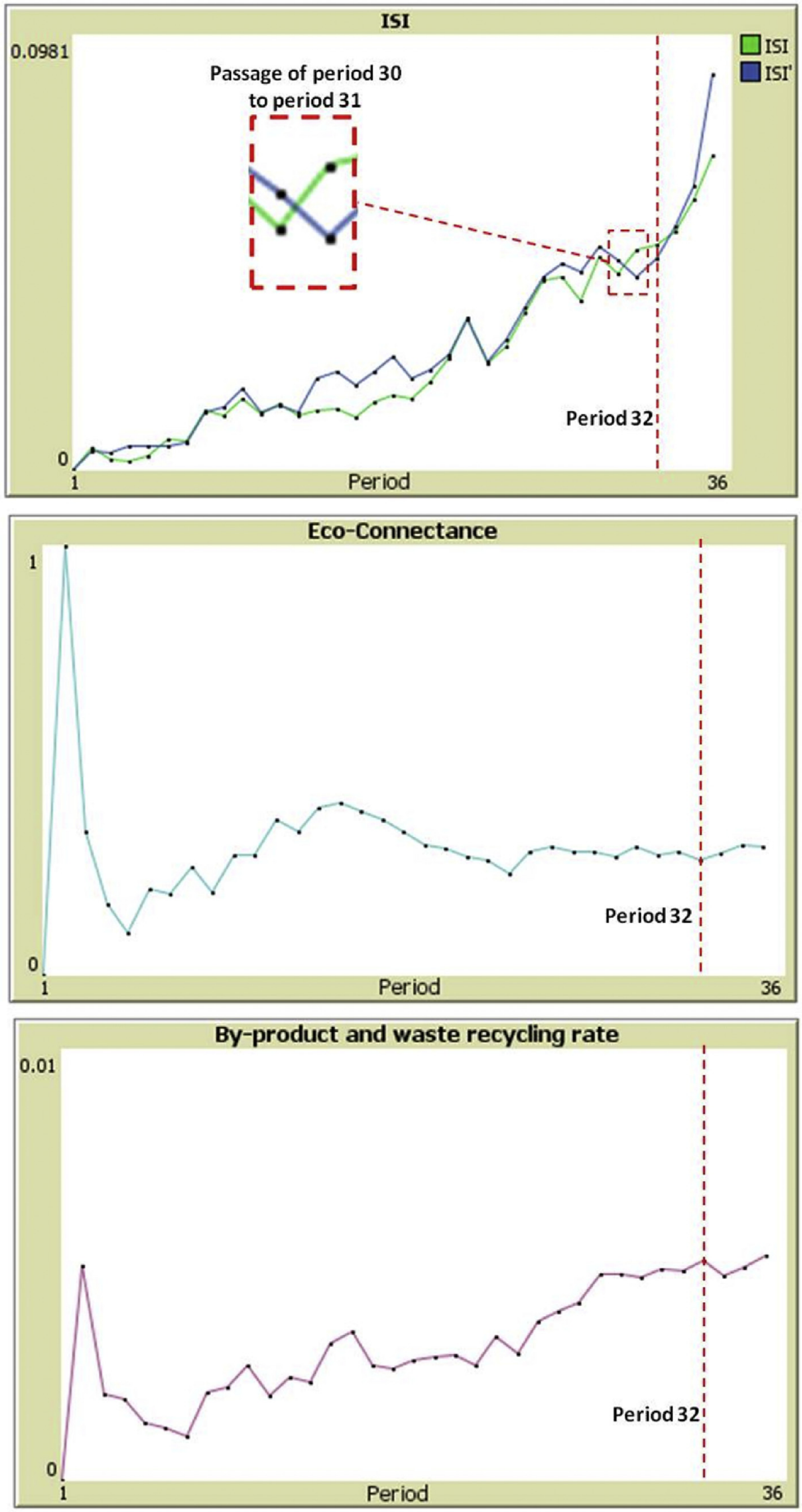

Fig. 5. Graphical evolution of indicators in Scenarios 2 and 2′.

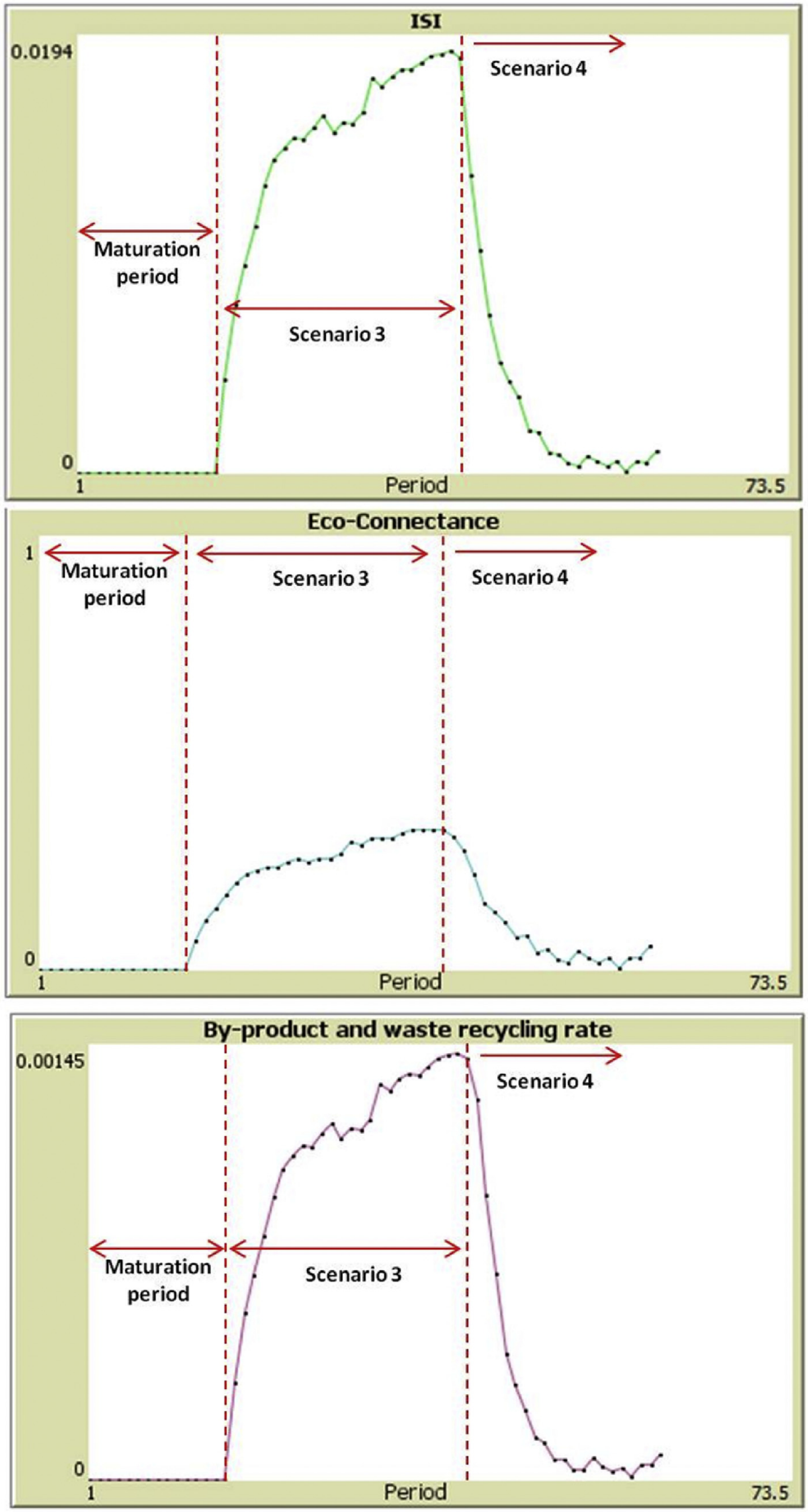

Fig. 6. Graphical evolution of indicators in Scenarios 3 and 4.

increase, although the waste quantities exchanged by the symbiotic links increase. This occurs because the increasing rate at which the companies' production, and consequently the by-products generated, increases. Only small changes are detected.

Alternately, as might be expected, the values of the three indicators displayed a steep decrease in Scenario 4. Although the values of the indicators in this simulation did not reach zero at any time, and in some periods a small increase was observed, the values of the indicators were always very low. In fact, for the last period they reached the following values: (i) ISI = 0.00096; (ii) Eco-Connectance = 0.05667; and (iii) By-product and Waste Recycling Rate = 0.00009. Furthermore, only 0.116% of the park's by-products were reused.

6. Conclusions

The results demonstrated that the *EIPSymb* model allowed for the calculation of the indicators and described their behaviors in different situations, reproducing different symbiosis conditions and wastes with distinct impact levels.

The simulation showed an enhanced robustness of the ISI results. The ISI was able to correctly represent increasing and decreasing trends during symbiosis and under conditions in which the indicators proposed by Tiejun (2010) failed. In other conditions, both proved to be sufficient.

Regarding the pair of indicators proposed by Tiejun (2010), the Eco-Connectance indicator always tended toward an equilibrium level, even when symbiosis was clearly being enhanced. The By-product and Waste Recycling Rate indicator presented misleading results in certain conditions, because its numerical value may have decreases even when the percentage of recycled by-products in the park increases, (see Scenarios 1 and 1′).

Although these restrictions are hypothetically identifiable in the indicator formula, the simulation allowed a systematic identification of the conditions of use of the indicators. The *EIPSymb* model allowed the identification of condition segments under which the indicators may present misleading information about the evolution of industrial symbiosis in the EIP. This type of analysis allows a more precise assessment of the robustness of the indicator for the park conditions and waste impact levels. Therefore, this model performs beyond the limits of mere conceptual validation even though real data was not used as an input.

Another advantage of this type of simulation is the fact that owing to its systematic nature, this model can be applied to a larger number of indicators, as, for example, the Eco-Efficiency indicator, by Park and Behera (2014). Thus, it allows comparisons in which the outcome is more didactic to users, as it provides more precise and detailed recommendations for the use of certain indicators to professionals in the area. This is certainly an advantage as the validation procedure must also convince the end users of the quality of the indicators.

The simulation clearly demonstrated the effect of the type of waste and its level of impact on the evaluation of the symbiosis. Therefore, this aspect must be taken into consideration in any system of indicators used to assess industrial symbiosis. Indicators that do not take into account these aspects are only useful in extreme conditions of perfect symbiosis or unfavorable environments for symbiosis. In addition, their use is not recommended in the case of turbulent environments or when measurements are performed for longer periods of time.

This work identified several issues for improvement in the *EIPSymb* model, such as the possibility of shipping the by-products not redeemed within the park to other EIPs. Another issue raised is the possibility of initiating the *residue-generated* and *residue-absorption-capacity* variables of the agent *company* and the *intensity* variable, associated with the symbiosis links, with different values instead of the same default value. These improvements should contribute to refining and enhancing the simulation model.

By enhancing and refining the *EIPSymb* model, many research outlets become possible: (i) consideration of other industrial symbiosis indicators, (ii) studying the financial aspects inherent to symbiotic interactions, and (iii) the use of actual data representing the evolution of a real EIP to calibrate the input data, thus creating scenarios that more closely resemble reality. These are just some of the possibilities.

Acknowledgements

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Appendix A. Submodels Flowcharts

The flowcharts of some submodels are presented in this appendix.

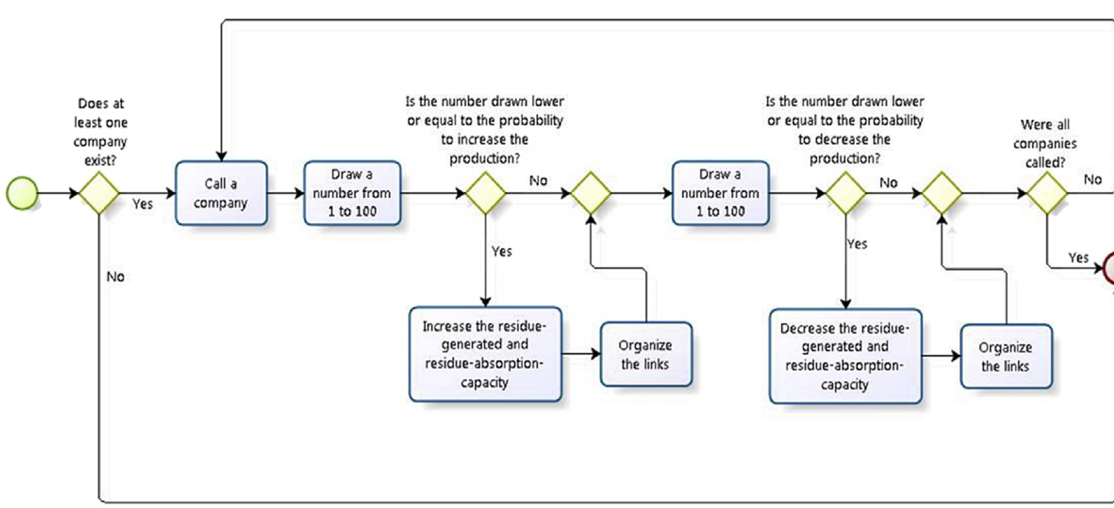

Fig. A.1. Flowchart of *Increment* submodel.

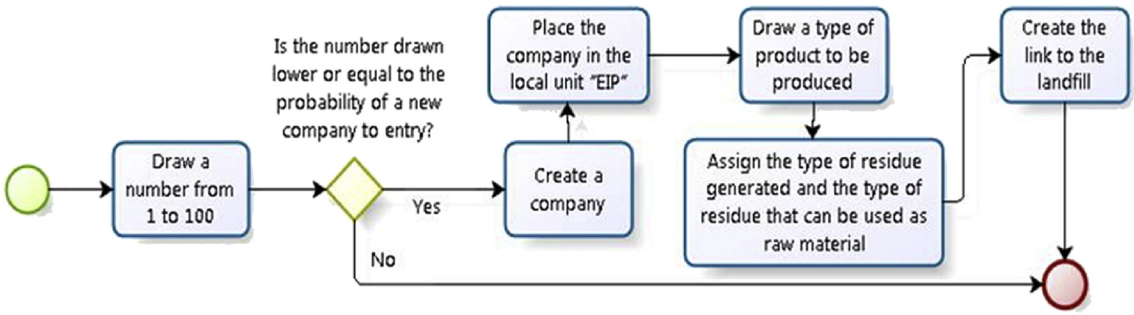

Fig. A.2. Flowchart of *New Company Entry* submodel.

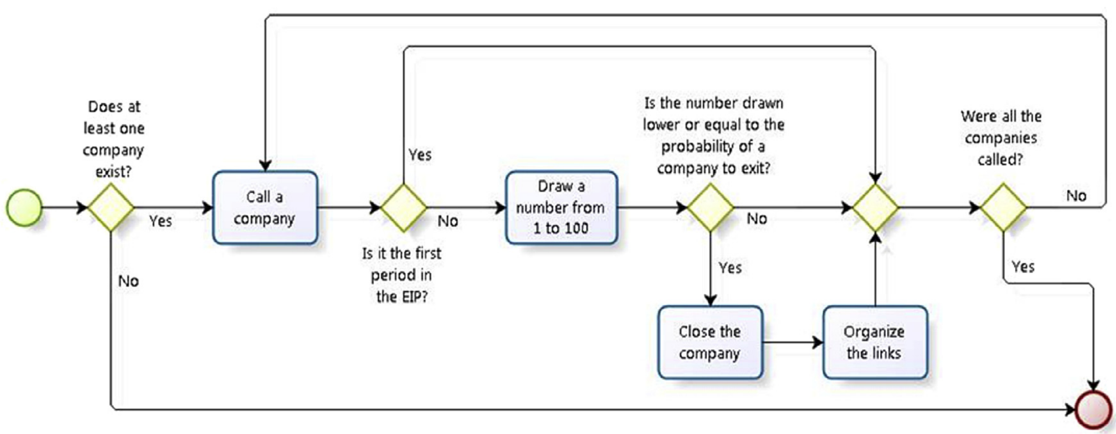

Fig. A.3. Flowchart of *Company Exit* submodel.

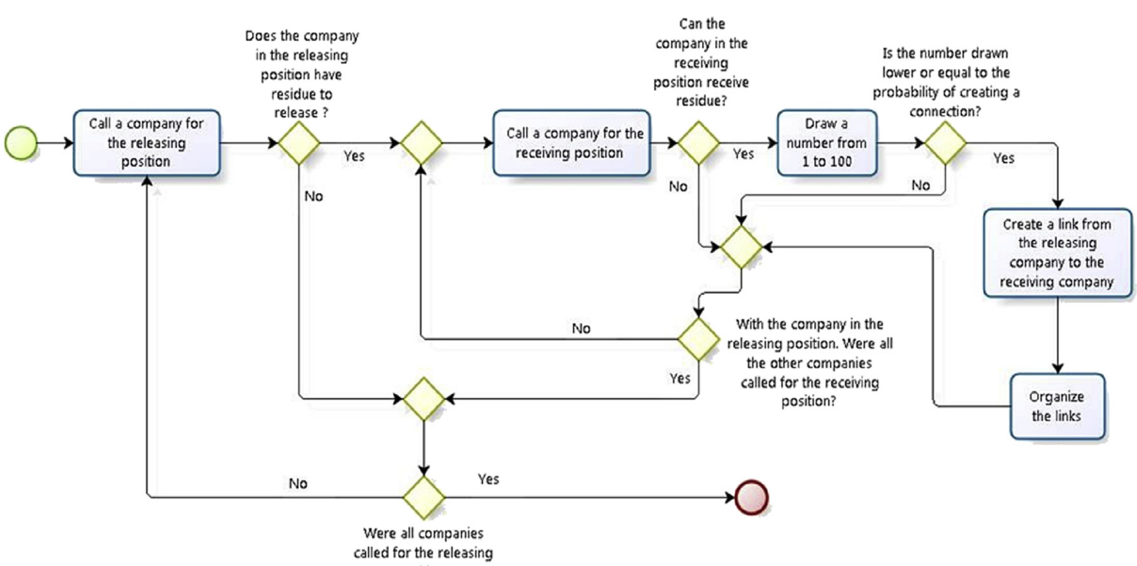

Fig. A.4. Flowchart of *Link Creation* submodel.

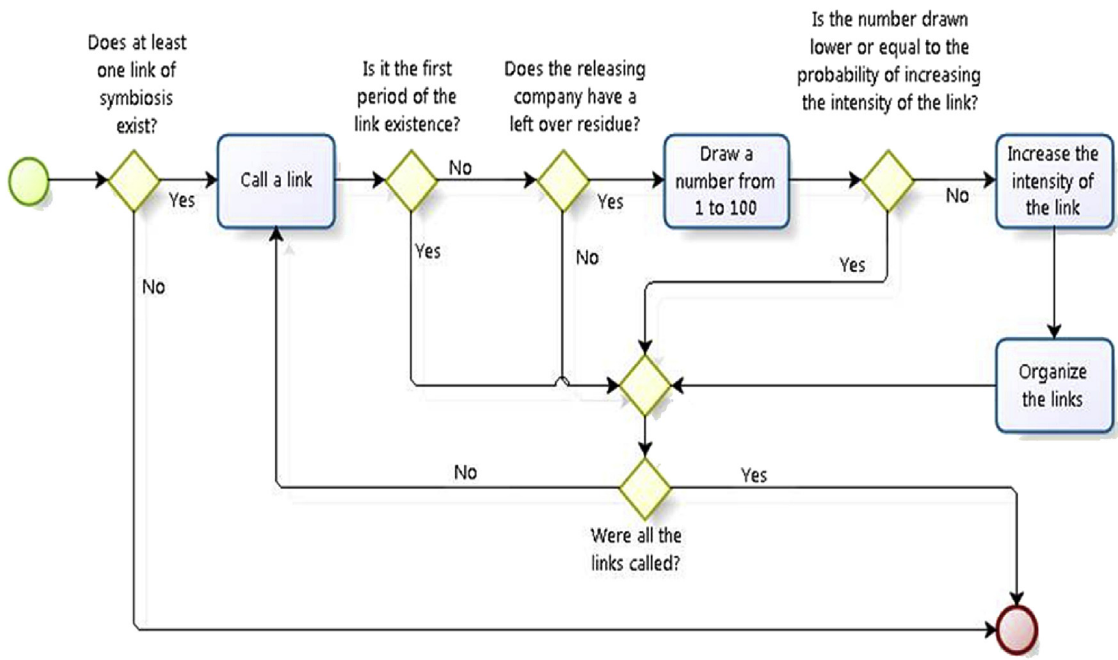

Fig. A.5. Flowchart of *Increased Links Intensity* submodel.

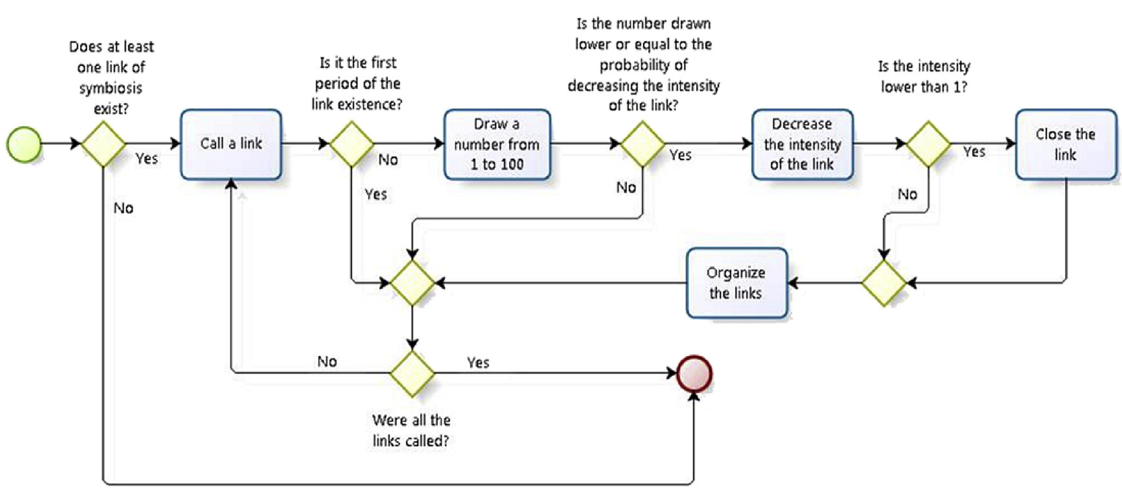

Fig. A.6. Flowchart of *Decreased Links Intensity* submodel.

The *Organize the links* activity can be found in most submodels' flowcharts. This activity is responsible for adjusting the *intensity* variable of each *link* that is influenced by previous activities of the submodel. If necessary, this activity can also create *links* to the landfill.

Appendix B. Scenarios Details

In this appendix, we present the output values and some details about the simulation of the scenarios. The Tables B.5 and B.6 are initiated at period 16, since there is a maturation period of 15 periods before the simulation of Scenario 3. The Tables B.7 and B.8 are initiated at period 41, because Scenario 4 begins after Scenario 3.

Table B.1
Values of the simulation of Scenarios 1 and 1′.

Scenarios 1 and 1′									
Period	ISI	ISI′	Eco-Connectance	By-product and waste recycling rate	Number of companies	Existing links	Possible links	Amount of generated by-product	% Of reused by-product
1	0.00000	0.00000	0.00000	0.00000	1	0	0	100.000	0.000
2	0.00477	0.00382	1.00000	0.00476	2	1	1	210.000	0.476
3	0.00913	0.00731	0.66666	0.00447	3	2	3	331.000	0.906
4	0.01752	0.01403	0.66666	0.00558	4	4	6	464.100	1.724
5	0.02861	0.02290	0.50000	0.00656	5	5	10	610.510	2.785
6	0.04891	0.03914	0.46666	0.00849	6	7	15	771.561	4.666
7	0.08455	0.06766	0.42857	0.01139	7	9	21	948.717	7.800
8	0.15205	0.12168	0.42857	0.01595	8	12	28	1143.589	13.204
9	0.28830	0.23071	0.38889	0.02274	9	14	36	1357.948	22.387
10	0.38283	0.30634	0.37778	0.02461	10	17	45	1593.743	27.693
11	0.51942	0.41564	0.43636	0.02700	11	24	55	1853.116	34.195
12	0.68518	0.54827	0.40909	0.02899	12	27	66	2138.429	40.669
13	0.85339	0.68286	0.38462	0.02967	13	30	78	2452.270	46.054
14	0.91606	0.73299	0.36264	0.02790	14	33	91	2797.499	47.818
15	0.99282	0.79441	0.34286	0.02655	15	36	105	3177.248	49.828
16	1.05807	0.84660	0.37500	0.02557	16	45	120	3594.973	51.418
17	1.20022	0.96033	0.36029	0.02559	17	49	136	4054.470	54.557
18	1.28119	1.02510	0.38562	0.02474	18	59	153	4559.917	56.169
19	1.29116	1.03307	0.40351	0.02314	19	69	171	5115.909	56.360
20	1.35007	1.08019	0.38474	0.02237	20	75	190	5727.500	57.453
21	1.45189	1.16165	0.40952	0.02215	21	86	210	6400.250	59.220
22	1.53225	1.22593	0.41991	0.02161	22	97	231	7140.275	60.514
23	1.63612	1.30902	0.42688	0.02117	23	108	253	7954.302	62.069
24	1.75534	1.40441	0.43116	0.02074	24	119	276	8849.732	63.711
25	1.85731	1.48598	0.43000	0.02025	25	129	300	9834.706	65.005

Table B.2
Details of the simulation of Scenarios 1 and 1′.

Scenarios 1 and 1′										
Period	Amount of generated by-product of type A	% Of reused by-product of type A	Amount of generated by-product of type B	% Of reused by-product of type B	Amount of generated by-product of type C	% Of reused by-product of type C	Amount of generated by-product of type D	% Of reused by-product of type D	Amount of generated by-product of type E	% Of reused by-product of type E
1	100.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	110.000	0.000	100.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000
3	221.000	0.000	110.000	2.727	0.000	0.000	0.000	0.000	0.000	0.000
4	243.100	0.823	121.000	4.959	0.000	0.000	0.000	0.000	100.000	0.000
5	267.410	1.496	133.100	9.016	0.000	0.000	100.000	0.000	110.000	0.909
6	294.151	2.720	246.410	10.552	0.000	0.000	110.000	0.000	121.000	1.653
7	323.566	4.945	371.051	14.553	0.000	0.000	121.000	0.000	133.100	3.005
8	355.893	9.553	408.156	26.460	0.000	0.000	133.100	0.000	246.410	3.652
9	391.515	17.368	548.971	39.711	0.000	0.000	146.400	0.000	271.051	6.641
10	430.666	32.043	603.869	44.109	0.000	0.000	161.051	0.000	398.156	9.293
11	573.733	37.800	664.256	51.606	0.000	0.000	177.156	0.000	437.972	16.896
12	631.106	40.937	730.681	62.998	0.000	0.000	294.872	0.000	481.769	31.343
13	694.217	46.642	903.749	64.754	0.000	0.000	324.359	0.000	529.946	41.581
14	763.639	57.013	994.124	65.539	0.000	0.000	456.795	0.000	582.940	43.022
15	840.003	66.688	1193.537	61.464	0.000	0.000	502.474	0.000	641.234	45.128
16	1024.003	64.180	1312.890	64.434	0.000	0.000	552.722	0.000	705.358	48.956
17	1126.403	68.882	1544.179	64.905	0.000	0.000	607.994	0.000	775.894	55.915
18	1239.044	68.882	1698.597	66.999	100.000	7.000	668.793	0.449	853.483	65.584
19	1362.948	68.882	1868.457	67.855	210.000	10.000	735.673	1.223	938.831	68.875
20	1499.243	68.882	2155.303	66.247	231.000	19.048	809.240	2.224	1032.714	74.375
21	1649.167	68.882	2370.833	68.713	354.100	27.111	890.164	4.381	1135.986	78.360
22	1914.084	65.284	2607.916	69.867	389.510	49.293	979.180	7.966	1249.584	78.360
23	2205.492	62.324	2868.708	70.293	428.461	73.064	1077.098	14.483	1374.543	78.360
24	2426.041	62.324	3155.579	70.701	571.307	71.802	1184.808	25.334	1511.997	78.360
25	2668.645	62.324	3571.137	69.517	628.438	82.431	1303.289	32.689	1663.196	78.360

Table B.3
Values of the simulation of Scenarios 2 and 2′.

Scenarios 2 and 2′									
Period	ISI	ISI′	Eco-Connectance	By-product and waste recycling rate	Number of companies	Existing links	Possible links	Amount of generated by-product	% Of reused by-product
1	0.00000	0.00000	0.00000	0.00000	1	0	0	100.000	0.000
2	0.00500	0.00400	1.00000	0.00500	2	1	1	200.000	0.500
3	0.00240	0.00389	0.33333	0.00200	3	1	3	266.667	0.375
4	0.00198	0.00517	0.16667	0.00188	4	1	6	383.333	0.391
5	0.00294	0.00522	0.10000	0.00135	5	1	10	466.667	0.482
6	0.00687	0.00527	0.20000	0.00120	6	3	15	616.667	0.689
7	0.00658	0.00596	0.19048	0.00101	7	4	21	694.444	0.720
8	0.01351	0.01295	0.25000	0.00205	8	7	28	644.444	1.513
9	0.01209	0.01423	0.19444	0.00216	9	7	36	688.889	1.524
10	0.01602	0.01826	0.27778	0.00267	9	10	36	811.111	1.973
11	0.01250	0.01303	0.27778	0.00197	9	10	36	1036.111	1.472
12	0.01475	0.01455	0.36111	0.00240	9	13	36	1154.167	1.679
13	0.01216	0.01306	0.33333	0.00229	9	12	36	1381.250	1.457
14	0.01328	0.02067	0.38889	0.00320	9	14	36	1394.444	1.936
15	0.01385	0.02220	0.40000	0.00343	10	18	45	1536.111	2.026
16	0.01180	0.01919	0.38182	0.00266	11	21	55	2112.500	1.749
17	0.01544	0.02198	0.36364	0.00257	12	24	66	2279.167	2.125
18	0.01681	0.02573	0.33333	0.00279	13	26	78	2648.958	2.389
19	0.01600	0.02050	0.30303	0.00285	12	20	66	2740.625	2.075
20	0.02002	0.02248	0.29487	0.00291	13	23	78	2747.569	2.416
21	0.02509	0.02614	0.27473	0.00265	14	25	91	2331.713	2.902
22	0.03450	0.03396	0.26667	0.00335	15	28	105	2249.306	3.840
23	0.02400	0.02430	0.23810	0.00296	15	25	105	2485.764	2.743
24	0.02791	0.02957	0.28571	0.00369	15	30	105	2825.347	3.257
25	0.03543	0.03679	0.30000	0.00392	16	36	120	3034.144	4.054
26	0.04292	0.04355	0.28676	0.00410	17	39	136	3063.310	4.808
27	0.04333	0.04646	0.28758	0.00477	18	44	153	3071.644	4.994
28	0.03816	0.04458	0.27485	0.00480	19	47	171	3791.030	4.617
29	0.04807	0.05033	0.30000	0.00471	20	57	190	3912.172	5.433
30	0.04440	0.04749	0.27895	0.00490	20	53	190	4284.761	5.106
31	0.04963	0.04361	0.28571	0.00488	21	60	210	4946.492	5.098
32	0.05067	0.04755	0.26840	0.00508	22	62	231	5540.982	5.395
33	0.05401	0.05500	0.28458	0.00475	23	72	253	5737.587	5.983
34	0.06106	0.06409	0.30435	0.00495	24	84	276	5801.939	6.814
35	0.07099	0.08915	0.30072	0.00523	24	83	276	5183.941	8.518

Table B.4
Details of the simulation of Scenarios 2 and 2′.

Scenarios 2 and 2′										
Period	Amount of generated by-product of type A	% Of reused by-product of type A	Amount of generated by-product of type B	% Of reused by-product of type B	Amount of generated by-product of type C	% Of reused by-product of type C	Amount of generated by-product of type D	% Of reused by-product of type D	Amount of generated by-product of type E	% Of reused by-product of type E
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	100.000	0.000
2	0.000	0.000	0.000	0.000	0.000	0.000	100.000	0.000	100.000	1.000
3	100.000	0.000	0.000	0.000	0.000	0.000	66.667	0.000	100.000	1.000
4	150.000	0.000	100.000	0.000	0.000	0.000	66.667	0.000	66.667	2.250
5	100.000	0.000	100.000	0.000	0.000	0.000	166.667	0.000	100.000	2.250
6	100.000	1.000	100.000	1.000	0.000	0.000	266.667	0.000	150.000	1.500
7	100.000	1.500	100.000	0.000	100.000	0.000	244.444	0.000	150.000	2.333
8	66.667	2.250	66.667	0.000	100.000	1.000	311.111	0.643	100.000	5.250
9	100.000	1.500	166.667	0.600	100.000	0.000	255.556	0.783	66.667	9.000
10	150.000	1.500	166.667	1.200	150.000	0.000	277.778	1.800	66.667	10.125
11	150.000	1.000	200.000	1.250	325.000	0.308	261.111	2.202	100.000	4.500
12	100.000	2.500	250.000	1.000	437.500	0.686	166.667	2.850	200.000	3.313
13	100.000	2.500	375.000	0.667	606.250	0.577	133.333	4.500	166.667	3.375
14	150.000	2.500	562.500	0.267	404.167	1.546	111.111	9.000	166.667	3.300
15	325.000	1.385	562.500	0.622	404.167	1.113	111.111	10.463	133.333	5.250
16	375.000	1.067	831.250	0.571	606.250	1.155	133.333	8.859	166.667	5.625
17	375.000	1.333	831.250	1.038	606.250	1.402	166.667	8.438	300.000	4.083
18	375.000	2.000	1134.375	0.909	606.250	1.649	166.667	10.969	366.667	4.688
19	487.500	1.487	993.750	1.393	859.375	1.338	66.667	18.984	333.333	3.488
20	656.250	1.848	787.500	2.240	826.042	1.271	66.667	16.453	411.111	3.687
21	487.500	2.731	675.000	2.725	606.250	1.588	166.667	5.063	396.296	4.518
22	325.000	4.942	712.500	3.345	572.917	2.105	166.667	7.181	472.222	4.751
23	437.500	3.529	425.000	1.118	826.042	1.721	144.444	7.853	652.778	3.437
24	572.917	3.305	391.667	1.213	803.819	2.451	166.667	10.359	890.278	3.522

Table B.4 (*continued*)

Scenarios 2 and 2′										
Period	Amount of generated by-product of type A	% Of reused by-product of type A	Amount of generated by-product of type B	% Of reused by-product of type B	Amount of generated by-product of type C	% Of reused by-product of type C	Amount of generated by-product of type D	% Of reused by-product of type D	Amount of generated by-product of type E	% Of reused by-product of type E
25	606.250	3.557	336.111	2.120	803.819	2.840	200.000	12.699	1087.963	4.237
26	606.250	4.113	336.111	3.366	803.819	3.758	166.667	16.214	1150.463	4.676
27	859.375	3.705	313.889	4.610	550.694	4.282	211.111	11.376	1136.574	5.234
28	1289.063	3.136	421.296	4.072	803.819	3.073	177.778	14.933	1099.074	6.024
29	1389.063	4.189	369.753	7.501	803.819	4.307	211.111	12.086	1138.426	5.842
30	1239.063	3.043	336.420	7.382	1168.692	3.824	294.444	8.915	1246.142	6.844
31	959.375	5.296	411.420	6.401	1738.223	2.596	294.444	9.552	1543.030	6.598
32	1355.729	4.991	444.753	6.427	1853.038	3.338	294.444	13.129	1593.017	6.414
33	1903.038	4.549	471.296	9.204	1268.692	4.945	491.667	9.758	1602.894	6.402
34	2003.038	4.026	454.630	14.491	1235.359	5.139	548.611	11.027	1560.301	8.000
35	2003.038	3.637	698.611	13.226	855.671	8.369	425.000	17.535	1201.620	10.832

Table B.5
Values of the simulation of Scenario 3.

Scenario 3								
Period	ISI	Eco-Connectance	By-product and waste recycling rate	Number of companies	Existing links	Possible links	Amount of generated by-product	% Of reused by-product
16	0.00417	0.06667	0.00032	15	7	105	1535.238	0.456
17	0.00750	0.11429	0.00056	15	12	105	1555.738	0.784
18	0.00925	0.14286	0.00068	15	15	105	1587.025	0.971
19	0.01094	0.17143	0.00082	15	18	105	1640.614	1.150
20	0.01273	0.20000	0.00095	15	21	105	1667.939	1.326
21	0.01390	0.21905	0.00104	15	23	105	1723.471	1.437
22	0.01443	0.22857	0.00108	15	24	105	1770.177	1.486
23	0.01487	0.23810	0.00112	15	25	105	1834.926	1.533
24	0.01478	0.23810	0.00111	15	25	105	1889.466	1.523
25	0.01534	0.24762	0.00115	15	26	105	1914.718	1.585
26	0.01585	0.25714	0.00119	15	27	105	1958.566	1.631
27	0.01513	0.24762	0.00114	15	26	105	2004.455	1.562
28	0.01553	0.25714	0.00117	15	27	105	2056.269	1.610
29	0.01548	0.25714	0.00116	15	27	105	2083.489	1.605
30	0.01597	0.26667	0.00120	15	28	105	2126.203	1.658
31	0.01753	0.29524	0.00132	15	31	105	2169.006	1.805
32	0.01711	0.28571	0.00130	15	30	105	2214.901	1.761
33	0.01761	0.30476	0.00134	15	32	105	2290.419	1.807
34	0.01789	0.30476	0.00136	15	32	105	2315.240	1.836
35	0.01791	0.30476	0.00135	15	32	105	2384.629	1.831
36	0.01819	0.31429	0.00138	15	33	105	2449.244	1.862
37	0.01851	0.32381	0.00140	15	34	105	2518.761	1.883
38	0.01857	0.32381	0.00141	15	34	105	2569.336	1.890
39	0.01869	0.32381	0.00142	15	34	105	2614.320	1.903
40	0.01844	0.32381	0.00140	15	34	105	2701.046	1.877

Table B.6
Details of the simulation of Scenario 3.

Scenario 3										
Period	Amount of generated by-product of type A	% Of reused by-product of type A	Amount of generated by-product of type B	% Of reused by-product of type B	Amount of generated by-product of type C	% Of reused by-product of type C	Amount of generated by-product of type D	% Of reused by-product of type D	Amount of generated by-product of type E	% Of reused by-product of type E
16	710.238	0.563	100.000	1.000	105.000	0.000	410.000	0.244	210.000	0.476
17	720.738	0.846	100.000	2.050	105.000	0.952	420.000	0.238	210.000	0.976
18	741.525	1.106	100.000	2.050	105.000	0.952	425.250	0.247	215.250	1.441
19	768.601	1.360	100.000	2.103	110.250	0.907	441.263	0.250	220.500	1.906
20	773.601	1.372	100.000	2.103	115.763	0.907	458.076	0.459	220.500	2.837
21	796.006	1.380	105.000	3.955	121.551	0.864	474.902	0.453	226.013	2.838
22	819.794	1.374	110.250	4.769	127.628	0.784	486.492	0.454	226.013	2.909
23	860.784	1.348	115.763	4.635	127.628	0.823	498.951	0.654	231.801	2.955
24	878.786	1.348	115.763	4.733	127.628	0.823	523.898	0.633	243.391	2.908
25	898.250	1.456	121.551	4.603	127.628	0.823	523.898	0.654	243.391	2.954
26	916.526	1.447	127.628	4.427	134.010	0.784	537.011	0.650	243.391	3.487
27	955.317	1.413	127.628	3.604	134.010	0.784	538.321	0.671	249.179	3.433

(*continued on next page*)

Table B.6 (*continued*)

Scenario 3										
Period	Amount of generated by-product of type A	% Of reused by-product of type A	Amount of generated by-product of type B	% Of reused by-product of type B	Amount of generated by-product of type C	% Of reused by-product of type C	Amount of generated by-product of type D	% Of reused by-product of type D	Amount of generated by-product of type E	% Of reused by-product of type E
28	975.832	1.529	134.010	3.474	134.010	0.823	550.780	0.679	261.638	3.322
29	983.589	1.517	134.010	3.483	134.010	0.823	563.862	0.686	268.019	3.313
30	1004.810	1.627	134.010	4.229	134.010	0.823	578.654	0.678	274.720	2.987
31	1032.768	1.615	134.010	5.852	134.010	0.864	593.499	0.843	274.720	3.084
32	1064.608	1.591	140.710	4.941	134.010	0.907	607.235	0.845	268.338	3.267
33	1111.457	1.621	140.710	5.811	140.710	0.864	622.822	0.824	274.720	3.220
34	1114.803	1.650	140.710	5.982	140.710	0.864	637.597	0.836	281.420	3.248
35	1147.941	1.544	140.710	6.187	147.746	0.864	652.741	0.857	295.491	3.509
36	1172.901	1.621	147.746	6.061	155.133	0.823	677.621	0.840	295.843	3.602
37	1215.238	1.599	147.746	6.233	155.133	0.864	703.746	0.812	296.899	3.952
38	1240.525	1.625	147.746	6.224	162.889	0.823	721.277	0.814	296.899	4.038
39	1260.241	1.638	147.746	6.400	171.034	0.823	730.256	0.813	305.043	4.035
40	1302.959	1.626	147.746	6.574	171.034	0.823	759.012	0.783	320.296	3.884

Table B.7
Values of the simulation of Scenario 4.

Scenario 4								
Period	ISI	Eco-Connectance	By-product and waste recycling rate	Number of companies	Existing links	Possible links	Amount of generated by-product	% Of reused by-product
41	0.01323	0.30769	0.00127	14	28	91	2621.470	1.584
42	0.00991	0.27473	0.00095	14	25	91	2846.374	1.196
43	0.00700	0.21978	0.00069	14	20	91	3070.032	0.852
44	0.00488	0.15238	0.00042	15	16	105	3554.572	0.591
45	0.00410	0.13333	0.00032	16	16	120	4053.757	0.494
46	0.00336	0.11029	0.00023	17	15	136	4612.368	0.402
47	0.00186	0.07353	0.00014	17	10	136	5332.766	0.228
48	0.00178	0.07843	0.00013	18	12	153	6209.227	0.219
49	0.00087	0.03922	0.00007	18	6	153	6648.426	0.108
50	0.00087	0.04575	0.00007	18	7	153	7174.737	0.108
51	0.00047	0.02339	0.00003	19	4	171	7885.546	0.059
52	0.00032	0.01754	0.00003	19	3	171	8130.629	0.042
53	0.00076	0.04211	0.00007	20	8	190	8599.774	0.095
54	0.00054	0.02857	0.00005	21	6	210	9059.830	0.068
55	0.00029	0.01732	0.00003	22	4	231	10186.109	0.039
56	0.00051	0.02767	0.00004	23	7	253	10830.199	0.065
57	0.00008	0.00395	0.00001	23	1	253	11884.501	0.008
58	0.00054	0.02899	0.00005	24	8	276	12335.398	0.065
59	0.00048	0.02899	0.00005	24	8	276	13584.326	0.059
60	0.00096	0.05667	0.00009	25	17	300	14645.408	0.116

Table B.8
Details of the simulation of Scenario 4.

Scenario 4										
Period	Amount of generated by-product of type A	% Of reused by-product of type A	Amount of generated by-product of type B	% Of reused by-product of type B	Amount of generated by-product of type C	% Of reused by-product of type C	Amount of generated by-product of type D	% Of reused by-product of type D	Amount of generated by-product of type E	% Of reused by-product of type E
41	1124.615	1.392	147.746	5.463	171.034	0.823	829.637	0.716	348.438	2.999
42	1157.193	1.190	147.746	3.453	205.241	0.571	953.986	0.566	382.208	2.252
43	1266.282	0.840	147.746	2.588	205.241	0.571	1068.556	0.360	382.208	1.747
44	1475.881	0.689	177.295	1.549	246.289	0.000	1136.982	0.224	518.125	1.075
45	1816.751	0.448	212.754	1.291	246.289	0.000	1259.838	0.224	518.125	1.219
46	2046.439	0.343	255.304	1.030	346.289	0.000	1383.110	0.204	581.226	1.046
47	2394.454	0.133	306.365	0.443	415.547	0.000	1542.930	0.328	673.471	0.379
48	2805.960	0.149	367.638	0.308	415.547	0.000	1811.917	0.279	808.165	0.402
49	3132.032	0.032	441.166	0.256	415.547	0.000	1851.516	0.204	808.165	0.154
50	3469.792	0.029	529.399	0.214	439.547	0.000	1899.034	0.240	836.965	0.124
51	3724.229	0.000	529.399	0.214	498.656	0.000	2221.819	0.160	911.443	0.000
52	4168.673	0.024	100.000	0.000	527.456	0.000	2330.142	0.103	1004.358	0.000
53	4403.646	0.091	100.000	1.000	468.347	0.000	2623.423	0.083	1004.358	0.100
54	4596.525	0.065	120.000	0.833	453.649	0.000	2815.271	0.077	1074.384	0.000
55	5085.864	0.059	144.000	0.000	544.379	0.184	3248.108	0.000	1163.758	0.000
56	5165.613	0.077	172.800	0.000	562.016	0.000	3517.292	0.057	1412.478	0.071
57	5871.522	0.000	207.360	0.000	603.488	0.000	3685.621	0.000	1516.509	0.066
58	6101.721	0.016	207.360	0.000	724.186	0.138	3685.621	0.027	1616.509	0.309
59	6409.839	0.031	248.832	0.000	869.023	0.115	4319.285	0.023	1737.347	0.230
60	7120.457	0.098	298.598	0.670	869.023	0.000	4443.285	0.045	1914.045	0.313

Appendix C. Downloading and using the *EIPSymb*

The *EIPSymb* is available in an online community of agent-based models. This community is named "Modeling Commons" and is intended for the sharing and discussing of models developed in the NetLogo platform (Modeling Commons, 2016).

The link to access the *EIPSymb* in the "Modeling Commons" community is: http://modelingcommons.org/browse/one_model/4780. There are details about the model function and how to use it. Anyone can download the model for free.

As the "Modeling Commons" is also an environment to collaborate on modeling projects (Modeling Commons, 2016), more than only download the model, it is also possible to upload other versions of the *EIPSymb*. As, for example, a version where others indicators for measuring the industrial symbiosis are automatically calculated.

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