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Methodological and Ideological Options

Ecosystem indicators for measuring industrial symbiosis

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A B S T R A C T

Industrial symbiosis (IS) is a collaborative approach among firms involving physical exchanges of materials, energy, and wastes, which creates economic advantages for firms and environmental benefits for the society. In this paper, we adopt an ecosystem approach to conceptualize the network of firms involved in IS relationships (ISN), in terms of organisms (firms), functions (waste exchange), and services (environmental benefits), and provide new insight on how to assess and compute IS performance indicators. In particular, we designed five classes of indicators aimed at assessing 1) the impact of services provided by ISNs on the environment, 2) the performance of the ISN services, 3) how the single functions contribute to ISN services, 4) the performance of the ISN functions, and 5) how the single firms contribute to ISN functions. A numerical example is also discussed showing how to compute them and the information they provide. The proposed indicators are useful to develop proper strategies to increase the efficiency of the system in exploiting the IS synergies, to improve the symbiotic exchanges carried out in ISNs, and to identify firms contributing most to IS benefits. Hence, they may assist managers of ISNs and policymakers in decision-making aspects, an urgent need of the literature.

1. Introduction

Industrial symbiosis (IS) is a subfield of industrial ecology that engages separate industries in a collective approach to competitive advantage, involving physical exchanges of materials, energy, and services (Chertow, 2000; Lombardi and Laybourn, 2012). In particular, wastes produced by one production process can be used by other processes – belonging to the same company or a different company – to replace production inputs (e.g., water, raw materials, energy) or be used to generate new products, which are sold in markets (Albino and Fraccascia, 2015). Companies adopting IS can reduce production costs, thus achieving economic benefits, and create environmental and social benefits for the entire collectivity simultaneously (Simboli et al., 2015; Taddeo et al., 2017; Yuan and Shi, 2009).

For this reason, IS is recognized as one of the key strategies to support the transition towards the circular economy (e.g., D'Amato et al., 2019; Diaz Lopez et al., 2019; Domenech and Bahn-Walkowiak, 2017; Korhonen et al., 2018). Furthermore, several studies indicate that IS can be a useful approach for companies to reduce their CO₂ emissions (Hashimoto et al., 2010; Liu et al., 2017; Sun et al., 2017), which is in line with the goals of the Paris agreement (Mathy et al., 2018; Nieto

et al., 2018). For these reasons, the European Commission has strongly recommended companies to implement IS (European Commission, 2015, 2011) and policymakers of many countries have introduced the IS practice in their environmental agenda (Costa et al., 2010; Husgafvel et al., 2013; Ministero dell'Ambiente e della Tutela del Territorio e del Mare and Ministero dello Sviluppo Economico, 2017; Mirata, 2004; Van Berkel et al., 2009).

One of the best strategies to promote IS is supporting the creation of industrial symbiosis networks (ISNs), i.e., networks of firms among which IS relationships exist (Chertow, 2007; Fichtner et al., 2005). An ISN can be designed by adopting a top-down approach, such as the eco-industrial park model (e.g., Boix et al., 2015), can emerge from the bottom as the result of a process undertaken by several firms spontaneously (Chertow and Ehrenfeld, 2012), or can be the result of a facilitation process driven by a public or private third-party organization (Boons et al., 2017).

Independent on the design approach, the need to quantify and assess the performance of ISNs has strongly emerged already in the early literature as a way to support the diffusion of IS in practice (e.g., Chiu and Yong, 2004). Thus, a high number of performance measurements has been developed in the literature, differing in purpose, scope,

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methodology, and scale – see the recent reviews by [Neves et al. \(2019\)](#) and [Fraccascia and Giannoccaro \(2020\)](#).

In particular, IS indicators have been designed for monitoring, evaluation, and – to a lesser extent – decision-making purposes. Monitoring is the first step to recognize applications of IS in practice and track their evolution over time. Evaluation is useful for identifying the best practices. Indicators are also essential to support decision-making by managers and policymakers at both local and national levels. They provide information useful to improve ISN exchanges and optimize specific performance.

As to the *scope*, different IS indicators have been proposed to measure the impacts of IS practice mainly in terms of economic or/and environmental benefits. Economic indicators focus on cost savings enabled by the adoption of IS, economic value created by IS synergies, and comprehensive economic feasibility of IS synergies (e.g., [Cao et al., 2017](#); [Tan et al., 2016](#); [Yazan and Fraccascia, 2020](#)). Environmental indicators quantify the reduction in the amounts of materials, energy, and water used as inputs by industrial processes (e.g., [Ali et al., 2019](#); [Han et al., 2017](#); [Hu et al., 2017](#); [Li et al., 2015](#)), as well as the reduction in the amounts of solid wastes discharged in the landfill, wastewater discharged, waste energy not exploited, and greenhouse gas emissions to the atmosphere (e.g., [Cao et al., 2017](#); [Domenech et al., 2019](#); [Maillé and Frayret, 2016](#); [Yu et al., 2015](#)). Hybrid indicators have been also developed, which consider simultaneously the economic and environmental benefits, such as the eco-efficiency indicators (e.g., [Chen et al., 2010](#); [Park and Behera, 2014](#); [Shah et al., 2020](#)) and resource productivity indicators (e.g., [Park and Behera, 2014](#); [Rosano and Schianetz, 2014](#); [Wen and Meng, 2015](#)).

As to the *methodology* adopted to design IS indicators, four classes can be distinguished: flow analysis, thermodynamics, Life Cycle Assessment (LCA), and network analysis ([Fraccascia and Giannoccaro, 2020](#)). In particular, flow analysis includes material flow analysis (e.g., [Sendra et al., 2007](#)), substance flow analysis (e.g., [Huang et al., 2012](#)), and the enterprise Input-Output approach (e.g., [Fraccascia et al., 2017a](#)). The thermodynamics category refers to two main methodologies, i.e., energy (e.g., [Geng et al., 2014](#)) and exergy analysis (e.g., [Wu et al., 2018](#)). The network analysis embraces social network analysis (e.g., [Song et al., 2018](#)), stakeholder value network approach (e.g., [Hein et al., 2017](#)), ecological network analysis (e.g., [Zhang et al., 2015](#)), and food web analysis (e.g., [Genc et al., 2019](#)). Each methodology has specific advantages but also inherent drawbacks, so that a preferred standard is currently lacking.

As to the *scale*, the IS indicators developed in the literature measure the beneficial effects associated to IS, mainly by taking into account a specific unit of analysis, i.e., the single firm, the IS relationship, or the symbiotic system as a whole, respectively.

Referring to the literature on the IS indicators, three main gaps can be highlighted. The first gap is that indicators that simultaneously address multiple scales are scarcely common. For example, eco-efficiency indicators adopted at the individual firm level do not provide information at the overall network level. Similarly, LCA indicators adopted at the level of the single IS relationship or at the network level do not provide information referring to the single firms. Indicators including measurements at multiple scales could be useful to quantify the extent to which each firm belonging to the network or each symbiotic exchange is contributing to the ISN benefits. The possibility to allocate the impacts at the network level on the single firms through LCA is highly complex from the methodological perspective and in any case quite controversial ([Guinée et al., 2004](#); [Martin et al., 2015](#)).

Second, we note that the indicators developed in the literature, being mainly designed to measure the impacts of IS practice, are unable to assess the extent to which the current performance could be further increased. This is because they do not include a reference point. Having a reference point would permit to understand whether the ISN is exploiting all the symbiotic exchanges, so that the highest possible benefits are achieved, or whether the IS exchange could be further enhanced. Third,

most of the indicators developed in the literature provide a static picture of the ISN performance with scant attention for measuring the functioning of symbiotic networks over time. This perspective is crucial to assist ISN managers and policymakers when driving the evolution of IS, from both the operational and strategic point of view.

All these limits confirm that there is a scarce availability of IS indicators useful for decision-making, which is an urgent need for supporting IS development ([Felicio et al., 2016](#)).

Therefore, in this paper we aim at designing an integrated set of IS indicators overcoming the above-mentioned limitations. In particular, they capture all the relevant IS dimensions (i.e., the firm, the symbiotic exchange, and the network) and provide information useful for monitoring, evaluation, and, more importantly, decision-making to managers and policymakers interested in favoring IS practices.

As to the methodology, we rely on the ecosystem theory and frame ISNs as industrial ecosystems ([Korhonen, 2001](#); [Lowe and Evans, 1995](#); [Schlüter et al., 2020](#)). According to our framing, firms correspond to organisms and perform specific functions for the system, which are associated with waste exchanges ([Fraccascia et al., 2017b](#); [Korhonen, 2001](#); [Korhonen and Baumgartner, 2009](#)). Two kinds of functions are distinguished: 1) recovering the produced wastes and 2) saving the required inputs. Through the functions performed, the ISN as a whole generates services to the external environment, in form of reduced environmental impacts of production activities (e.g., GHG emissions, water consumption, raw materials consumption, etc.). In this way, all the relevant dimensions of IS are taken into account. Based on this conceptualization, we design proper indicators to quantify: 1) the performance of the single functions, 2) the extent to which the single organisms contribute to the single functions, 3) the impact of ISN services, 4) the performance of ISN services, and 5) the contribution of the single functions to the different services. This set of indicators provides multiple information, which can be specifically adopted for decision-making aims. They offer a clear assessment of all the possible opportunities coming from the waste exchanges (reference point), if they are fully exploited and, if not, what are the reasons for this inefficacy. Furthermore, they quantify the specific contribution of the single firms/waste exchanges to the ISN operations, so that their importance in the network functioning can be easily assessed.

The rest of the paper is organized as follows. [Section 2](#) provides the theoretical background of the paper by conceptualizing ISNs as ecosystems. [Section 3](#) presents the numerical indicators developed. [Section 4](#) proposes a numerical case example aimed at showing how to compute the proposed indicators, as well as their usefulness in practice. The paper ends with discussion and conclusions in [Section 5](#) and [Section 6](#).

2. Industrial symbiosis networks as ecosystems

ISNs have been recognized as an example of industrial ecosystems, i.e., natural ecosystems in industrial contexts (e.g., [Allenby and Cooper, 1994](#); [Lowe and Evans, 1995](#)). A natural ecosystem is composed of an environment (abiotic component) and a set of living organisms (biotic component), which interact among them through a network of highly complex relationships and food webs. In industrial ecosystems, companies correspond to the organisms of a natural ecosystem, while the physical locations in which business operates are analogous to the environment (e.g., [Genc et al., 2019](#); [Geng and Côté, 2007](#); [Liwarska-Bizukoje et al., 2009](#)). The relationships of IS among companies evoke the metaphor of mutualistic symbiosis among organisms in natural ecosystems ([Ayres, 1989](#); [Korhonen, 2001](#)). A mutualistic symbiotic relationship occurs when one organism obtains at least one resource from the other organism in return for at least one service provided (e.g., [Ollerton, 2006](#)). As a result, both organisms benefit from the relationship. In the IS context, companies exchanging wastes for inputs correspond to natural organisms exchanging resources for services.

A relevant feature of natural ecosystems is that the overall system provides some services to the external environment, with the organisms

belonging to the system collectively contributing to operate these services by carrying out specific functions (e.g., Millennium Ecosystem Assessment, 2005). The same occurs in industrial ecosystems (e.g., Liu and Côté, 2017).

Four principles of natural ecosystems can be applied to ISNs framed as industrial ecosystems: *roundput*, *diversity*, *locality*, and *gradual change* (Korhonen, 2001).

Roundput is related to recycling materials and energy within the system so that the efficiency in resource usage is increased as much as possible, as well as the amounts of wastes disposed of outside the system are reduced as much as possible. In ISNs, this principle is fully accomplished when the overall amount of wastes produced by companies is recovered into the ISN, so that no wastes are disposed of in the landfill outside the network (Yazan et al., 2016).

Diversity is related to the diversity in elements belonging to the system. Companies belonging to ISNs usually come from different industrial sectors: therefore, they produce different kinds of wastes and require different kinds of inputs. Furthermore, these companies can belong to different supply chains and they would not have collaborated among them if not involved in waste exchanges. The diversity principle is fundamental for ISNs, since allows that different wastes are produced and different inputs are required into the same ISN (Fraccascia et al., 2017b). In fact, the more differentiated the companies within the ISN are, the higher the chance to create IS relationships and to obtain a system stable over the long period (Côté and Smolenaars, 1997). However, “The diversity of the involved actors means the diversity of interests, preferences and values, which can be conflicted” (Geng and Côté, 2007, p. 332). In this regard, “the organisational cultures of the participating firms are different. Management models and styles vary. The more diversity existing in the system, the more complex and challenging are the harmonising and alignment efforts between the individual firm strategies and the overall network strategy” (Korhonen and Baumgartner, 2009, p. 32).

Locality is related to exploiting local resources produced into the system so that the amounts of input required from outside the system is reduced as much as possible. This requires the cooperation between local actors inside the system and calls for the interdependence of these actors (Afshari et al., 2020; Schlüter et al., 2020). Locality in ISNs translates into replacing production inputs with wastes generated by companies belonging to the ISN as much as possible, according to operational issues related, e.g., to the match between demand and supply of wastes, as well as technical issues related to using wastes to replace production inputs, e.g., the waste quality (Bansal and McNight, 2009; Herczeg et al., 2018; Prossman and Wæhrens, 2019).

Finally, *gradual change* means that the system is able to evolve over time, in terms of changing structure and patterns. ISNs are not static systems, but they can evolve following multiple logics. Since companies are involved in a dynamic business environment, both the types and amounts of wastes produced and inputs required can fluctuate over time, as well as the ceasing costs thanks to IS and the additional costs required to operate IS (Yazan and Fraccascia, 2020). Hence, new symbiotic opportunities can emerge over time, as well as existing symbiotic opportunities can become no more convenient (Ashton et al., 2017). Any firm autonomously decides to establish IS relationships with other firms, aimed at reducing its production costs and gaining a competitive advantage over other companies not implementing IS (e.g., Ashton, 2011; Esty and Porter, 1998; Lyons, 2007; Yuan and Shi, 2009). Hence, in the long period, new companies can decide to enter a given ISN (Chertow and Ehrenfeld, 2012). Accordingly, the types and number of wastes produced and inputs required into the ISN can change over time, as well as the ISN topology. In this regard, companies are characterized by an individual propensity to establish and keep IS relationships, which specifies the extent to which the relationship should be economically beneficial. Accordingly, firms may decide to interrupt IS relationships in which they are involved if they are assessed as not enough economically convenient (Chopra and Khanna, 2014; Li and Shi, 2015; Wang et al., 2017a; Wu et al., 2017).

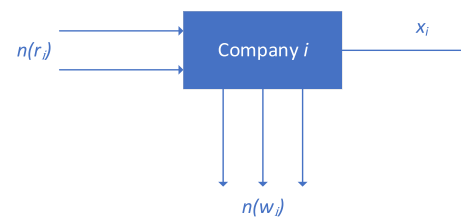


Fig. 1. Graphical representation of a generic company in the ISN model.

3. Methods

We frame the ISN as an ecosystem, where firms correspond to organisms and perform specific functions for the system (Fraccascia et al., 2017b; Korhonen, 2001; Korhonen and Baumgartner, 2009). Two kinds of *functions* are distinguished: 1) *recovering* the produced wastes and 2) *saving* the required inputs. Firms contribute to these functions by exchanging wastes for inputs. By performing the ISN functions, the companies can reduce their production cost and thus increase their economic performance, which in turn contributes to enhance the survivability of companies into their markets. At the same time, through the functions performed internally, the ISN as a whole generates several services to the external environment, in form of reduced environmental impacts of production activities (e.g., GHG emissions, water consumption, raw materials consumption, etc.).

In the following, we first describe how we model the building blocks of an ISN ecosystem using the Enterprise Input-Output (EIO) approach (Section 3.1). Then, we design the ecosystem-based indicators of ISNs (Section 3.2).

3.1. Modeling the companies and waste flows among them

In this section, we employ the Enterprise Input-Output (EIO) approach (Grubbstrom and Tang, 2000) to model waste flows among firms. The EIO model describes the ISN as a network of companies using an input-output approach at the enterprise level (Fraccascia et al., 2017a). The network is made up of firms that procure materials and energy (primary inputs), transform them into outputs, and produce wastes. Without any IS exchange occurring, primary inputs are purchased from conventional suppliers and wastes are disposed of in landfills.

We model a generic ISN made of n companies. For the sake of simplicity, we assume that each company produces only one main output, which is sold on the market.¹ Hence, n outputs are produced into the ISN.

In this regard, let $x(t)$ be the $n \times 1$ vector of gross outputs produced at time t . The amounts of outputs produced are considered dependent on the market demand for the main products (Yazan, 2016).

To produce its output, company i requires $n(r_i)$ primary inputs and generates $n(w_i)$ wastes (Fig. 1). Overall, the ISN requires $n(r)$ primary inputs, with $n(r) \leq \sum_{i=1}^n n(r_i)$, and generates $n(w)$ wastes, with $n(w) \leq \sum_{i=1}^n n(w_i)$. Equality holds when either each primary input is used by only one company or each waste is produced by only one company, respectively.

Let $r(t)$ be the $n(r) \times 1$ vector of primary inputs overall used by companies at time t and let $w(t)$ be the $n(w) \times 1$ vector of wastes overall generated by companies. Both primary inputs requirement and wastes production are related to the gross outputs by the following equations:

¹ This limitation is common to other EIO models (e.g., Fraccascia et al., 2017a; Yazan, 2016; Yazan et al., 2016) and can be overcome by modeling one company as composed by several production processes, each of them having input.

$$r(t) = Rx(t) \tag{1}$$

$$w(t) = Wx(t) \tag{2}$$

where the $n(r) \times n$ matrix of primary input coefficient R and the $n(w) \times n$ matrix of waste output coefficients W are obtained from observed data. The generic element R_{lj} denotes the quantity of primary input l required to produce one unit of the output of company j . Similarly, the element W_{kj} denotes the quantity of waste k generated to produce one unit of the output of company j .

When IS occurs between two companies, wastes produced by a company can be used to replace primary inputs by other companies. This corresponds to exchange wastes for primary inputs.

In order to model waste flows taking place among companies, for each couple of companies i and j we can define $e^{i \rightarrow j}$ as the $n(w) \times 1$ vector of the observed symbiotic flows between i and j . The generic element $e_k^{i \rightarrow j}(t)$ denotes the amount of the k -th waste flowing from company i to company j at time t . Let us assume that waste k produced by company i can be used by company j to replace input l . The amount of exchanged waste cannot be higher than either the amount of waste k produced by company i or the correspondent amount of input l that is required by company j . From the numerical point of view, the following condition must thus be verified²:

$$e_k^{i \rightarrow j}(t) \leq \min \left\{ W_{ki} x_i(t); \frac{R_{lj}}{s_{l \rightarrow k}} \cdot x_j(t) \right\} \forall (i, j, k, l), s_{l \rightarrow k} \neq 0 \tag{3}$$

where $s_{l \rightarrow k}$ denotes how many units of input l can be replaced by one unit of waste k .

Let us now focus on the generic company i . The amount of the generic k -th waste recovered by this company (i.e., not disposed of in landfills) at time t because adopting IS can be computed as follows:

$$w_{ki}^S(t) = \sum_{j=1}^n e_k^{i \rightarrow j}(t) \tag{4}$$

Similarly, the amount of the generic l -th primary inputs saved by this company (i.e., replaced by wastes and hence not purchased from conventional suppliers) at time t because adopting IS can be computed as follows:

$$r_{li}^S(t) = \sum_{k=1}^{n(w)} \sum_{j=1}^n s_{l \rightarrow k} \cdot e_k^{j \rightarrow i}(t) \tag{5}$$

At the level of ISN, the amount of k -th waste and l -th input saved at time t can be computed as follows:

$$w_k^S(t) = \sum_{i=1}^n w_{ki}^S(t) \tag{6}$$

$$r_l^S(t) = \sum_{i=1}^n r_{li}^S(t) \tag{7}$$

3.2. Ecosystem-based ISN indicators

Based on the conceptualization of ISN as ecosystem and the EIO model of waste flows, we design five classes of indicators: 1) indicators assessing the performance of each function (Section 3.2.1), 2) indicators assessing the contribution that each organism is providing to each

² It might happen that one waste can replace more than one input. Let us assume that waste k can replace both input l and input m required by company j . The Equation (3) can be expressed as follows:

$$e_k^{i \rightarrow j}(t) \leq \min \left\{ W_{ki} x_i(t); \left[\frac{R_{lj}}{s_{l \rightarrow k}} + \frac{R_{mj}}{s_{m \rightarrow k}} \right] \cdot x_j(t) \right\}$$

function (Section 3.2.2), 3) indicators assessing the impact of ISN services to the external environment (Section 3.2.3), 4) indicators assessing the performance of ISN services (Section 3.2.4), and 5) indicators assessing the contribution that each function is providing to each service (Section 3.2.5). Fig. 2 graphically shows a framework of the above-mentioned indicators.

3.2.1. Performance indicators for functions

These performance indicators aim at quantifying the ability of ISN to perform given IS functions, in particular by taking into account the extent to which each function is currently performed. We distinguish two classes of performance indicators for functions, i.e., for waste recovering and input saving.

For each generic function “recovering waste k ”, the following performance indicator is defined:

$$\phi_k^W(t) = \frac{w_k^S(t)}{w_k(t)} \tag{8}$$

where $w_k^S(t)$ is the amount of waste k recovered at time t (see Eq. (6)) and $w_k(t)$ is the amount of waste k produced at time t by firms belonging to the ISN (see Eq. (2)). Overall, $\phi_k^W(t)$ ranges between zero and one. In particular, $\phi_k^W(t) = 0$ when the ISN is not recovering any amount of waste k produced; alternatively, $\phi_k^W(t) = 1$ when the ISN is recovering the overall amount of waste k produced.

$\phi_k^W(t)$ can be decomposed as the product of two factors, as follows:

$$\phi_k^W(t) = \frac{w_k^S(t)}{w_k(t)} = \frac{w_k^S(t)}{E_k^W(t)} \times \frac{E_k^W(t)}{w_k(t)} \tag{9}$$

where $E_k^W(t)$ is the highest amount of waste k which is possible to recover through exchanges at time t . In particular, $E_k^W(t) =$

$\min \left\{ w_k(t); \sum_{l=1}^{n(r)} \sum_{j=1}^n \frac{r_{lj}(t)}{s_{l \rightarrow k}} \right\}$, where $w_k(t)$ is the available supply of waste k at time t and $\sum_{l=1}^{n(r)} \sum_{j=1}^n \frac{r_{lj}(t)}{s_{l \rightarrow k}}$ is the demand for waste k at time t .

This decomposition is useful to investigate the reason why the performance is not optimized. In particular, the first factor of Eq. (9), $\frac{w_k^S(t)}{E_k^W(t)}$, denotes the amount of waste k currently recovered, compared to the highest possible quantity to be recovered. In particular, $\frac{w_k^S(t)}{E_k^W(t)}$ ranges between zero and one: it is equal to one when the ISN is recovering the highest possible amount of waste k , otherwise it is lower than one. Thus, it measures the extent to which the operations carried out in the ISN are able to recover the maximum amount of the waste available. The second factor of Eq. (9), $\frac{E_k^W(t)}{w_k(t)}$, denotes the highest possible quantity of waste k to be recovered (i.e., the demand of waste k for recovery), compared to the overall amount of waste k produced (i.e., the total supply of waste k). In particular, $\frac{E_k^W(t)}{w_k(t)}$ ranges between zero and one. It is equal to one when the demand for waste k is equal to or higher than the available supply, otherwise it is lower than one. The lower $\frac{E_k^W(t)}{w_k(t)}$, the higher the mismatch between demand and supply for waste k . Thus, this factor takes into account the level of match between demand and supply for waste k due to the structure of waste exchanges inside the ISN. If $\frac{E_k^W(t)}{w_k(t)} < 1$, the performance of the function cannot be optimized.

Similarly, for each generic function “saving input l ”, the following performance indicator is defined:

$$\phi_l^R(t) = \frac{r_l^S(t)}{r_l(t)} \tag{10}$$

where $r_l^S(t)$ is the amount of input l saved at time t (see Eq. (7)) and $r_l(t)$ is the amount of input l required at time t by firms belonging to the ISN (see Eq. (1)). Overall, $\phi_l^R(t)$ ranges between zero and one. In particular, $\phi_l^R(t) = 0$ when the ISN is not saving any amount of input l produced;

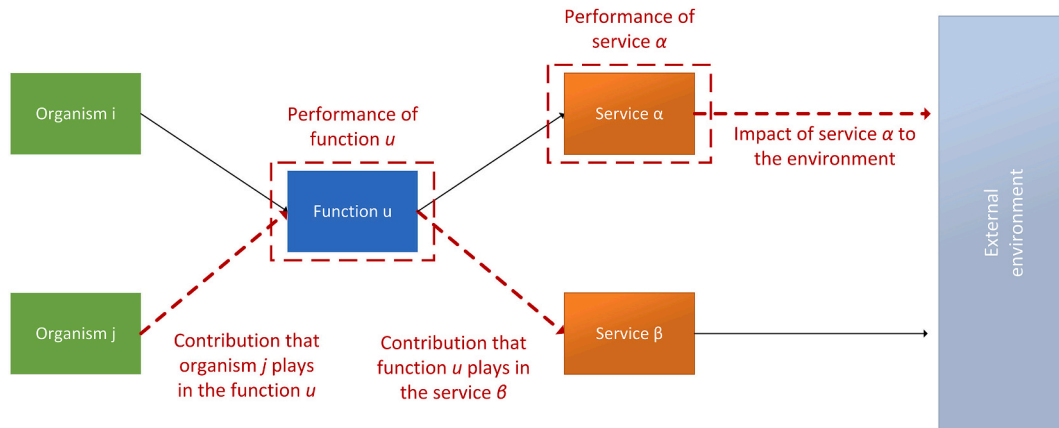


Fig. 2. Designing ISN indicators using an ecosystem approach. Organisms contribute to operate functions, which in turn contribute to create services for the external environments.

Table 1
Meaning of factors in Eqs. (9) and (11).

	<1	1	
Operational performance	$\frac{w_k^S(t)}{E_k^W(t)}$	The amount of waste k recovered is lower than the highest possible amount	The ISN is recovering the highest possible amount of waste k
	$\frac{r_l^S(t)}{E_l^R(t)}$	The amount of input l saved is lower than the highest possible amount	The ISN is saving the highest possible amount of input l
Structural performance	$\frac{E_k^R(t)}{w_k(t)}$	The demand for waste k is lower than the available supply	The demand for waste k is equal to or higher than the available supply
	$\frac{E_l^R(t)}{r_l(t)}$	The supply for input l is lower than the available demand	The supply for input l is equal to or higher than the available demand

alternatively, $\varphi_l^R(t) = 1$ when the ISN is saving the overall amount of input l required.

Similarly to the above, $\varphi_l^R(t)$ can be decomposed into two factors, the first one measuring the operational performance of the function and the second one the level of match between waste demand and supply:

$$\varphi_l^R(t) = \frac{r_l^S(t)}{r_l(t)} = \frac{r_l^S(t)}{E_l^R(t)} \times \frac{E_l^R(t)}{r_l(t)} \tag{11}$$

where $E_l^R(t)$ is the highest amount of input l which is possible to save through waste exchanges. In particular, $E_l^R(t) = \min\left\{r_l; \sum_{k=1}^n \sum_{i=1}^n s_{l \leftarrow k} w_{ki}(t)\right\}$, where k is the generic waste that can replace input l .

The factor $\frac{r_l^S(t)}{E_l^R(t)}$ corresponds to the amount of input l saved in percentage to the highest possible quantity to procure. In particular, $\frac{r_l^S(t)}{E_l^R(t)}$ ranges between zero and one: it is equal to one when the ISN is saving the highest amount of input l , otherwise it is lower than one. The factor $\frac{E_l^R(t)}{r_l(t)}$ denotes the highest possible quantity of input l to save compared to the overall amount of input l required. In particular, $\frac{E_l^R(t)}{r_l(t)}$ ranges between zero and one. It is equal to one when the production input l is equal to or higher than the available supply, otherwise it is lower than one: the higher the mismatch between demand and supply for input l , the lower $\frac{E_l^R(t)}{r_l(t)}$ will be.

Table 1 depicts the meaning of the factors of Eqs. (9) and (11).

3.2.2. Contribution indicators for organisms to functions

In ISN ecosystems any organism contributes to at least one function. The extent to which each organism is contributing to a given function

measures the relevance of that organism in the system.

In light of the ISN framing as an ecosystem, we design indicators that measure the extent to which a company is contributing to recovering wastes and saving inputs.

Let us consider the contribution that the company i provides to the function “recovering waste k ”. We define the indicator $\chi_{i \rightarrow k}^W(t)$ as the ratio between the amount of waste k recovered by firm i and the total amount of waste k recovered into the ISN. It follows that:

$$\chi_{i \rightarrow k}^W(t) = \frac{w_{ki}^S(t)}{w_k^S(t)} \tag{12}$$

The value of this indicator ranges between zero and one. It is equal to zero when company i does not contribute to recover waste k whereas it is equal to one when company i is the only firm within the ISN recovering waste k .

Let us consider the contribution that company i provides to the function “saving input l ”. The indicator $\chi_{i \rightarrow l}^R(t)$ is defined as the ratio between the amount of input l saved by firm i and the total amount of input l saved into the ISN:

$$\chi_{i \rightarrow l}^R(t) = \frac{r_{il}^S(t)}{r_l^S(t)} \tag{13}$$

The value of $\chi_{i \rightarrow l}^R(t)$ ranges between zero and one. It is equal to zero when company i does not contribute to save input l whereas it is equal to one when company i is the only firm within the ISN saving input l .

3.2.3. Impact indicators for services

In our model, the ISN provides the external environment with one or more services corresponding to environmental benefits (e.g., the reduction in CO₂ emissions, the reduction in water consumption, etc.). Assessing the impact of a given service means to quantify the environmental benefit provided by that service. Consider the service α , the

Table 2

Nomenclature of performance indicators and contribution indicators defined, as well as terms defined in the equations.

Performance indicators for functions – Section 3.2.1	
$\varphi_k^W(t)$	Performance indicator for the function “recovering waste k ”
$\varphi_l^R(t)$	Performance indicator for the function “saving input l ”
Contribution indicators for organisms to functions – Section 3.2.2	
$\chi_{i \rightarrow k}^W(t)$	Contribution indicator that company i provides to the function “recovering waste k ”
$\chi_{i \rightarrow l}^R(t)$	Contribution indicator that company i provides to the function “saving input l ”
Impact indicator for services – Section 3.2.3	
$\varepsilon_\alpha(t)$	Indicator of the impact of service α to the external environment
Performance indicators for services – Section 3.2.4	
$\sigma_\alpha(t)$	Performance indicator for the service α
Contribution indicators for functions to services – Section 3.2.5	
$\pi_{k \rightarrow \alpha}^W(t)$	Contribution indicator that the function “recovering waste k ” provides to the creation of service α at time t
$\pi_{l \rightarrow \alpha}^R(t)$	Contribution indicator that the function “saving input l ” provides to the creation of service α at time t
Single terms	
$w_{k\alpha}^S(t)$	Amount of waste k recovered by firm i at time t
$w_k^S(t)$	Amount of waste k recovered at time t
$E_k^W(t)$	Highest amount of waste k which is possible to recover through waste exchanges at time t
$w_k(t)$	Amount of waste k produced at time t
$r_{il}^S(t)$	Amount of input l saved by firm i at time t
$r_l^S(t)$	Amount of input l saved at time t
$E_l^R(t)$	Highest amount of input l which is possible to save through waste exchanges
$r_l(t)$	Amount of input l required at time t
$I_{k \rightarrow \alpha}^W$	Impact that recovering one unit of waste k has on the creation of service α
$I_{l \rightarrow \alpha}^R$	Impact that saving one unit of input l has on the creation of service α

impact of this service at time t , denoted as $\varepsilon_\alpha(t)$, can be computed as follows:

$$\varepsilon_\alpha(t) = \sum_{u=1}^{n(w)} I_{u \rightarrow \alpha}^W \cdot w_u^S(t) + \sum_{v=1}^{n(r)} I_{v \rightarrow \alpha}^R \cdot r_v^S(t) \tag{14}$$

where $I_{u \rightarrow \alpha}^W$ stands for the impact that recovering one unit of waste u has on the creation of service α and $I_{v \rightarrow \alpha}^R$ stands for the impact that saving one unit of input v has on the creation of service α .

For example, consider α as the service “reducing CO₂emissions”: $I_{u \rightarrow \alpha}^W$ denotes the amount of CO₂ emissions avoided by recovering one unit of waste k and $I_{v \rightarrow \alpha}^R$ denotes the amount of CO₂ emissions avoided by saving one unit of input v .

3.2.4. Performance indicators for services

This performance indicator aims at quantifying the ability of ISN to provide the external environment with given services, in particular by taking into account the extent to which each service is currently performed.

For the generic service α , the performance indicator $\sigma_\alpha(t)$ is defined as the ratio between the current impact of the service and the impact that it would be provided whether all the ISN functions would have the highest performance, i.e., when the overall amount of wastes produced is recovered and the overall amount of inputs required is saved.

It follows that:

$$\sigma_\alpha(t) = \frac{\varepsilon_\alpha(t)}{\sum_{u=1}^{n(w)} I_{u \rightarrow \alpha}^W \cdot w_u^S(t) + \sum_{v=1}^{n(r)} I_{v \rightarrow \alpha}^R \cdot r_v^S(t)} \tag{15}$$

Overall, $\sigma_\alpha(t)$ ranges between zero and one. In particular, $\sigma_\alpha(t) = 0$ when the ISN is not creating the service α at all; alternatively, $\sigma_\alpha(t) = 1$ when the impact created by service α is maximized.

3.2.5. Contribution indicators for functions to services

The services that the ISN is able to offer to the environment are determined by the ISN functions. Since each generic function differently

contributes to each service, we design proper indicators to assess this contribution.

The contribution indicator that each generic function “recovering waste k ” provides to the creation of service α at time t is so defined:

$$\pi_{k \rightarrow \alpha}^W(t) = \frac{I_{k \rightarrow \alpha}^W \cdot w_k^S(t)}{\sum_{u=1}^{n(w)} I_{u \rightarrow \alpha}^W \cdot w_u^S(t) + \sum_{v=1}^{n(r)} I_{v \rightarrow \alpha}^R \cdot r_v^S(t)} \tag{16}$$

This contribution indicator is thus defined as the ratio between the impact provided by function “recovering waste k ” to the creation of service α and the total impact provided by all the ISN functions to the creation of service α . The higher the contribution, the higher the importance of the function k for performing the service α .

In particular, the value of $\pi_{k \rightarrow \alpha}^W(t)$ ranges between zero and one. It is equal to zero when the function “recovering waste k ” does not provide any contribution to the creation of service α . Alternatively, it is equal to one when “recovering waste k ” is the only function contributing to the service α . Of course, $\sum_{k=1}^{n(w)} \pi_{k \rightarrow \alpha}^W(t) = 1 \forall \alpha$.

It is useful to decompose $\pi_{k \rightarrow \alpha}^W(t)$ into two terms as follows:

$$\pi_{k \rightarrow \alpha}^W(t) = \frac{I_{k \rightarrow \alpha}^W \cdot w_k^S(t)}{\sum_{u=1}^{n(w)} I_{u \rightarrow \alpha}^W \cdot w_u^S(t) + \sum_{v=1}^{n(r)} I_{v \rightarrow \alpha}^R \cdot r_v^S(t)} = \frac{I_{k \rightarrow \alpha}^W \cdot w_k^S(t)}{\sum_{u=1}^{n(w)} I_{u \rightarrow \alpha}^W \cdot w_u^S(t)} \cdot \frac{\sum_{u=1}^{n(w)} I_{u \rightarrow \alpha}^W \cdot w_u^S(t)}{\sum_{u=1}^{n(w)} I_{u \rightarrow \alpha}^W \cdot w_u^S(t) + \sum_{v=1}^{n(r)} I_{v \rightarrow \alpha}^R \cdot r_v^S(t)} \tag{17}$$

In such a way, the first factor $\left(\frac{I_{k \rightarrow \alpha}^W \cdot w_k^S(t)}{\sum_{u=1}^{n(w)} I_{u \rightarrow \alpha}^W \cdot w_u^S(t)} \right)$ expresses the

contribution that the function “recovery waste k ” plays on the service α compared to the contribution provided by all the waste recovery functions to the same service. This factor ranges between zero and one: it is equal to zero when the k -th waste recovery function does not provide

any contribution to the α -th service, it is equal to one when the k -th waste recovery function is the only waste recovery function contributing

$$\text{to the } \alpha\text{-th service. The second factor } \left(\frac{\sum_{u=1}^{n(w)} I_{u \rightarrow \alpha}^W \cdot w_u^S(t)}{\sum_{u=1}^{n(w)} I_{u \rightarrow \alpha}^W \cdot w_u^S(t) + \sum_{v=1}^{n(r)} I_{v \rightarrow \alpha}^R \cdot r_v^S(t)} \right)$$

corresponds to the contribution that all the waste recovery functions provide to the service α . This factor ranges between zero and one: it is equal to zero when the service α is created only by input saving functions, it is equal to one when the service α is created only by waste recovery functions.

Similarly, we define the contribution indicator that the generic function “saving input l ” provides to the creation of service α at time t as follows:

$$\pi_{l \rightarrow \alpha}^R(t) = \frac{I_{l \rightarrow \alpha}^R \cdot r_l^S(t)}{\sum_{u=1}^{n(w)} I_{u \rightarrow \alpha}^W \cdot w_u^S(t) + \sum_{v=1}^{n(r)} I_{v \rightarrow \alpha}^R \cdot r_v^S(t)} \quad (18)$$

The value of $\pi_{l \rightarrow \alpha}^R(t)$ ranges between zero and one. In particular, it is equal to zero when the function “saving input l ” does not provide any contribution to the creation of service α . Alternatively, it is equal to one when “saving input l ” is the only function contributing to creating the service α . Of course, $\sum_{l=1}^{n(r)} \pi_{l \rightarrow \alpha}^R(t) = 1 \forall \alpha$.

To assess the two factors explaining its value, $\pi_{l \rightarrow \alpha}^R(t)$ can be decomposed as follows:

$$\pi_{l \rightarrow \alpha}^R(t) = \frac{I_{l \rightarrow \alpha}^R \cdot r_l^S(t)}{\sum_{u=1}^{n(w)} I_{u \rightarrow \alpha}^W \cdot w_u^S(t) + \sum_{v=1}^{n(r)} I_{v \rightarrow \alpha}^R \cdot r_v^S(t)} = \frac{I_{l \rightarrow \alpha}^R \cdot r_l^S(t)}{\sum_{v=1}^{n(r)} I_{v \rightarrow \alpha}^R \cdot r_v^S(t)} \cdot \frac{\sum_{v=1}^{n(r)} I_{v \rightarrow \alpha}^R \cdot r_v^S(t)}{\sum_{u=1}^{n(w)} I_{u \rightarrow \alpha}^W \cdot w_u^S(t) + \sum_{v=1}^{n(r)} I_{v \rightarrow \alpha}^R \cdot r_v^S(t)} \quad (19)$$

The first factor, $\left(\frac{I_{l \rightarrow \alpha}^R \cdot r_l^S(t)}{\sum_{v=1}^{n(r)} I_{v \rightarrow \alpha}^R \cdot r_v^S(t)} \right)$, denotes the contribution that the

input l saving function plays on the service α compared to the contribution provided by all the input saving functions. This factor ranges between zero and one: it is equal to zero when the input l saving function does not provide any contribution to the service α , it is equal to one when the input l saving function is the only input saving function contributing to the service α . The second factor

$\left(\frac{\sum_{v=1}^{n(r)} I_{v \rightarrow \alpha}^R \cdot r_v^S(t)}{\sum_{u=1}^{n(w)} I_{u \rightarrow \alpha}^W \cdot w_u^S(t) + \sum_{v=1}^{n(r)} I_{v \rightarrow \alpha}^R \cdot r_v^S(t)} \right)$ indicates the contribution that all the input

saving functions provide to the service α . This factor ranges between zero and one: it is equal to zero when the service α is created only by waste recovering functions, it is equal to one when the service α is created only by input saving functions.

Table 2 shows the nomenclature of all the indicators defined in Section 3.2, as well as all the single terms used in the eqs. (8)–(19).

4. Numerical case example

In this section, we develop an application of our methodology, based on a numerical case example (e.g., Fieberg and Jenkins, 2005; Ghodspour and O’Brien, 1998; Hill, 1999), to show how the proposed indicators can be computed and the information they provide.

Table 3

Amount of wastes produced and inputs required by each company belonging to the ISN.

	Wastes produced		Inputs required		
	Carcasses (w_1)	Wheel rims (w_2)	Coal (r_1)	Resilient granules (r_2)	Iron (r_3)
Company A	$w_{1A}(t) = 150 \text{ t}$	$w_{2A}(t) = 150 \text{ t}$	–	–	–
Company B	–	–	$r_{1B}(t) = 87.7 \text{ t}$	–	–
Company C	–	–	$r_{1C}(t) = 101.48 \text{ t}$	–	–
Company D	–	–	–	$r_{2D}(t) = 31.5 \text{ t}$	–
Company E	–	–	–	–	$r_{3E}(t) = 100 \text{ t}$

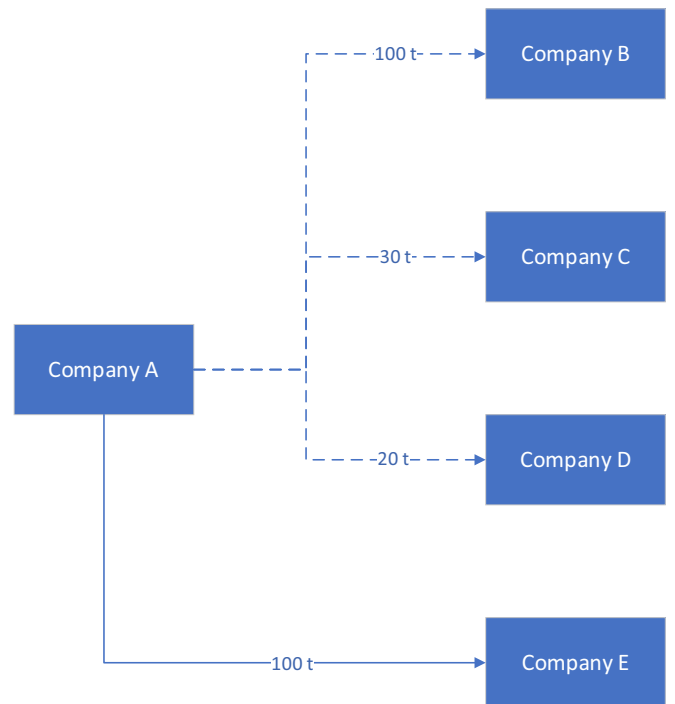


Fig. 3. Waste exchanges implemented among companies into the ISN. Dotted lines indicate the exchange of carcasses. The continuous line indicates the exchange of wheel rims.

4.1. Case description

The numerical case example presented in this section is adapted from Fraccascia et al. (2017a). The analyzed ISN is composed of five companies: one exhausted tires collector (company A), two cement producers (company B and company C), one synthetic grass producer (company D), and one iron and steel producer (company E). For the sake of simplicity, only wastes and primary inputs that can be involved in symbiotic exchanges are considered. In this regard, two wastes are used to replace three inputs: hence, $n(w) = 2$ and $n(r) = 3$. In particular, company A generates two kinds of wastes from exhausted tires collection: carcasses (w_1) and wheel rims (w_2). On the side of inputs, coal (r_1) is required by company B and company C, resilient granules (r_2) are required by company D, and iron (r_3) is required by company E. The amounts of wastes produced and inputs required by each company are shown in Table 3.

Carcasses (w_1) can replace both coal (r_1) and resilient granules (r_2). In this regard, the practice of substituting fossil fuels like coal with ground tires is widespread in the cement industry (e.g., Albino et al.,

Table 4
Performance indicators computed for “recovering waste” functions.

		$w_k^S(t)$	$E_k^W(t)$	$\frac{w_k^S(t)}{E_k^W(t)}$	$\frac{E_k^W(t)}{w_k(t)}$	$\phi_k^W(t)$
W-1	Recovering carcasses	150 t	150 t	1	1	1
W-2	Recovering wheel rims	100 t	100 t	1	0.66	0.66

2011), since positive environmental effects can be produced, mainly in form of reducing CO₂ and NO_x emissions (e.g., European Cement Association, 2009; IEA, 2009). Similarly, the use of exhausted tires as a substitute for resilient granules in synthetic grass production is recognized as positive from the environmental point of view. In particular, it is assumed that one ton of tires can replace 0.877 t of coal (Corti and Lombardi, 2004) or 0.8 t of resilient granules (Albino and Yazan, 2013). Furthermore, it is assumed that one ton of wheel rims (w_2) can replace one ton of iron (r_3). It follows that $s_{1-1} = 0.877$, $s_{2-1} = 0.8$, and $s_{3-2} = 1$.

Symbiotic exchanges implemented among companies are shown in Fig. 3. Concerning exchanges of carcasses, it is assumed that, at time t , 100 t are sent from company A to company B ($e_1^{A-B}(t) = 100$), 30 t are sent from company A to company C ($e_1^{A-C}(t) = 30$), and 20 t are sent from company A to company D ($e_1^{A-D}(t) = 20$). Furthermore, company A sends 100 t of wheel rims to company E ($e_2^{A-E}(t) = 100$).

In light of our conceptualization of ISNs as ecosystems, the companies in the ISN perform the following five functions: (W-1) recovering carcasses; (W-2) recovering wheel rims; (R-1) saving coal; (R-2) saving resilient granules; and (R-3) saving iron. The ISN provides the environment with a few services. Three services are considered for this case: (α) reduction of CO₂ emissions, (β) reduction of CH₄ emissions, and (γ) reduction of water consumption.³

In the following, we compute the proposed ISN indicators and discuss the relevant meanings.

4.2. Performance indicators for functions

In this Section, we compute the performance indicators for functions described in Section 3.2.1. Performance indicators for the provided functions concerning the two classes “recovering waste” and “saving inputs” functions are shown in Table 4 and Table 5, respectively.

Data show that the value of the performance indicators for the functions “recovering carcasses” (W-1) and “saving iron” (R-3) is equal to one. This means that the overall amounts of carcasses produced is recovered into the ISN and the overall amount of iron required into the ISN is replaced by wastes produced by other companies. Hence, overall, the ISN does not dispose of any unit of carcasses in the landfill and does not purchase any unit of iron from conventional suppliers. The best performance is thus achieved.

Let us consider the performance indicators of the functions W-2, R-1, and R-2, whose values are lower than one. The two factors permit to identify the reason. In particular, three different cases can be highlighted. For the function “recovering wheel rims” (W-2), $\frac{w_k^S(t)}{E_k^W(t)} = 1$ and $\frac{E_k^W(t)}{w_k(t)} < 1$. This means that the performance of this function is lower than one because of the mismatch between the production of wheel rims (i.e., 150 t) and its correspondent demand (i.e., 100 t). In fact, 50 units of wheel rims are currently disposed of in landfills. For the function “saving resilient granules” (R-2), $\frac{r_1^S(t)}{E_1^R(t)} < 1$ and $\frac{E_1^R(t)}{r_1(t)} = 1$. This means that, despite

³ We are aware that many other services could have been considered. For the sake of simplicity in the case explanation and discussion, we have chosen to address only these three services, in order to show how our indicators work. The impact of other services can be easily computed by following the methodology described in Section 3.

resilient granules could have been fully replaced by the correspondent wastes (since the demand for resilient granules is 31.5 t and the production of carcasses, able to replace this input, is 150 t, which corresponds to $150 \times 0.8 = 120$ t), the ISN is not recovering the highest possible amount of resilient granules. Finally, for the function “saving coal” (R-1), both $\frac{r_1^S(t)}{E_1^R(t)}$ and $\frac{E_1^R(t)}{r_1(t)}$ are lower than one. This means that the performance of this function is lower than one because of two reasons: 1) the ISN is not saving the highest possible amount of coal – in fact, if the overall amount of carcasses produced (150 t) would have been used to replace coal, the amount of coal saved would have been 131.55 t; however, only 114.01 t of coal are saved, since part of the carcasses produced is used to replace resilient granules, and 2) the mismatch between the demand of coal (i.e., 189.18 t) and the production of wastes able to replace this input (i.e., 150 t of carcasses, which correspond to $150 \times 0.877 = 131.55$ t of input). In fact, 57.63 t of coal are currently purchased from conventional suppliers.

The numerical value of these indicators is extensively computed in the Appendix.

4.3. Contribution indicators for organisms to functions

In this Section, we compute the contribution indicators for organisms to functions described in Section 3.2.2. These quantify the extent to which each company contributes to waste recovery and input saving, rating, therefore, its importance. Numerical values are shown in Table 6.

The indicators show that each company contributes to one function, except for company A, which contributes to operate two functions – i.e., “recovering carcasses” (W-1) and “recovering wheel rims” (W-2). Furthermore, each function is operated by one company, except for the function “saving coal” (R-1), to which both company B and company C contribute. In particular, company B contributes to operate the 76.92% of this function, while the remaining 23.08% is operated by company C. From the structural perspective, it can be noted that company A is the only waste producer in the ISN; in fact, $\chi_{A-1}^W(t) = 1$ and $\chi_{A-2}^W(t) = 1$. This means that, if company A decides to abandon the ISN, the overall network would disappear.

The numerical value of these indicators is extensively computed in the Appendix.

4.4. Impact indicators for services

In this Section, we compute the impact indicators for services described in Section 3.2.3. As stated in Section 4.1, we consider three services provided by the ISN: 1) reduction of CO₂ emissions; 2) reduction of CH₄ emissions; and 3) reduction of water consumption.

This requires to assess first the coefficients $I_{u-\alpha}^W$ and $I_{v-\alpha}^R$. Their values, obtained from the database of OpenLCA,⁴ are reported in Table 7.⁵ For instance, $I_{1-\alpha}^W = 0.06102$ means that recovering one kg of carcasses contributes to reducing CO₂ emissions to the air by 0.06102 kg. Similarly, $I_{2-\gamma}^R = 17.9$ means that saving one kg of resilient granules contributes to reducing water consumption by 17.9 kg.

Overall, through performing the ISN functions described above, the services provided by the ISN have the following impact: 1) reduction of CO₂ emissions – $\varepsilon_\alpha(t)$ – equal to 147.56 t; 2) reduction of CH₄ emissions – $\varepsilon_\beta(t)$ – equal to 1.2559 t; and 3) reduction of water consumption – $\varepsilon_\gamma(t)$ –

⁴ OpenLCA is a free LCA software available at <http://www.openlca.org/>.

⁵ For the sake of simplicity in the case example, these numerical data only consider the impact of avoided waste disposal and avoided input production. Therefore, they do not take into account the additional benefits created by replacing input with wastes (e.g., the fact that burning carcasses instead of coal might further contribute to reduce emissions to the air). However, this does not impact on the case example, which is devoted to show how the designed indicators work, independently on the specific numerical values.

Table 5
Performance indicators computed for “saving input” functions.

		$r_1^S(t)$	$E_1^R(t)$	$\frac{r_1^S(t)}{E_1^R(t)}$	$\frac{E_1^R(t)}{r_1(t)}$	$\varphi_1^R(t)$
R-1	Saving coal	114.01 t	131.55 t	0.8667	0.6954	0.6027
R-2	Saving resilient granules	16 t	31.5 t	0.5079	1	0.5079
R-3	Saving iron	100 t	100 t	1	1	1

Table 6
Values of contribution indicators for organisms to functions.

	Functions				
	W-1	W-2	R-1	R-2	R-3
	Recovering carcasses	Recovering wheel rims	Saving coal	Saving resilient granules	Saving iron
Company A	$\chi_{A \rightarrow 1}^W(t) = 1$	$\chi_{A \rightarrow 2}^W(t) = 1$	–	–	–
Company B	–	–	$\chi_{B \rightarrow 1}^R(t) = 0.7692$	–	–
Company C	–	–	$\chi_{C \rightarrow 1}^R(t) = 0.2308$	–	–
Company D	–	–	–	$\chi_{D \rightarrow 2}^R(t) = 1$	–
Company E	–	–	–	–	$\chi_{E \rightarrow 3}^R(t) = 1$

equal to 911.87 t.

The numerical value of these indicators is extensively computed in the Appendix.

4.5. Performance indicators for services

In this Section, we compute the performance indicators for services described in Section 3.2.4. Three performance indicators are computed: 1) the performance of reduction in CO₂ emissions – $\sigma_\alpha(t)$ – is 0.8183; 2) the performance of reduction in CH₄ emissions – $\sigma_\beta(t)$ – is 0.6047; and 3) the performance of reduction in water consumption – $\sigma_\gamma(t)$ – is 0.6755. None of these performances is equal to one, meaning that the ISN can

further increase the impact of its services on the environment. For instance, the performance of reduction in water consumption – $\sigma_\gamma(t)$ – will become equal to one if the overall amounts of coal and resilient granules required by companies belonging to the ISN are saved.

The numerical value of these indicators is extensively computed in the Appendix.

4.6. Contribution indicators for functions to services

In this Section, we compute the contribution indicators for functions to services described in Section 3.2.5. They assess the contribution of each function (recovering carcasses; recovering wheel rims; saving coal;

Table 7
Values of coefficients $I_{k \rightarrow \alpha}^W$ and $I_{l \rightarrow \alpha}^R$.

		Services			
			α	β	γ
			Reduction in the CO ₂ emissions to the air	Reduction in the CH ₄ emissions to the air	Reduction of water consumption
ISN functions	W-1	Recovering carcasses	$I_{1 \rightarrow \alpha}^W = 0.06102[\text{kg CO}_2/\text{kg carcasses}]$	$I_{1 \rightarrow \beta}^W = 0.00036[\text{kg CH}_4/\text{kg carcasses}]$	$I_{1 \rightarrow \gamma}^W = 0[\text{kg water/kg carcasses}]$
	W-2	Recovering wheel rims	$I_{2 \rightarrow \alpha}^W = 0.01084[\text{kg CO}_2/\text{kg wheel rims}]$	$I_{2 \rightarrow \beta}^W = 0.00014[\text{kg CH}_4/\text{kg wheel rims}]$	$I_{2 \rightarrow \gamma}^W = 0[\text{kg water/kg wheel rims}]$
	R-1	Saving coal	$I_{1 \rightarrow \alpha}^R = 0.1058[\text{kg CO}_2/\text{kg coal}]$	$I_{1 \rightarrow \beta}^R = 0.0079[\text{kg CH}_4/\text{kg coal}]$	$I_{1 \rightarrow \gamma}^R = 2.1373[\text{kg water/kg coal}]$
	R-2	Saving resilient granules	$I_{2 \rightarrow \alpha}^R = 1.5667[\text{kg CO}_2/\text{kg resilient granules}]$	$I_{2 \rightarrow \beta}^R = 0.0142[\text{kg CH}_4/\text{kg resilient granules}]$	$I_{2 \rightarrow \gamma}^R = 17.9[\text{kg water/kg resilient granules}]$
	R-3	Saving iron	$I_{3 \rightarrow \alpha}^R = 1.0019[\text{kg CO}_2/\text{kg iron}]$	$I_{3 \rightarrow \beta}^R = 0.0006[\text{kg CH}_4/\text{kg iron}]$	$I_{3 \rightarrow \gamma}^R = 3.818[\text{kg water/kg iron}]$

Table 8
Values of contribution indicators for functions to services.

		Services			
			α	β	γ
			Reduction in the CO ₂ emissions to the air	Reduction in the CH ₄ emissions to the air	Reduction in the water consumption
ISN functions	W-1	Recovering carcasses	$\pi_{1 \rightarrow \alpha}^W(t) = 0.0620$	$\pi_{1 \rightarrow \beta}^W(t) = 0.0430$	$\pi_{1 \rightarrow \gamma}^W(t) = 0$
	W-2	Recovering wheel rims	$\pi_{2 \rightarrow \alpha}^W(t) = 0.0073$	$\pi_{2 \rightarrow \beta}^W(t) = 0.0111$	$\pi_{2 \rightarrow \gamma}^W(t) = 0$
	R-1	Saving coal	$\pi_{1 \rightarrow \alpha}^R(t) = 0.0817$	$\pi_{1 \rightarrow \beta}^R(t) = 0.7172$	$\pi_{1 \rightarrow \gamma}^R(t) = 0.2672$
	R-2	Saving resilient granules	$\pi_{2 \rightarrow \alpha}^R(t) = 0.1699$	$\pi_{2 \rightarrow \beta}^R(t) = 0.1809$	$\pi_{2 \rightarrow \gamma}^R(t) = 0.3141$
	R-3	Saving iron	$\pi_{3 \rightarrow \alpha}^R(t) = 0.6790$	$\pi_{3 \rightarrow \beta}^R(t) = 0.0478$	$\pi_{3 \rightarrow \gamma}^R(t) = 0.4187$

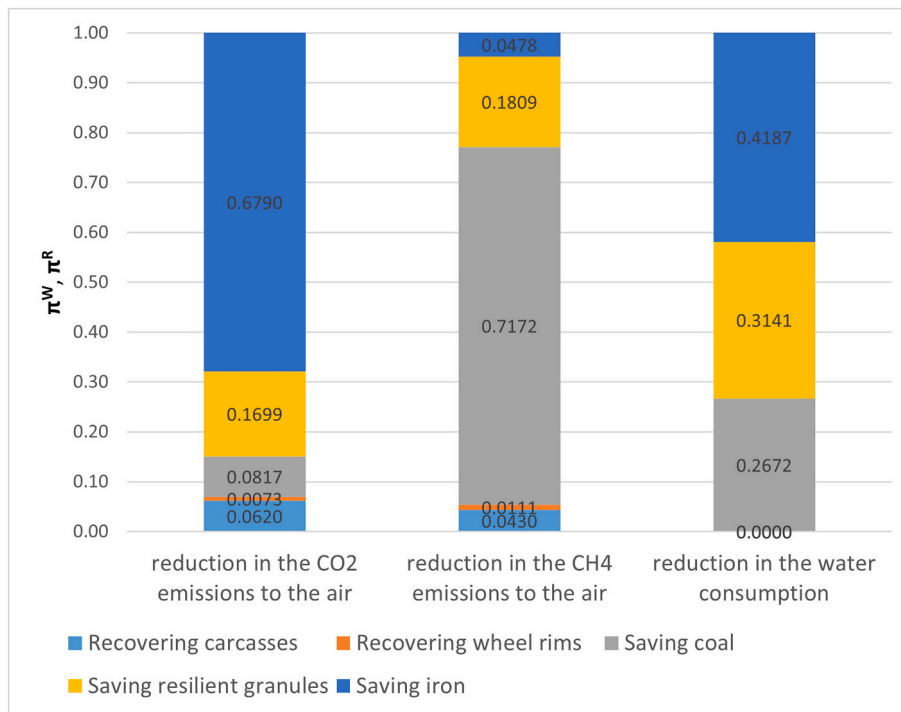


Fig. 4. Values of contribution indicators for functions to services (graphical representation).

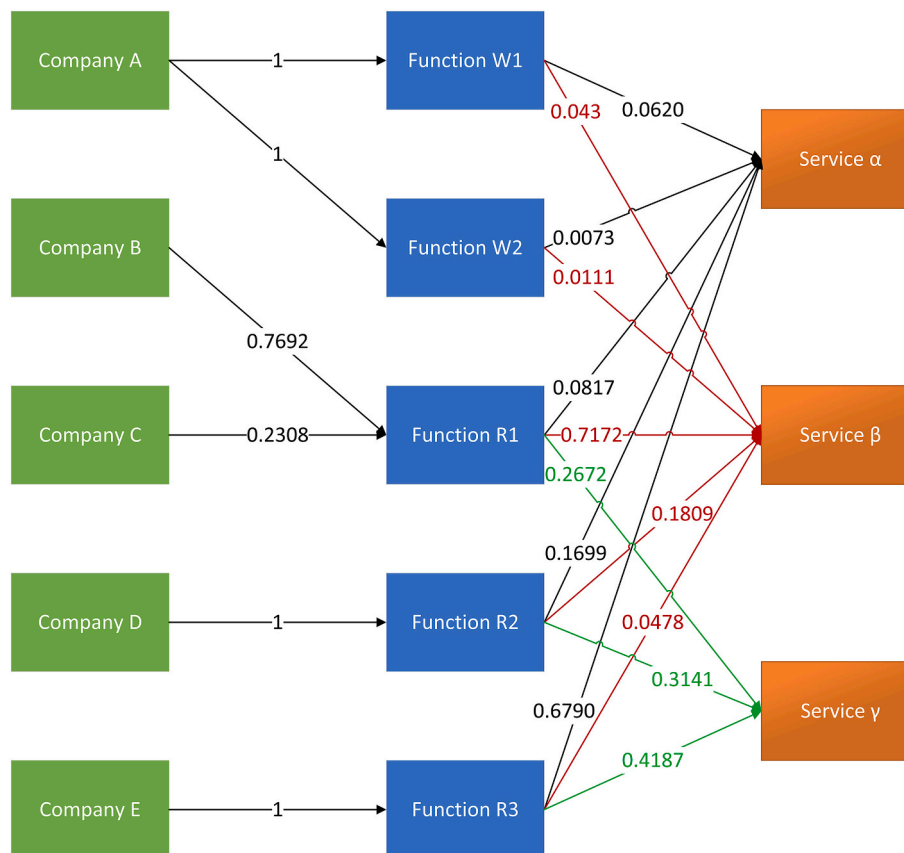


Fig. 5. Numerical indicators of contribution indicators of companies to functions (see Table 6) and of functions to services (see Table 8).

saving resilient granules; and saving iron) to each service (reduction of CO₂ emissions; reduction of CH₄ emissions; and reduction of water consumption). A graphical representation is also given in Fig. 4.

It can be noted that input saving functions contribute more to the environmental services than waste recovery functions. In particular, the function “saving iron” (R-3) is the one that mostly contributes to reducing CO₂ emissions and water consumption. In fact, it contributes to 67.9% of the CO₂ emissions reduction and to 41.87% of the water consumption reduction. The function “saving coal” (R-1) plays an important role in reducing CH₄ emissions, since contributing to the 71.72% of the overall CH₄ emission reduction provided by the ISN. The function “saving resilient granules” (R-2) is the second function contributing to all the services: it contributes to 16.99% of the CO₂ emissions reduction, to 18.09% of the CH₄ emission reduction, and to 31.34% of the water consumption reduction.

The two waste recovery functions provide a limited contribution to the services provided by the ISN. The function “recovery carcasses” (W-1) contributes to the 6.20% of the CO₂ emissions reduction and to the 4.3% of the CH₄ emissions reduction. The function “recovery wheel rims” (W-2) contributes to the 0.73% of the CO₂ emissions reduction and to the 1.11% of the CH₄ emissions reduction. None of the waste recovery function contributes to reducing water consumption.

The numerical value of these indicators is extensively computed in the Appendix.

Fig. 5 shows the numerical indicators of contribution indicators of companies to functions and of functions to services.

For instance, from Fig. 5 it can be synoptically noted that Company A contributes to operate two functions (i.e., Function W-1 and Function W-2) and both these functions are fully operated by Company A (e.g., no other companies contribute to operate these functions). In turn, Function W-1 contributes to the 6.20% of Service α (i.e., is responsible to the 6.20% of the overall CO₂ reduction thanks to the ISN) and to the 4.30% of Service β (i.e., is responsible to the 4.30% of the overall CH₄ reduction thanks to the ISN). The function R-1 is operated by two companies, B and C: Company B contributes to 76.92% of the function and Company C contributes to the remaining 23.08%. Finally, Service γ is created thanks to three functions, R-1, R-2, and R-3, which contribute to 26.72%, 31.41%, and 41.87%, respectively.

5. Discussion

This paper contributes to the literature on IS performance indicators – a topic that is receiving increasing attention in IS field (Domenech et al., 2019; Fraccascia and Giannoccaro, 2020; Neves et al., 2019) – by proposing a new and integrated set of IS indicators useful for monitoring, evaluation, and, in particular, decision-making, an urgent need of the referred literature. The proposed indicators are mainly addressed to managers involved in ISN at the firm and network levels, but also policymakers interested to develop actions to support the design of effective ISNs. In doing so, we contribute to a recent field of studies designing dynamic indicators for ISN planning and evolution.

We conceptualized ISNs as ecosystems and employed the Enterprise Input-Output approach to model the flows of waste exchanges. In particular, we framed the ISN as made up of firms (organisms) performing specific functions enabled by waste exchanges, i.e., waste recovering and input saving. These multiple functions contribute to the ability of the ISN to provide environmental services in terms of reduced environmental impacts of production processes. This approach is innovative, since it permits to consider all the relevant dimensions involved in the IS, i.e., the firms (organisms), the waste exchanges (functions), and the network (the services). In doing so, we address a gap in the literature, which has been mainly proposed indicators including only one dimension (Felicio et al., 2016).

Furthermore, we extend previous literature, since our approach provides a measure of the environmental impacts of the ISN (impact indicators for services), but meaningfully offers indicators to assess its

functioning. In particular, we designed specific indicators to highlight: 1) the impact of services provided by the ISN, 2) the extent to which the impact of services is maximized, 3) which symbiotic exchanges contribute more to the environmental services, 4) whether the symbiotic exchanges implemented are optimized, and 5) the extent to which the firms belonging to the ISN contribute to these exchanges. Therefore, we extend IS indicators based on eco-efficiency measurements (e.g., Park and Behera, 2014), LCA methods (e.g., Mattila et al., 2012), input-output approach (e.g., Yazan, 2016), and material flow analysis (e.g., Sendra et al., 2007), which mainly provide a measure of IS impacts referred to a single dimension (system vs. single relationship) and to a short and specific period of time.

The above-mentioned indicators provide three types of information: impact, performance, and contribution. The impact indicators of services provide information on the environmental contribution provided by the ISN to the external environment, in terms of reduction in the environmental pressure caused by production processes belonging to the ISN. Although many indicators have been designed to this aim – see Fraccascia and Giannoccaro (2020) – our indicators provide a methodological advance because able to integrate the EIO approach for IS with some elements of LCA, i.e., the coefficients of environmental impact of the single functions (see Section 3.2.3). While the integration between input-output modeling and LCA has already been explored for environmental assessment at the product level (Hendrickson et al., 1998) or for traditional waste management processes (Nakamura and Kondo, 2002), as well as for input-output analysis at the macro-level (Tukker et al., 2009), to the best of our knowledge this paper is the first that integrates EIO models for IS with LCA elements.

The performance indicators provide indications about the extent to which services and functions are optimized. The indicators evaluating the performance of the single ISN services provide information about the extent to which the impact of the ISN services to the external environment is maximized. A value of the indicators lower than one means that the impact of the service is not maximized compared to the theoretical potential, due to the non-optimal network functioning. In this regard, the indicators evaluating the performance of the single ISN functions are useful to provide knowledge about the symbiotic exchanges carried out inside the ISN. Two classes of performance indicators were defined, one assessing whether the ISN is able to recover all the amounts produced of a given waste and the other one evaluating whether the ISN is able to save all the amounts of a given input by using the wastes produced into the network. A value of the indicators lower than one means that the function is not optimized. More interestingly, we also showed that the indicators can be decomposed into two factors, aimed at identifying the extent to which the performance of a given function is affected by the operational issues of IS exchanges carried out by the firms and the mismatch between demand and supply of waste. In such a way, the cause of not optimal performance can be detected and proper strategies can be designed to improve ISN performance, by managers involved in ISN planning.

The contribution indicators provide information about the relevance of single companies and functions for the ISN. The indicators quantifying the extent to which each firm contributes to ISN functions provide useful information on their importance for ISN functioning. This is useful to rate firms belonging to ISN based on their relevance for the ISN. This information can be useful for managers of single companies to be aware of their relevance, especially when they are negotiating the clauses of a symbiotic contract. The higher the relevance, the higher the contractual power would be, *ceteris paribus*.

Furthermore, this set of indicators is relevant for ISN resilience to disruptive events. In this context, the contribution of the single firm to the ISN functions can be considered as a measure of the impact on the ISN in the case of a firm’s abandonment. The higher the contribution of a given company for ISN functions, the greater the impact on the ISN if the company abandons the network will be, *ceteris paribus* (Benjamin et al., 2015; Chopra and Khanna, 2014; Li et al., 2017; Wang et al., 2017b,

2018; Zeng et al., 2013; Zhu and Ruth, 2013). Furthermore, these indicators provide information useful to assess the ubiquity of single wastes, a further structural feature affecting the resilience of ISN (Fraccascia et al., 2017b). When a function is operated just by one firm (low ubiquity), this means that, in the case of firm removal, the corresponding function will be no more carried out by the ISN. Therefore, the resilience of ISN against such events is very low. Alternatively, when a function is operated by more companies (high ubiquity), if one of them fails, the function can still be operated by the other companies. Furthermore, companies can be involved in operating multiple functions in the ISN. These companies could be very important for the ISN when they are the only ones operating these functions. Such information is thus very useful for managers involved in ISN planning with the aim of improving its resilience to firm removal.

The indicators assessing the contributions each function provides to the single services are useful to identify and assess the sources of the environmental services provided by the ISN. This information is important for ecosystem services valorization and design payment systems. Furthermore, note that, in a given area, some services can be considered more important than others. For instance, in a given area characterized by few water sources, reducing the water consumption could be a priority compared to reducing CH₄ emissions to the air. Alternatively, in a highly polluted area, reducing CO₂ emissions to the air could be a priority compared to reducing water consumption. Hence, the proposed indicators are useful to identify which functions contribute more to the service with high priority. This information can be used by policymakers to design proper incentives more effectively, by promoting those symbiotic exchanges having a high priority for a given area.

Finally, a methodological consideration concerns the Enterprise Input-Output approach used to build the indicators. Compared to most common approaches adopted to assess environmental indicators, this approach is particularly beneficial because permits to compute indicators based on dynamic parameters, whose values are time-dependent, as well as to highlight the primary drivers of these parameters – e.g., the amounts of wastes produced and inputs required can be computed at the specific time t and depend, in turn, on the amounts of main outputs produced by companies (Fraccascia, 2019). Hence, in case of changes in the production volumes the values of the proposed indicators can be dynamically computed, without carrying out further analysis on a new scenario. This is a further advantage of the indicators proposed in this paper compared to traditional ones, which adopt a static perspective.

As to the computational efforts required, computing the proposed indicators requires the following data, for all the involved companies, as inputs: 1) data on the main outputs produced by companies and technical production coefficient, 2) amounts of wastes exchanged among companies, 3) the impact coefficients of each function to each service. While the first two classes are related to primary data, collected from the companies belonging to the ISN, the last class is related to secondary data, available from LCA databases. Computing the proposed indicators does not require specific software and the computational effort is minimum.

6. Conclusions

The growing interest in designing and management of ISNs,

considered as an effective strategy to pursue circular economy and achieve sustainable development, has pushed scholars to investigate more proper ways to measure IS. Which are the environmental benefits provided by an ISN? Can they be enhanced? Are the symbiotic exchanges fully exploited? How they can be improved? Which are the most important firms providing the highest contribution to the symbiotic exchange?

We tackled this issue, by focusing on environmental services provided by ISNs and by designing an integrated set of indicators addressing all the questions, based on an ecosystem approach. In particular, a set of indicators were designed, able to: 1) quantify the contribution of ISNs in reducing the environmental impacts of production processes, 2) quantify the performance of the environmental services, 3) compute the contribution of symbiotic exchanges to environmental services, 4) quantify the efficiency of the symbiotic exchanges carried out in the ISN, and 5) measure how single firms contribute to the symbiotic exchanges. Hence, they not only quantify the environmental benefits offered by the ISN, but provide an assessment of the ISN functioning from multiple points of view in an easy, understandable, and immediate way.

The usefulness of the indicators for decision-making aims was illustrated by developing a numerical case study, which showed for a hypothetical ISN how the methodology should be adopted and how the indicators should be computed. Furthermore, we highlighted how they are useful to identify proper strategies to increase the efficiency of the system in exploiting the IS synergies and to improve its efficacy.

The paper presents some limitations. The environmental services considered in the case example concern a limited set of environmental impacts (e.g., CO₂ emissions, CH₄ emissions, and water consumption). However, note that depending on the specific symbiotic exchanges realized in the ISN, any other indicator could be included, computed according to the methodology proposed in Section 3.2. Furthermore, we do not consider how this environmental performance might in turn impact higher-level environmental indicators, such as the global warming. The next step of the research could address this issue. Further research will be also devoted to extending the application of these indicators to analyze the impact of functions on the economic and social performance of networks and companies. In doing so, the approach will cover all the dimensions of sustainability so as to offer a battery of indicators to be used, depending on the specific needs.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Computation of indices and performance indicators

The amounts of each waste recovered into the ISN and of each input saved into the ISN are computed as follows:

$$w_1^S(t) = e_1^{A \rightarrow B}(t) + e_1^{A \rightarrow C}(t) + e_1^{A \rightarrow D}(t) = 100 + 30 + 20 = 150$$

$$w_2^S(t) = e_2^{A \rightarrow E}(t) = 100$$

$$r_1^S(t) = s_{1-1} \cdot [e_1^{A \rightarrow B}(t) + e_1^{A \rightarrow C}(t)] = 0.877 \cdot (100 + 30) = 114.01$$

$$r_2^S(t) = s_{2-1} \cdot e_1^{A \rightarrow D}(t) = 0.8 \cdot 20 = 16$$

$$r_3^S(t) = s_{3-2} \cdot e_2^{A \rightarrow E}(t) = 1 \cdot 100 = 100$$

The parameters $E_k^W(t)$ and $E_k^R(t)$ are computed as follows:

$$E_1^W(t) = \min \left\{ w_1(t); \frac{r_{1B}(t)}{s_{1-1}} + \frac{r_{1C}(t)}{s_{1-1}} + \frac{r_{2D}(t)}{s_{2-1}} \right\} = \min \left\{ 150; \frac{87.7}{0.877} + \frac{101.48}{0.877} + \frac{31.5}{0.8} \right\} = 150$$

$$E_2^W(t) = \min \left\{ w_2(t); \frac{r_{3E}(t)}{s_{3-2}} \right\} = \min \left\{ 150; \frac{100}{1} \right\} = 100$$

$$E_1^R(t) = \min \{ r_1(t); s_{1-1} \cdot w_{1A}(t) \} = \min \{ 189.18; 0.877 \cdot 150 \} = 131.55$$

$$E_2^R(t) = \min \{ r_2(t); s_{2-1} \cdot w_{1A}(t) \} = \min \{ 31.5; 0.8 \cdot 150 \} = 31.5$$

$$E_3^R(t) = \min \{ r_3(t); s_{3-2} \cdot w_{2A}(t) \} = \min \{ 100; 1 \cdot 150 \} = 100$$

The performance indicator of functions operated into the ISN (see Section 3.2.1) are computed as follows:

$$\phi_1^W(t) = \frac{w_1^S(t)}{E_1^W(t)} \times \frac{E_1^W(t)}{w_1(t)} = 1 \times 1 = 1$$

$$\phi_2^W(t) = \frac{w_2^S(t)}{E_2^W(t)} \times \frac{E_2^W(t)}{w_2(t)} = 1 \times 0.66 = 0.66$$

$$\phi_1^R(t) = \frac{r_1^S(t)}{E_1^R(t)} \times \frac{E_1^R(t)}{r_1(t)} = 0.8667 \times 0.6954 = 0.6027$$

$$\phi_2^R(t) = \frac{r_2^S(t)}{E_2^R(t)} \times \frac{E_2^R(t)}{r_2(t)} = 0.5079 \times 1 = 0.5079$$

$$\phi_3^R(t) = \frac{r_3^S(t)}{E_3^R(t)} \times \frac{E_3^R(t)}{r_3(t)} = 1 \times 1 = 1$$

The contribution indicators of organisms to functions (see Section 3.2.2) are computed as follows:

$$\chi_{A \rightarrow 1}^W(t) = \frac{w_{1A}^S}{w_1^S} = \frac{150}{150} = 1$$

$$\chi_{A \rightarrow 2}^W(t) = \frac{w_{2A}^S}{w_2^S} = \frac{150}{150} = 1$$

$$\chi_{B \rightarrow 1}^R(t) = \frac{r_{1B}^S}{r_1^S} = \frac{87.7}{114.01} = 0.7692$$

$$\chi_{C \rightarrow 1}^R(t) = \frac{r_{1C}^S}{r_1^S} = \frac{26.31}{114.01} = 0.2308$$

$$\chi_{D \rightarrow 2}^R(t) = \frac{r_{2D}^S}{r_2^S} = \frac{16}{16} = 1$$

$$\chi_{E \rightarrow 3}^R(t) = \frac{r_{3E}^S}{r_3^S} = \frac{100}{100} = 1$$

The impact indicators for services (see Section 3.2.3) are computed as follows:

$$\varepsilon_\alpha(t) = I_{1 \rightarrow \alpha}^W \cdot w_1^S(t) + I_{2 \rightarrow \alpha}^W \cdot w_2^S(t) + I_{1 \rightarrow \alpha}^R \cdot r_1^S(t) + I_{2 \rightarrow \alpha}^R \cdot r_2^S(t) + I_{3 \rightarrow \alpha}^R \cdot r_3^S(t) = 0.06102 \cdot 150 + 0.01084 \cdot 100 + 0.1058 \cdot 114.01 + 1.5667 \cdot 16 + 1.0019 \cdot 100 = 147.56$$

$$\varepsilon_\beta(t) = I_{1 \rightarrow \beta}^W \cdot w_1^S(t) + I_{2 \rightarrow \beta}^W \cdot w_2^S(t) + I_{1 \rightarrow \beta}^R \cdot r_1^S(t) + I_{2 \rightarrow \beta}^R \cdot r_2^S(t) + I_{3 \rightarrow \beta}^R \cdot r_3^S(t) = 0.00036 \cdot 150 + 0.00014 \cdot 100 + 0.0079 \cdot 114.01 + 0.0142 \cdot 16 + 0.0006 \cdot 100 = 1.2559$$

$$\varepsilon_\gamma(t) = I_{1 \rightarrow \gamma}^W \cdot w_1^S(t) + I_{2 \rightarrow \gamma}^W \cdot w_2^S(t) + I_{1 \rightarrow \gamma}^R \cdot r_1^S(t) + I_{2 \rightarrow \gamma}^R \cdot r_2^S(t) + I_{3 \rightarrow \gamma}^R \cdot r_3^S(t) = 0 \cdot 150 + 0 \cdot 150 + 2.1373 \cdot 114.01 + 17.9 \cdot 16 + 3.818 \cdot 100 = 911.87$$

The performance indicators for services (see Section 3.2.4) are computed as follows:

$$\sigma_\alpha(t) = \frac{\varepsilon_\alpha(t)}{I_{1 \rightarrow \alpha}^W \cdot w_1(t) + I_{2 \rightarrow \alpha}^W \cdot w_2(t) + I_{1 \rightarrow \alpha}^R \cdot r_1(t) + I_{2 \rightarrow \alpha}^R \cdot r_2(t) + I_{3 \rightarrow \alpha}^R \cdot r_3(t)} = \frac{147.56}{0.06102 \cdot 150 + 0.01084 \cdot 150 + 0.1058 \cdot 189.18 + 1.5667 \cdot 31.5 + 1.0019 \cdot 100} = 0.8183$$

$$\sigma_\beta(t) = \frac{\varepsilon_\beta(t)}{I_{1\rightarrow\beta}^W \cdot w_1(t) + I_{2\rightarrow\beta}^W \cdot w_2(t) + I_{1\rightarrow\beta}^R \cdot r_1(t) + I_{2\rightarrow\beta}^R \cdot r_2(t) + I_{3\rightarrow\beta}^R \cdot r_3(t)} = \frac{1.2559}{0.00036 \cdot 150 + 0.00014 \cdot 150 + 0.0079 \cdot 189.18 + 0.0142 \cdot 31.5 + 0.0006 \cdot 100} = 0.6047$$

$$\sigma_\gamma(t) = \frac{\varepsilon_\gamma(t)}{I_{1\rightarrow\gamma}^W \cdot w_1(t) + I_{2\rightarrow\gamma}^W \cdot w_2(t) + I_{1\rightarrow\gamma}^R \cdot r_1(t) + I_{2\rightarrow\gamma}^R \cdot r_2(t) + I_{3\rightarrow\gamma}^R \cdot r_3(t)} = \frac{911.87}{0 \cdot 150 + 0 \cdot 150 + 2.1373 \cdot 189.18 + 17.9 \cdot 31.5 + 3.818 \cdot 100} = 0.6755$$

The contribution indicators for functions are computed as follows:

$$\pi_{1\rightarrow\alpha}^W(t) = \frac{I_{1\rightarrow\alpha}^W \cdot w_1^S(t)}{I_{1\rightarrow\alpha}^W \cdot w_1^S(t) + I_{2\rightarrow\alpha}^W \cdot w_2^S(t) + I_{1\rightarrow\alpha}^R \cdot r_1^S(t) + I_{2\rightarrow\alpha}^R \cdot r_2^S(t) + I_{3\rightarrow\alpha}^R \cdot r_3^S(t)} = \frac{0.06102 \cdot 150}{0.06102 \cdot 150 + 0.01084 \cdot 100 + 0.1058 \cdot 114.01 + 1.5667 \cdot 16 + 1.0019 \cdot 100} = 0.0620$$

$$\pi_{2\rightarrow\alpha}^W(t) = \frac{I_{2\rightarrow\alpha}^W \cdot w_2^S(t)}{I_{1\rightarrow\alpha}^W \cdot w_1^S(t) + I_{2\rightarrow\alpha}^W \cdot w_2^S(t) + I_{1\rightarrow\alpha}^R \cdot r_1^S(t) + I_{2\rightarrow\alpha}^R \cdot r_2^S(t) + I_{3\rightarrow\alpha}^R \cdot r_3^S(t)} = \frac{0.01084 \cdot 100}{0.06102 \cdot 150 + 0.01084 \cdot 100 + 0.1058 \cdot 114.01 + 1.5667 \cdot 16 + 1.0019 \cdot 100} = 0.0073$$

$$\pi_{1\rightarrow\beta}^W(t) = \frac{I_{1\rightarrow\beta}^W \cdot w_1^S(t)}{I_{1\rightarrow\beta}^W \cdot w_1^S(t) + I_{2\rightarrow\beta}^W \cdot w_2^S(t) + I_{1\rightarrow\beta}^R \cdot r_1^S(t) + I_{2\rightarrow\beta}^R \cdot r_2^S(t) + I_{3\rightarrow\beta}^R \cdot r_3^S(t)} = \frac{0.00036 \cdot 150}{0.00036 \cdot 150 + 0.00014 \cdot 100 + 0.0079 \cdot 114.01 + 0.0142 \cdot 16 + 0.0006 \cdot 100} = 0.0430$$

$$\pi_{2\rightarrow\beta}^W(t) = \frac{I_{2\rightarrow\beta}^W \cdot w_2^S(t)}{I_{1\rightarrow\beta}^W \cdot w_1^S(t) + I_{2\rightarrow\beta}^W \cdot w_2^S(t) + I_{1\rightarrow\beta}^R \cdot r_1^S(t) + I_{2\rightarrow\beta}^R \cdot r_2^S(t) + I_{3\rightarrow\beta}^R \cdot r_3^S(t)} = \frac{0.00014 \cdot 100}{0.00036 \cdot 150 + 0.00014 \cdot 100 + 0.0079 \cdot 114.01 + 0.0142 \cdot 16 + 0.0006 \cdot 100} = 0.0111$$

$$\pi_{1\rightarrow\gamma}^W(t) = \frac{I_{1\rightarrow\gamma}^W \cdot w_1^S(t)}{I_{1\rightarrow\gamma}^W \cdot w_1^S(t) + I_{2\rightarrow\gamma}^W \cdot w_2^S(t) + I_{1\rightarrow\gamma}^R \cdot r_1^S(t) + I_{2\rightarrow\gamma}^R \cdot r_2^S(t) + I_{3\rightarrow\gamma}^R \cdot r_3^S(t)} = 0$$

$$\pi_{2\rightarrow\gamma}^W(t) = \frac{I_{2\rightarrow\gamma}^W \cdot w_2^S(t)}{I_{1\rightarrow\gamma}^W \cdot w_1^S(t) + I_{2\rightarrow\gamma}^W \cdot w_2^S(t) + I_{1\rightarrow\gamma}^R \cdot r_1^S(t) + I_{2\rightarrow\gamma}^R \cdot r_2^S(t) + I_{3\rightarrow\gamma}^R \cdot r_3^S(t)} = 0$$

$$\pi_{1\rightarrow\alpha}^R(t) = \frac{I_{1\rightarrow\alpha}^R \cdot r_1^S(t)}{I_{1\rightarrow\alpha}^W \cdot w_1^S(t) + I_{2\rightarrow\alpha}^W \cdot w_2^S(t) + I_{1\rightarrow\alpha}^R \cdot r_1^S(t) + I_{2\rightarrow\alpha}^R \cdot r_2^S(t) + I_{3\rightarrow\alpha}^R \cdot r_3^S(t)} = \frac{0.1058 \cdot 114.01}{0.06102 \cdot 150 + 0.01084 \cdot 100 + 0.1058 \cdot 114.01 + 1.5667 \cdot 16 + 1.0019 \cdot 100} = 0.0817$$

$$\pi_{2\rightarrow\alpha}^R(t) = \frac{I_{2\rightarrow\alpha}^R \cdot r_2^S(t)}{I_{1\rightarrow\alpha}^W \cdot w_1^S(t) + I_{2\rightarrow\alpha}^W \cdot w_2^S(t) + I_{1\rightarrow\alpha}^R \cdot r_1^S(t) + I_{2\rightarrow\alpha}^R \cdot r_2^S(t) + I_{3\rightarrow\alpha}^R \cdot r_3^S(t)} = \frac{1.5667 \cdot 16}{0.06102 \cdot 150 + 0.01084 \cdot 100 + 0.1058 \cdot 114.01 + 1.5667 \cdot 16 + 1.0019 \cdot 100} = 0.1699$$

$$\pi_{3\rightarrow\alpha}^R(t) = \frac{I_{3\rightarrow\alpha}^R \cdot r_3^S(t)}{I_{1\rightarrow\alpha}^W \cdot w_1^S(t) + I_{2\rightarrow\alpha}^W \cdot w_2^S(t) + I_{1\rightarrow\alpha}^R \cdot r_1^S(t) + I_{2\rightarrow\alpha}^R \cdot r_2^S(t) + I_{3\rightarrow\alpha}^R \cdot r_3^S(t)} = \frac{1.0019 \cdot 100}{0.06102 \cdot 150 + 0.01084 \cdot 100 + 0.1058 \cdot 114.01 + 1.5667 \cdot 16 + 1.0019 \cdot 100} = 0.6790$$

$$\pi_{1\rightarrow\beta}^R(t) = \frac{I_{1\rightarrow\beta}^R \cdot r_1^S(t)}{I_{1\rightarrow\beta}^W \cdot w_1^S(t) + I_{2\rightarrow\beta}^W \cdot w_2^S(t) + I_{1\rightarrow\beta}^R \cdot r_1^S(t) + I_{2\rightarrow\beta}^R \cdot r_2^S(t) + I_{3\rightarrow\beta}^R \cdot r_3^S(t)} = \frac{0.0079 \cdot 114.01}{0.00036 \cdot 150 + 0.00014 \cdot 100 + 0.0079 \cdot 114.01 + 0.0142 \cdot 16 + 0.0006 \cdot 100} = 0.7172$$

$$\pi_{2\rightarrow\beta}^R(t) = \frac{I_{2\rightarrow\beta}^R \cdot r_2^S(t)}{I_{1\rightarrow\beta}^W \cdot w_1^S(t) + I_{2\rightarrow\beta}^W \cdot w_2^S(t) + I_{1\rightarrow\beta}^R \cdot r_1^S(t) + I_{2\rightarrow\beta}^R \cdot r_2^S(t) + I_{3\rightarrow\beta}^R \cdot r_3^S(t)} = \frac{0.0142 \cdot 16}{0.00036 \cdot 150 + 0.00014 \cdot 100 + 0.0079 \cdot 114.01 + 0.0142 \cdot 16 + 0.0006 \cdot 100} = 0.1809$$

$$\pi_{3\rightarrow\beta}^R(t) = \frac{I_{3\rightarrow\beta}^R \cdot r_3^S(t)}{I_{1\rightarrow\beta}^W \cdot w_1^S(t) + I_{2\rightarrow\beta}^W \cdot w_2^S(t) + I_{1\rightarrow\beta}^R \cdot r_1^S(t) + I_{2\rightarrow\beta}^R \cdot r_2^S(t) + I_{3\rightarrow\beta}^R \cdot r_3^S(t)} = \frac{0.0006 \cdot 100}{0.00036 \cdot 150 + 0.00014 \cdot 100 + 0.0079 \cdot 114.01 + 0.0142 \cdot 16 + 0.0006 \cdot 100} = 0.0478$$

$$\pi_{1\rightarrow\gamma}^R(t) = \frac{I_{1\rightarrow\gamma}^R \cdot r_1^S(t)}{I_{1\rightarrow\gamma}^W \cdot w_1^S(t) + I_{2\rightarrow\gamma}^W \cdot w_2^S(t) + I_{1\rightarrow\gamma}^R \cdot r_1^S(t) + I_{2\rightarrow\gamma}^R \cdot r_2^S(t) + I_{3\rightarrow\gamma}^R \cdot r_3^S(t)} = \frac{2.1373 \cdot 114.01}{0 \cdot 150 + 0 \cdot 100 + 2.1373 \cdot 114.01 + 17.9 \cdot 16 + 3.818 \cdot 100} = 0.2672$$

$$\pi_{2\rightarrow\gamma}^R(t) = \frac{I_{2\rightarrow\gamma}^R \cdot r_2^S(t)}{I_{1\rightarrow\gamma}^W \cdot w_1^S(t) + I_{2\rightarrow\gamma}^W \cdot w_2^S(t) + I_{1\rightarrow\gamma}^R \cdot r_1^S(t) + I_{2\rightarrow\gamma}^R \cdot r_2^S(t) + I_{3\rightarrow\gamma}^R \cdot r_3^S(t)} = \frac{17.9 \cdot 16}{0 \cdot 150 + 0 \cdot 100 + 2.1373 \cdot 114.01 + 17.9 \cdot 16 + 3.818 \cdot 100} = 0.3141$$

$$\pi_{3\rightarrow\gamma}^R(t) = \frac{I_{3\rightarrow\gamma}^R \cdot r_3^S(t)}{I_{1\rightarrow\gamma}^W \cdot w_1^S(t) + I_{2\rightarrow\gamma}^W \cdot w_2^S(t) + I_{1\rightarrow\gamma}^R \cdot r_1^S(t) + I_{2\rightarrow\gamma}^R \cdot r_2^S(t) + I_{3\rightarrow\gamma}^R \cdot r_3^S(t)} = \frac{3.818 \cdot 100}{0 \cdot 150 + 0 \cdot 100 + 2.1373 \cdot 114.01 + 17.9 \cdot 16 + 3.818 \cdot 100} = 0.4187$$

References

- Afshari, H., Tosarkani, B.M., Jaber, M.Y., Searcy, C., 2020. The effect of environmental and social value objectives on optimal design in industrial energy symbiosis: A multi-objective approach. *Resour. Conserv. Recycl.* 158 <https://doi.org/10.1016/j.resconrec.2020.104825>.
- Albino, V., Fraccascia, L., 2015. The industrial symbiosis approach: A classification of business models. *Procedia Environ. Sci. Eng. Manag.* 2, 217–223.
- Albino, V., Yazan, D.M., 2013. Economic and environmental benefits of industrial symbiosis. An enterprise input-output analysis. In: 21st International Input-Output Conference, Kitakyushu, Japan, 9th-12nd June.
- Albino, V., Dangelico, R.M., Natalicchio, A., Yazan, D.M., 2011. Alternative energy sources in cement manufacturing. In: A Systematic Review of the Body of Knowledge.
- Ali, A.K., Wang, Y., Alvarado, J.L., 2019. Facilitating industrial symbiosis to achieve circular economy using value-added by design: A case study in transforming the automobile industry sheet metal waste-flow into Voronoi facade systems. *J. Clean. Prod.* 234, 1033–1044. <https://doi.org/10.1016/j.jclepro.2019.06.202>.
- Allenby, B.R., Cooper, W.E., 1994. Understanding industrial ecology from a biological systems perspective. *Environ. Qual. Manag.* 3, 343–354. <https://doi.org/10.1002/tqem.3310030310>.
- Ashton, W.S., 2011. Managing performance expectations of industrial symbiosis. *Bus. Strateg. Environ.* 20, 297–309. <https://doi.org/10.1002/bse.696>.
- Ashton, W.S., Chopra, S.S., Kashyap, R., 2017. Life and death of industrial ecosystems. *Sustainability* 9, 605. <https://doi.org/10.3390/su9040605>.
- Ayres, R.U., 1989. Industrial metabolism. *Technol. Environ.* 1989, 23–49.
- Bansal, P., McNight, B., 2009. Looking forward, pushing back and peering sideways: Analyzing the sustainability of industrial symbiosis. *J. Supply Chain Manag.* 45, 26–37. <https://doi.org/10.1111/j.1745-493X.2009.03174.x>.
- Benjamin, M.F.D., Tan, R.R., Razon, L.F., 2015. Probabilistic multi-disruption risk analysis in bioenergy parks via physical input-output modeling and analytic hierarchy process. *Sustain. Prod. Consum.* 1, 22–33. <https://doi.org/10.1016/j.spc.2015.05.001>.
- Boix, M., Montastruc, L., Azzaro-Pantel, C., Domenech, S., 2015. Optimization methods applied to the design of eco-industrial parks: A literature review. *J. Clean. Prod.* 87, 303–317. <https://doi.org/10.1016/j.jclepro.2014.09.032>.
- Boons, F., Chertow, M., Park, J., Spekkink, W., Shi, H., 2017. Industrial symbiosis dynamics and the problem of equivalence: Proposal for a comparative framework. *J. Ind. Ecol.* 21, 938–952. <https://doi.org/10.1111/jiec.12468>.
- Cao, X., Wen, Z., Tian, H., De Clercq, D., Qu, L., 2017. Transforming the cement industry into a key environmental infrastructure for urban ecosystem: A case study of an industrial city in China. *J. Ind. Ecol.* 22, 881–893. <https://doi.org/10.1111/jiec.12638>.
- Chen, X., Geng, Y., Fujita, T., 2010. An overview of municipal solid waste management in China. *Waste Manag.* 30, 716–724. <https://doi.org/10.1016/j.wasman.2009.10.011>.
- Chertow, M.R., 2000. Industrial symbiosis: Literature and taxonomy. *Annu. Rev. Energy Environ.* 25, 313–337. [https://doi.org/10.1002/\(SICI\)1099-0526\(199711/12\)3:2<16::AID-CPLX4>3.0.CO;2-K](https://doi.org/10.1002/(SICI)1099-0526(199711/12)3:2<16::AID-CPLX4>3.0.CO;2-K).
- Chertow, M.R., 2007. "Uncovering" industrial symbiosis. *J. Ind. Ecol.* 11, 11–30. <https://doi.org/10.1162/jiec.2007.1110>.
- Chertow, M.R., Ehrenfeld, J., 2012. Organizing self-organizing systems. *J. Ind. Ecol.* 16, 13–27. <https://doi.org/10.1111/j.1530-9290.2011.00450.x>.
- Chiu, A.S., Yong, G., 2004. On the industrial ecology potential in Asian developing countries. *J. Clean. Prod.* 12, 1037–1045. <https://doi.org/10.1016/j.jclepro.2004.02.013>.
- Chopra, S.S., Khanna, V., 2014. Understanding resilience in industrial symbiosis networks: Insights from network analysis. *J. Environ. Manag.* 141, 86–94. <https://doi.org/10.1016/j.jenvman.2013.12.038>.
- Corti, A., Lombardi, L., 2004. End life tyres: Alternative final disposal processes compared by LCA. *Energy* 29, 2089–2108. <https://doi.org/10.1016/j.energy.2004.03.014>.
- Costa, L., Massard, G., Agarwal, A., 2010. Waste management policies for industrial symbiosis development: Case studies in European countries. *J. Clean. Prod.* 18, 815–822. <https://doi.org/10.1016/j.jclepro.2009.12.019>.
- Côté, R.P., Smolenaars, T., 1997. Supporting pillars for industrial ecosystems. *J. Clean. Prod.* 5, 67–74. [https://doi.org/10.1016/S0959-6526\(97\)00016-4](https://doi.org/10.1016/S0959-6526(97)00016-4).
- D'Amato, D., Korhonen, J., Toppinen, A., 2019. Circular, green, and bio economy: How do companies in land-use intensive sectors align with sustainability concepts? *Ecol. Econ.* 158, 116–133. <https://doi.org/10.1016/j.ecolecon.2018.12.026>.
- Diaz Lopez, F.J., Bastain, T., Tukker, A., 2019. Business model innovation for resource-efficiency, circularity and cleaner production: What 143 cases tell us. *Ecol. Econ.* 155, 20–35. <https://doi.org/10.1016/j.ecolecon.2018.03.009>.
- Domenech, T., Bahn-Walkowiak, B., 2017. Transition towards a resource efficient circular economy in Europe: Policy lessons from the EU and the member states. *Ecol. Econ.* <https://doi.org/10.1016/j.ecolecon.2017.11.001>.
- Domenech, T., Bleischwitz, R., Doranova, A., Panayotopoulos, D., Roman, L., 2019. Mapping industrial symbiosis development in Europe, typologies of networks, characteristics, performance and contribution to the circular economy. *Resour. Conserv. Recycl.* 141, 76–98. <https://doi.org/10.1016/j.resconrec.2018.09.016>.
- Esty, D.C., Porter, M.E., 1998. Industrial ecology and competitiveness. *J. Ind. Ecol.* 2, 35–43. <https://doi.org/10.1162/jiec.1998.2.1.35>.
- European Cement Association, 2009. Sustainable Cement Production - Co-Processing of Alternative Fuels and Raw Materials in the European Cement Industry.
- European Commission, 2011. Roadmap to a Resource Efficient Europe. Bruxelles.
- European Commission, 2015. Closing the Loop - An EU Action Plan for the Circular Economy. COM, Bruxelles.
- Felicio, M., Amaral, D., Esposto, K., Gabarrell Durany, X., 2016. Industrial symbiosis indicators to manage eco-industrial parks as dynamic systems. *J. Clean. Prod.* 118, 54–64. <https://doi.org/10.1016/j.jclepro.2016.01.031>.
- Fichtner, W., Tietze-Stöckinger, I., Frank, M., Rentz, O., 2005. Barriers of interorganisational environmental management: Two case studies on industrial symbiosis. *Prog. Ind. Ecol. Int. J.* 2, 73–88. <https://doi.org/10.1504/PIE.2005.006778>.
- Fieberg, J., Jenkins, K.J., 2005. Assessing uncertainty in ecological systems using global sensitivity analyses: A case example of simulated wolf reintroduction effects on elk. *Ecol. Model.* 187, 259–280. <https://doi.org/10.1016/j.ecolmodel.2005.01.042>.
- Fraccascia, L., 2019. The impact of technical and economic disruptions in industrial symbiosis relationships: An enterprise input-output approach. *Int. J. Prod. Econ.* 213, 161–174. <https://doi.org/10.1016/j.ijpe.2019.03.020>.
- Fraccascia, L., Giannoccaro, I., 2020. What, where, and how measuring industrial symbiosis: A reasoned taxonomy of relevant indicators. *Resour. Conserv. Recycl.* 157, 104799. <https://doi.org/10.1016/j.resconrec.2020.104799>.
- Fraccascia, L., Albino, V., Garavelli, C.A., 2017a. Technical efficiency measures of industrial symbiosis networks using enterprise input-output analysis. *Int. J. Prod. Econ.* 183, 273–286. <https://doi.org/10.1016/j.ijpe.2016.11.003>.
- Fraccascia, L., Giannoccaro, I., Albino, V., 2017b. Rethinking resilience in industrial symbiosis: Conceptualization and measurements. *Ecol. Econ.* 137, 148–162. <https://doi.org/10.1016/j.ecolecon.2017.02.026>.
- Geng, O., van Capelleveen, G., Erdis, E., Yildiz, O., Yazan, D.M., 2019. A socio-ecological approach to improve industrial zones towards eco-industrial parks. *J. Environ. Manag.* 250, 109507. <https://doi.org/10.1016/j.jenvman.2019.109507>.
- Geng, Y., Côté, R., 2007. Diversity in industrial ecosystems. *Int. J. Sustain. Dev. World Ecol.* 14, 329–335. <https://doi.org/10.1080/13504500709469733>.
- Geng, Y., Liu, Z., Xue, B., Dong, H., Fujita, T., Chiu, A., 2014. Energy-based assessment on industrial symbiosis: A case of Shenyang economic and technological development zone. *Environ. Sci. Pollut. Res.* 21, 13572–13587. <https://doi.org/10.1007/s11356-014-3287-8>.
- Ghodspour, S.H., O'Brien, C., 1998. A decision support system for supplier selection using an integrated analytic hierarchy process and linear programming. *Int. J. Prod. Econ.* 56–57, 199–212. [https://doi.org/10.1016/S0925-5273\(97\)00009-1](https://doi.org/10.1016/S0925-5273(97)00009-1).
- Grubbstrom, R.W., Tang, O., 2000. An overview of input-output analysis applied to production-inventory systems. *Econ. Syst. Res.* 12, 3–25. <https://doi.org/10.1080/095353100111254>.
- Guinée, J.B., Heijungs, R., Huppes, G., 2004. Economic allocation: Examples and derived decision tree. *Int. J. Life Cycle Assess.* 9, 23–33. <https://doi.org/10.1007/BF02978533>.
- Han, F., Liu, Y., Liu, W., Cui, Z., 2017. Circular economy measures that boost the upgrade of an aluminum industrial park. *J. Clean. Prod.* 168, 1289–1296. <https://doi.org/10.1016/j.jclepro.2017.09.115>.
- Hashimoto, S., Fujita, T., Geng, Y., Nagasawa, E., 2010. Realizing CO2 emission reduction through industrial symbiosis: A cement production case study for Kawasaki. *Resour. Conserv. Recycl.* 54, 704–710. <https://doi.org/10.1016/j.resconrec.2009.11.013>.
- Hein, A.M., Jankovic, M., Feng, W., Farel, R., Yune, J.H., Yannou, B., 2017. Stakeholder power in industrial biospheres: A stakeholder value network approach. *J. Clean. Prod.* 148, 923–933. <https://doi.org/10.1016/j.jclepro.2017.01.136>.
- Hendrickson, C., Horvath, A., Joshi, S., Lave, L., 1998. Economic input-output models for environmental life-cycle assessment. *Environ. Sci. Technol.* 32 <https://doi.org/10.1021/es983471i>.
- Herczeg, G., Akkerman, R., Hauschild, M.Z., 2018. Supply chain collaboration in industrial symbiosis networks. *J. Clean. Prod.* 171, 1058–1067. <https://doi.org/10.1016/j.jclepro.2017.10.046>.
- Hill, R.M., 1999. The optimal production and shipment policy for the single-vendor single-buyer integrated production-inventory problem. *Int. J. Prod. Res.* 37, 2463–2475. <https://doi.org/10.1080/002075499190617>.
- Hu, Y., Wen, Z., Lee, J.C.K., Luo, E., 2017. Assessing resource productivity for industrial parks using adjusted raw material consumption (ARMC). *Resour. Conserv. Recycl.* <https://doi.org/10.1016/j.resconrec.2017.04.009>.
- Huang, C.L., Vause, J., Ma, H.W., Yu, C.P., 2012. Using material/substance flow analysis to support sustainable development assessment: A literature review and outlook. *Resour. Conserv. Recycl.* <https://doi.org/10.1016/j.resconrec.2012.08.012>.
- Husgafvel, R., Watkins, G., Linkosalmi, L., Dahl, O., 2013. Review of sustainability management initiatives within Finnish forest products industry companies—Translating EU level steering into proactive initiatives. *Resour. Conserv. Recycl.* 76, 1–11. <https://doi.org/10.1016/j.resconrec.2013.04.006>.
- IEA, 2009. Cement Technology Roadmap 2009.
- Korhonen, J., 2001. Four ecosystem principles for an industrial ecosystem. *J. Clean. Prod.* 9, 253–259. [https://doi.org/10.1016/S0959-6526\(00\)00058-5](https://doi.org/10.1016/S0959-6526(00)00058-5).
- Korhonen, J., Baumgartner, R.J., 2009. The industrial ecosystem balanced scorecard. *Int. J. Innov. Sustain. Dev.* 4, 24–42. <https://doi.org/10.1504/IJISD.2009.024854>.
- Korhonen, J., Honkasalo, A., Seppälä, J., 2018. Circular economy: The concept and its limitations. *Ecol. Econ.* 143, 37–46. <https://doi.org/10.1016/j.ecolecon.2017.06.041>.

- Li, Y., Shi, L., 2015. The resilience of interdependent industrial symbiosis networks: A case of Yixing economic and technological development zone. *J. Ind. Ecol.* 19, 264–273. <https://doi.org/10.1111/jiec.12267>.
- Li, W., Cui, Z., Han, F., 2015. Methods for assessing the energy-saving efficiency of industrial symbiosis in industrial parks. *Environ. Sci. Pollut. Res.* 22, 275–285. <https://doi.org/10.1007/s11356-014-3327-4>.
- Li, B., Xiang, P., Hu, M., Zhang, C., Dong, L., 2017. The vulnerability of industrial symbiosis: a case study of Qijiang Industrial Park, China. *J. Clean. Prod.* 157, 267–277. <https://doi.org/10.1016/J.JCLEPRO.2017.04.087>.
- Liu, C., Côté, R., 2017. A framework for integrating ecosystem services into China's circular economy: The case of eco-industrial parks. *Sustainability* 9, 1510. <https://doi.org/10.3390/su9091510>.
- Liu, Z., Adams, M., Cote, R.P., Geng, Y., Chen, Q., Liu, W., Sun, L., Yu, X., 2017. Comprehensive development of industrial symbiosis for the response of greenhouse gases emission mitigation: Challenges and opportunities in China. *Energy Policy* 102, 88–95. <https://doi.org/10.1016/j.enpol.2016.12.013>.
- Liwarska-Bizukojc, E., Bizukojc, M., Marcinkowski, A., Doniec, A., 2009. The conceptual model of an eco-industrial park based upon ecological relationships. *J. Clean. Prod.* 17, 732–741. <https://doi.org/10.1016/j.jclepro.2008.11.004>.
- Lombardi, D.R., Laybourn, P., 2012. Redefining industrial symbiosis. *J. Ind. Ecol.* 16, 28–37. <https://doi.org/10.1111/j.1530-9290.2011.00444.x>.
- Lowe, E.A., Evans, L.K., 1995. Industrial ecology and industrial ecosystems. *J. Clean. Prod.* 3, 47–53. [https://doi.org/10.1016/0959-6526\(95\)00045-G](https://doi.org/10.1016/0959-6526(95)00045-G).
- Lyons, D., 2007. A spatial analysis of loop closing among recycling, remanufacturing, and waste treatment firms in Texas. *J. Ind. Ecol.* 11, 43–54. <https://doi.org/10.1162/jiec.2007.1029>.
- Maillé, M., Frayret, J.-M., 2016. Industrial waste reuse and by-product synergy optimization. *J. Ind. Ecol.* 20, 1284–1294. <https://doi.org/10.1111/jiec.12403>.
- Martin, M., Svensson, N., Eklund, M., 2015. Who gets the benefits? An approach for assessing the environmental performance of industrial symbiosis. *J. Clean. Prod.* 98, 263–271. <https://doi.org/10.1016/j.jclepro.2013.06.024>.
- Mathy, S., Menanteau, P., Criqui, P., 2018. After the Paris agreement: Measuring the global decarbonization wedges from national energy scenarios. *Ecol. Econ.* 150, 273–289. <https://doi.org/10.1016/j.ecolecon.2018.04.012>.
- Mattila, T., Lehtoranta, S., Sokka, L., Melanen, M., Nissinen, A., 2012. Methodological aspects of applying life cycle assessment to industrial symbioses. *J. Ind. Ecol.* 16, 51–60. <https://doi.org/10.1111/j.1530-9290.2011.00443.x>.
- Millennium Ecosystem Assessment, 2005. *Ecosystems and Human Well-Being: Synthesis*. Ministero dell'Ambiente e della Tutela del Territorio e del Mare, Ministero dello Sviluppo Economico, 2017. Verso un modello di economia circolare per l'Italia. [in italian].
- Mirata, M., 2004. Experiences from early stages of a national industrial symbiosis programme in the UK: Determinants and coordination challenges. *J. Clean. Prod.* 12, 967–983. <https://doi.org/10.1016/j.jclepro.2004.02.031>.
- Nakamura, S., Kondo, Y., 2002. Input-output analysis of waste management. *J. Ind. Ecol.* 6, 39–63. <https://doi.org/10.1162/108819802320971632>.
- Neves, A., Godina, R., Azevedo, S.G., Matias, J.C.O., 2019. Environmental, economic, and social impact of industrial symbiosis: Methods and indicators review. In: *Springer Proceedings in Mathematics and Statistics*. Springer New York LLC, pp. 157–165. https://doi.org/10.1007/978-3-030-14973-4_15.
- Nieto, J., Carpintero, Ó., Miguel, L.J., 2018. Less than 2 °C? An economic-environmental evaluation of the Paris agreement. *Ecol. Econ.* 146, 69–84. <https://doi.org/10.1016/j.ecolecon.2017.10.007>.
- Ollerton, J., 2006. "Biological barter": Patterns of specialization compared across different mutualisms. In: Waser, N.M., Ollerton, J. (Eds.), *Plant-Pollinator Interactions: From Specialization to Generalization*. The University of Chicago Press, Chicago and London.
- Park, H.-S., Behera, S.K., 2014. Methodological aspects of applying eco-efficiency indicators to industrial symbiosis networks. *J. Clean. Prod.* 64, 478–485. <https://doi.org/10.1016/J.JCLEPRO.2013.08.032>.
- Prosman, E.J., Wæhrens, B.V., 2019. Managing waste quality in industrial symbiosis: Insights on how to organize supplier integration. *J. Clean. Prod.* 234, 113–123. <https://doi.org/10.1016/J.JCLEPRO.2019.06.169>.
- Rosano, M., Schianetz, K., 2014. Measuring sustainability performance in industrial parks: A case study of the Kwinana industrial area. *Int. J. Sustain. Dev.* 17, 261. <https://doi.org/10.1504/IJSD.2014.064181>.
- Schlüter, L., Mortensen, L., Kørnøv, L., 2020. Industrial symbiosis emergence and network development through reproduction. *J. Clean. Prod.* 252 <https://doi.org/10.1016/j.jclepro.2019.119631>.
- Sendra, C., Gabarrell, X., Vicent, T., 2007. Material flow analysis adapted to an industrial area. *J. Clean. Prod.* 15, 1706–1715. <https://doi.org/10.1016/j.jclepro.2006.08.019>.
- Shah, I.H., Dong, L., Park, H.-S., 2020. Tracking urban sustainability transition: An eco-efficiency analysis on eco-industrial development in Ulsan, Korea. *J. Clean. Prod.* 262, 121286. <https://doi.org/10.1016/j.jclepro.2020.121286>.
- Simboli, A., Taddeo, R., Morgante, A., 2015. The potential of industrial ecology in agri-food clusters (AFCs): A case study based on valorisation of auxiliary materials. *Ecol. Econ.* 111, 65–75. <https://doi.org/10.1016/J.ECOLECON.2015.01.005>.
- Song, X., Geng, Y., Dong, H., Chen, W., 2018. Social network analysis on industrial symbiosis: A case of Gujiao eco-industrial park. *J. Clean. Prod.* 193, 414–423. <https://doi.org/10.1016/J.JCLEPRO.2018.05.058>.
- Sun, L., Li, H., Dong, L., Fang, K., Ren, J., Geng, Y., Fujii, M., Zhang, W., Zhang, N., Liu, Z., 2017. Eco-benefits assessment on urban industrial symbiosis based on material flows analysis and energy evaluation approach: A case of Liuzhou city, China. *Resour. Conserv. Recycl.* 119, 78–88. <https://doi.org/10.1016/j.resconrec.2016.06.007>.
- Taddeo, R., Simboli, A., Morgante, A., Erkman, S., 2017. The development of industrial symbiosis in existing contexts. Experiences from three Italian clusters. *Ecol. Econ.* 139, 55–67. <https://doi.org/10.1016/J.ECOLECON.2017.04.006>.
- Tan, R.R., Benjamin, M.F.D., Cayamanda, C.D., Aviso, K.B., Razon, L.F., 2016. P-graph approach to optimizing crisis operations in an industrial complex. *Ind. Eng. Chem. Res.* 55, 3467–3477. <https://doi.org/10.1021/acs.iecr.5b03205>.
- Tukker, A., Poliakov, E., Heijungs, R., Hawkins, T., Neuwahl, F., Rueda-Cantuche, J.M., Giljum, S., Moll, S., Oosterhaven, J., Bouwmeester, M., 2009. Towards a global multi-regional environmentally extended input-output database. *Ecol. Econ.* 68, 1928–1937. <https://doi.org/10.1016/j.ecolecon.2008.11.010>.
- Van Berkel, R., Fujita, T., Hashimoto, S., Fujii, M., 2009. Quantitative assessment of urban and industrial Symbiosis in Kawasaki, Japan. *Environ. Sci. Technol.* 43, 1271–1281. <https://doi.org/10.1021/es803319r>.
- Wang, D., Li, J., Wang, Y., Wan, K., Song, X., Liu, Y., 2017a. Comparing the vulnerability of different coal industrial symbiosis networks under economic fluctuations. *J. Clean. Prod.* 149, 636–652. <https://doi.org/10.1016/J.JCLEPRO.2017.02.137>.
- Wang, D., Zheng, J., Song, X., Ma, G., Liu, Y., 2017b. Assessing industrial ecosystem vulnerability in the coal mining area under economic fluctuations. *J. Clean. Prod.* 142, 4019–4031. <https://doi.org/10.1016/j.jclepro.2016.10.049>.
- Wang, Q., Tang, H., Yuan, X., Zuo, J., Zhang, J., Gao, Z., Hong, J., 2018. Investigating vulnerability of ecological industrial symbiosis network based on automatic control theory. *Environ. Sci. Pollut. Res.* 1–13. <https://doi.org/10.1007/s11356-018-2753-0>.
- Wen, Z., Meng, X., 2015. Quantitative assessment of industrial symbiosis for the promotion of circular economy: A case study of the printed circuit boards industry in China's Suzhou New District. *J. Clean. Prod.* 90, 211–219. <https://doi.org/10.1016/J.JCLEPRO.2014.03.041>.
- Wu, J., Guo, Y., Li, C., Qi, H., 2017. The redundancy of an industrial symbiosis network: A case study of a hazardous waste symbiosis network. *J. Clean. Prod.* 149, 49–59. <https://doi.org/10.1016/J.JCLEPRO.2017.02.038>.
- Wu, J., Pu, G., Guo, Y., Lv, J., Shang, J., 2018. Retrospective and prospective assessment of exergy, life cycle carbon emissions, and water footprint for coking network evolution in China. *Appl. Energy* 218, 479–493. <https://doi.org/10.1016/J.APENERGY.2018.03.003>.
- Yazan, D.M., 2016. Constructing joint production chains: An enterprise input-output approach for alternative energy use. *Resour. Conserv. Recycl.* 107, 38–52. <https://doi.org/10.1016/j.resconrec.2015.11.012>.
- Yazan, D.M., Fraccascia, L., 2020. Sustainable operations of industrial symbiosis: An enterprise input-output model integrated by agent-based simulation. *Int. J. Prod. Res.* 58, 392–414. <https://doi.org/10.1080/00207543.2019.1590660>.
- Yazan, D.M., Romano, V.A., Albino, V., 2016. The design of industrial symbiosis: An input-output approach. *J. Clean. Prod.* 129, 537–547. <https://doi.org/10.1016/j.jclepro.2016.03.160>.
- Yu, B., Li, X., Shi, L., Qian, Y., 2015. Quantifying CO2 emission reduction from industrial symbiosis in integrated steel mills in China. *J. Clean. Prod.* <https://doi.org/10.1016/j.jclepro.2014.08.015>.
- Yuan, Z., Shi, L., 2009. Improving enterprise competitive advantage with industrial symbiosis: Case study of a smeltery in China. *J. Clean. Prod.* 17, 1295–1302. <https://doi.org/10.1016/j.jclepro.2009.03.016>.
- Zeng, Y., Xiao, R., Li, X., 2013. A resilience approach to symbiosis networks of ecoindustrial parks based on cascading failure model. *Math. Probl. Eng.* 2013 <https://doi.org/10.1155/2013/372368>. Article ID 372368.
- Zhang, Y., Zheng, H., Fath, B.D., 2015. Ecological network analysis of an industrial symbiosis system: A case study of the Shandong Lubei eco-industrial park. *Ecol. Model.* 306, 174–184. <https://doi.org/10.1016/J.ECOLMODEL.2014.05.005>.
- Zhu, J., Ruth, M., 2013. Exploring the resilience of industrial ecosystems. *J. Environ. Manag.* 122, 65–75. <https://doi.org/10.1016/J.JENVMAN.2013.02.052>.