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What, where, and how measuring industrial symbiosis: A reasoned taxonomy of relevant indicators

Luca Fraccascia[a,b,*], Ilaria Giannoccaro[c]

[a] Department of Computer, Control, and Management Engineering "Antonio Ruberti" - Sapienza University of Rome, via Ariosto 25, 00185 Rome, Italy
[b] Department of Industrial Engineering and Business Information Systems, University of Twente, Enschede, the Netherlands
[c] Department of Mechanics, Mathematics, and Management, Polytechnic University of Bari, Bari, Italy

ABSTRACT

During the last two decades, the literature devoted great attention to industrial symbiosis (IS) as an effective strategy to achieve environmental, economic, and social benefits. Accordingly, a wide range of numerical indicators – highly different among them for scope, definition, purpose, and applications – have been developed, to characterize and measure IS. The paper proposes a taxonomy of these indicators with the aim of facilitating their adoption and proper usage in practice. The taxonomy is developed on the basis of a literature review and is addressed to answer three main questions: (1) what to measure, (2) where to measure, and (3) how to measure. This offers a clear picture of available relevant IS indicators in terms of purpose, context, and methodology.

1. Introduction

Industrial symbiosis (IS) is a sub-field of industrial ecology engaging "*traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products*" (Chertow, 2000, p. 313). The adoption of IS can create economic benefits for companies, as well as environmental and social benefits for the society (e.g., Jacobsen, 2006; Taddeo et al., 2017b). Nowadays, IS is considered a key strategy supporting the transition towards the circular economy, so that the attention received in the literature by the topic is grown a lot (e.g., Baldassarre et al., 2019; Domenech et al., 2019; European Commission, 2015; Lüdeke-Freund et al., 2019; Taddeo et al., 2017a). In fact, according to Scopus, since the late 90 s around 1000 scientific papers have been published (Fig. 1) by more than 1900 scholars, who are part of a large scientific community with several research groups spread across the world (Fig. 2). The above-mentioned contributions include both practical (e.g., the description of case studies) and conceptual papers (e.g., aimed at developing new theories about the development of the IS practice), which can be classified on the basis of four main dimensions: (1) evolution and development, (2) operation carriers, (3) driving mechanisms, and (4) efficiency evaluation of industrial systems (Huang et al., 2019a).

Recently, an issue that is receiving increasing attention in the referred literature concerns the development of indicators assessing the features of IS models and measuring the performance of IS synergies (e.g., Mantese and Amaral, 2018). The term "indicator" traces back to the Latin verb *indicare*, which means "to disclose" or "to point out", as well as "to announce" or "to make publicly known". According to Gallopín (1996), indicators are useful tools to assess conditions and trends (even in relation to specific goals and targets), to compare across places and situations, to provide early warning information, and to anticipate future conditions and trends. From the sustainability perspective, indicators can play an important communication function (Beratan et al., 2004), by summarizing or simplifying relevant information, making perceptible phenomena of interest, and quantifying and measuring relevant information (Gallopín, 1996). Such a communication function is likely to have a high impact on supporting and improving policy and decision-making processes at different levels (Gallopín, 2005).

In the IS field, indicators can be used for monitoring, evaluation, and decision-making. In fact, they can support decision-making by governmental authority managers and policymakers at both local and national levels, when developing strategies towards the IS development and implementation (Chiu and Yong, 2004; Park and Behera, 2014). Nevertheless, at the company level, indicators can support managers to tackle operational issues, such as identifying opportunities for IS currently not (fully) exploited and increasing the efficiency in exploiting the existing IS synergies (e.g., Fraccascia et al., 2017a).

A wide range of numerical indicators – highly different among them for scope, definition, purpose, and possible application – is currently available in the literature. As a response to this recent growing number of multi-layered indicators, classifying IS indicators is required, to facilitate their diffusion and proper usages. Nevertheless, there are few

* Corresponding author.
E-mail address: luca.fraccascia@uniroma1.it (L. Fraccascia).

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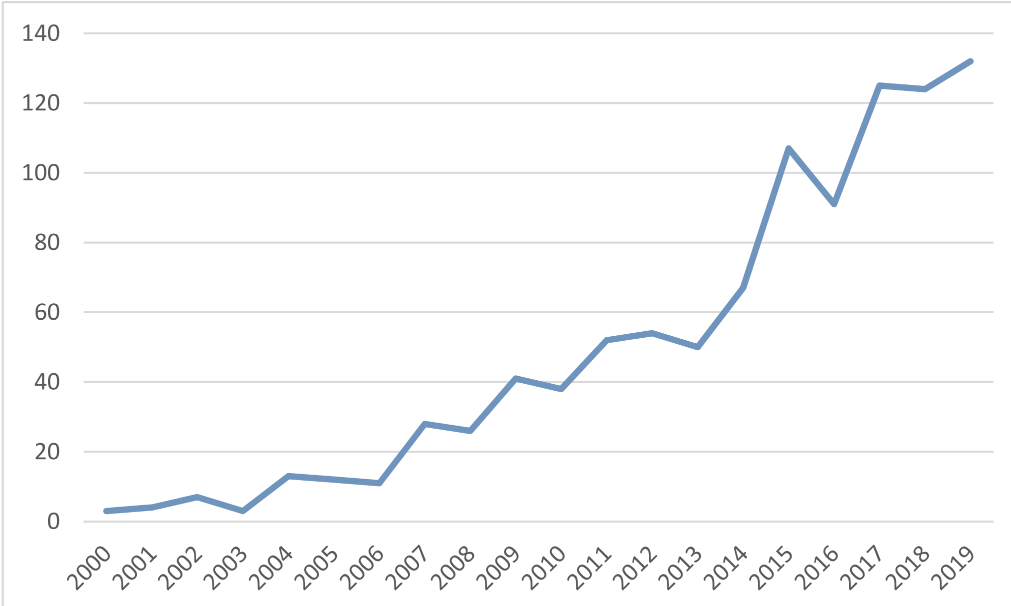

Fig. 1. Number of IS papers published per year – source: Scopus database.

studies aimed at classifying IS indicators. In this regard, Valenzuela-Venegas et al. (2016) have identified 249 sustainability indicators that can be used to assess the performance of eco-industrial parks (eco-industrial parks are defined in Section 2) and have classified them according to the three dimensions – i.e., social, environmental, and economic – of sustainability. Felicio et al. (2016) have classified IS indicators into three groups according to the methodology used to compute them – i.e., eco-efficiency, Life Cycle Assessment (LCA), and Material Flow Analysis (MFA). However, the above-mentioned classifications proposed in the literature devote attention just to one taxonomic aspect, the sustainability performance in the one case and the methodology adopted in the other. Therefore, they do not provide a comprehensive view of the topic, which still is needed.

In this paper, we propose a taxonomy of IS indicators, which is based on three dimensions, each of them aimed at replying to a practical question: (1) what to measure, (2) where to measure, and (3) how to measure. The taxonomy is developed by analyzing 638 papers, which result from a systematic literature review on the topic.

The rest of the paper is as follows. Section 2 introduces the concept of IS. Section 3 presents the methodology followed in the paper and describes the three dimensions of the developed taxonomy. Section 4 addresses the taxonomy of IS indicators. Finally, Section 5 concerns discussion and conclusions.

2. Industrial symbiosis

The IS practice involves several companies in physical trades of by-products. In particular, two companies – defined as the waste producer and the waste user, respectively – establish an IS relationship when one waste of the waste producer is exploited by the waste user (Chertow, 2000), who can use the waste to replace inputs to production processes or to make new products (Fraccascia et al., 2016). The operation of IS can contribute to creating relevant environmental benefits for the overall society, thanks to the reduction in the amounts of wastes discharged (from the waste producer perspective), primary inputs – i.e., raw materials, energy, water – used in production processes (from the waste user perspective), and greenhouse gas emissions (e.g., Jacobsen, 2006; Kim et al., 2018b). Furthermore, the IS practice is potentially able to create social benefits, in terms of new jobs or improvements in the quality of existing ones (e.g., Domenech et al., 2019). IS synergies can be implemented at several spatial levels, i.e.: (1) among production processes within a single firm (e.g., Zhu et al., 2008); (2) among firms co-located in a given area, e.g., an industrial park (e.g., Jacobsen, 2006); (3) among firms not co-located (e.g., Jensen et al., 2011). The choice of the spatial level is strongly affected by the economic logic of the companies involved (e.g., Lyons, 2007; Sterr and Ott, 2004). This means that even firms distant from each other can be willing to establish an IS relationship, as far as the synergy convenient from the economic perspective. In fact, the literature highlights as the first driver motivating companies towards the IS approach is the economic benefit they can achieve, while other issues – such as social aspects, e.g., personal relationships among managers of the involved companies (e.g., Hewes and Lyons, 2008) – play a secondary role, *ceteris paribus* (e.g., Ashton and Bain, 2012). Economic benefits refer to reductions in waste disposal and input purchasing costs, as well as include extra revenues coming from exchanging wastes and selling the new products (Fraccascia et al., 2019a). Nevertheless, *ceteris paribus*, these benefits achieved via IS can provide the involved companies with competitive advantage on other companies that are not implementing IS, (Esty and Porter, 1998; Yuan and Shi, 2009). However, apart from the economic perspective, IS synergies have to be feasible even from the technical and legal point of view, simultaneously (e.g., Golev et al., 2015). In this regard, companies face several operational challenges when implementing and managing an IS relationship, such as the lack of information, willingness to cooperate of (potential) IS partner(s), and trust between key players, as well as the difference between supply and demand of wastes (e.g., Fichtner et al., 2005; Golev et al., 2015; Herczeg et al., 2018; Madsen et al., 2015). For a comprehensive review of the critical factors for the emergence of IS relationships, readers are referred to a recent work by Mortensen and Kørnøv (2019).

A recent review by Neves et al. (2019) highlights that cases of IS have been growing over the past years and are disseminated at the global level. Furthermore, the review highlighted that, although the IS approach has been conceived for industrial areas, IS synergies have been implemented also in urban areas and rural areas, confirming the high potential of such an approach for the sustainable development. On the one hand, IS synergies adopted in urban areas are aimed at exploiting urban wastes as inputs for production activities and/or industrial wastes (e.g., waste heat) as inputs for urban processes (e.g., Geng et al., 2010a; Li et al., 2015; Ohnishi et al., 2017). On the other hand, IS synergies implemented in rural areas are aimed at exploiting wastes from the agricultural sector (e.g., Alfaro and Miller, 2014;

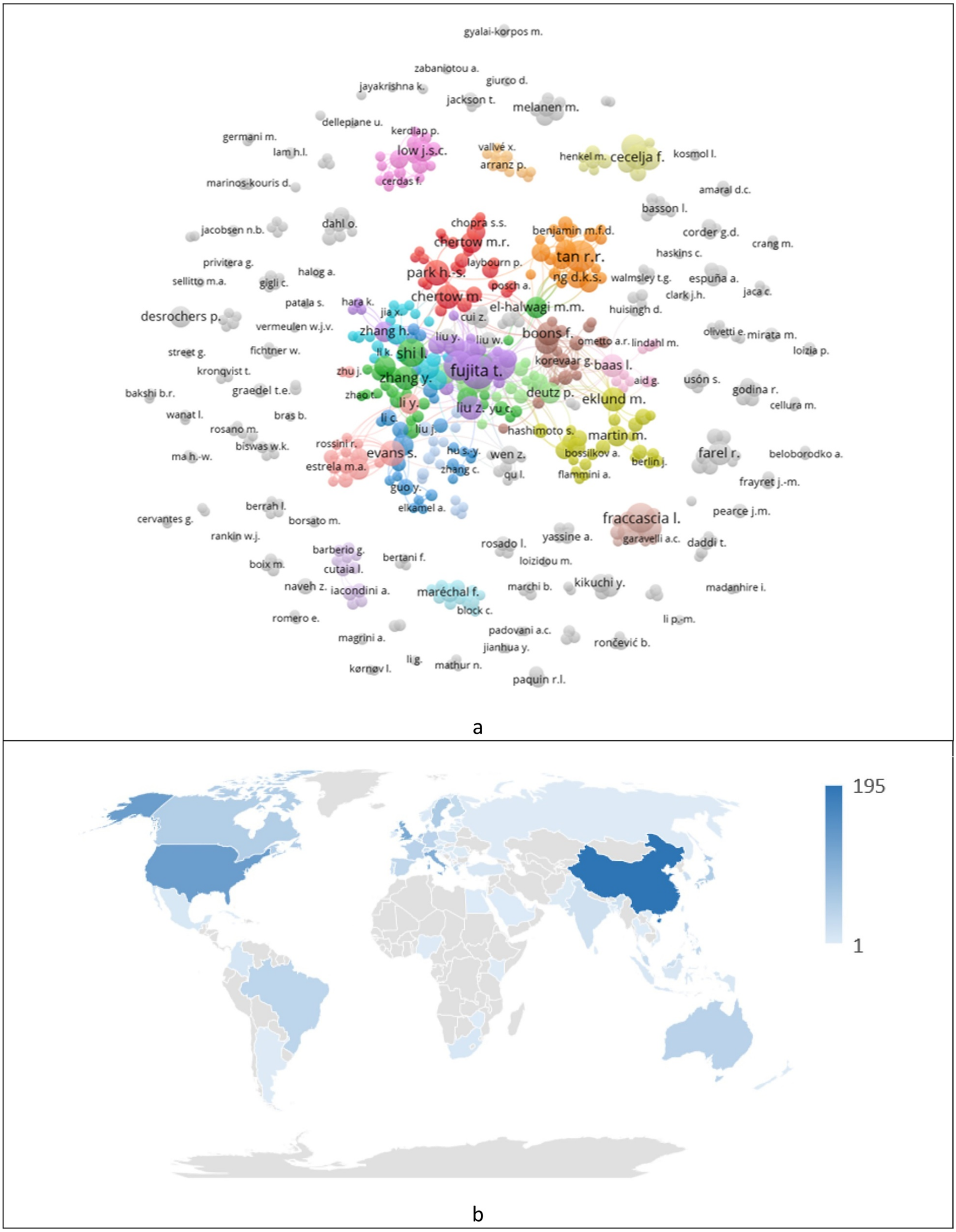

Fig. 2. (a) Research groups on IS and their interrelationships; (b) diffusion of IS research around the world (number of IS papers published per country) – source: Scopus database.

Yazan et al., 2018, 2016b).

When more than two companies exchange at least two different wastes among them, an IS network (ISN) arises (Chertow, 2007). Two formation mechanisms for ISNs are distinguished: accordingly, ISNs can be designed following the top-down approach or emerge from the bottom, because companies spontaneously start to symbiotically cooperate. The so-called "eco-industrial parks" are examples of top-down ISNs (e.g., Afshari et al., 2018; Geng et al., 2009), while the so-called "self-organized ISNs" are examples of bottom-up ISNs (e.g., Chertow and Ehrenfeld, 2012; Ghali et al., 2017).

3. Materials and methods

To develop the taxonomy, we firstly conducted a bibliographic research. The analysis was conducted in September 2019 and the data were retrieved from Scopus, an academic search service and citation indexing of Elsevier. We decided to first collect all papers on IS available in the literature. Therefore, the research keyword "industrial symbiosis" has been applied to title, abstract, and keywords of papers. The keywords used in the search string are generic, since our aim is to collect information concerning the indicators used in assessments (Valenzuela-Venegas et al., 2016). Then, papers not published in scientific journals (e.g., conference proceedings) have been excluded from the analysis, in order to rely only on peer-reviewed articles (e.g., Boix et al., 2015; Meerow and Newell, 2015). Furthermore, papers published in other languages than English have been excluded from the analysis. As a result, the analyzed sample is made by 638 papers. The full text of each paper has been analyzed, with the aim to identify whether the paper provides numerical analysis on IS and which indicators are used. These data are used to develop a reasoned taxonomy of the indicators developed in the literature.

The proposed taxonomy is developed along three dimensions: *what to measure, where to measure*, and *how to measure*. The dimension *what to measure* focuses on the goals of the measurement. It highlights what it is important to measure for internal and external communicating purposes. The dimension *where to measure* focuses on the spatial scale of the measurement. IS can be applied at multiple levels and measurements can differ on the basis of this, so that a proper indication is useful. Finally, the dimension *how to measure* focuses on the methodologies which are needed to conduct the measurement, highlighting their main characteristics and applications. The overall methodological process, we used to conduct the research, is graphically shown in Fig. 3.

4. Taxonomy of IS indicators

This section is organized into three subsections, each of them addressing one dimension of the proposed taxonomy: *what to measure* (Section 4.1), *where to measure* (Section 4.2), and *how to measure* (Section 4.3). Because of the large body of the literature addressing the measurement of IS, the references provided in the following subsections related to examples of applications are not intended to be exhaustive of each topic. In some cases, when available, readers are referred to literature reviews on specific topics.

4.1. What to measure

This section concerns the goals of the indicators used in IS, i.e., what they measure. In particular, two main classes can be distinguished: (1) *benefits generated by the adoption of IS* and (2) *structural features of IS*. They are discussed below.

Benefits generated by the adoption of IS. The benefits associated with IS can be distinguished in actual benefits and potential benefits, depending on whether the IS synergies are currently implemented (here the benefits are assessed by comparing the current scenario with a hypothetical scenario where IS synergies are not implemented, *ceteris paribus*) or not implemented (here the benefits are assessed by comparing the current scenario with to a hypothetical scenario where IS synergies are implemented, *ceteris paribus*). Both actual and potential benefits can be measured by referring to environmental, economic, and social dimensions.

As to the environmental dimension, the reduction in the environmental impact of the system analyzed can be quantified from both the upstream and the downstream perspective. The upstream perspective concerns the measurement of 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). Alternatively, the downstream perspective concerns the measurement of the reduction in the amounts of solid wastes discharged in landfill or disposed conventionally, 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). The above-mentioned perspectives can be analyzed separately or simultaneously. Overall, each of these indicators has a different unit of measure; therefore, comparing different indicators from a comprehensive perspective is a matter of challenge. In fact, by using only these indicators, it is hard or even impossible to assess whether it is better, from the environmental perspective, reducing the disposal of waste x by k units or the disposal of waste y by z units. In order to overcome this challenge, the indicators concerning different units of measure can be converted into the same unit of measure: examples of them are the aggregated environmental impact (Trokanas et al., 2015), carbon footprint indicators (e.g., Ohnishi et al., 2017), life-cycle assessment indicators (e.g., Daddi et al., 2017) (see Section 4.3.3), emergy indicators (e.g., Dong et al., 2018) (see Section 4.3.2), and exergy indicators (e.g., Usón et al., 2012) (see Section 4.3.2).

As to the economic dimension, three types of measurements can be done: (1) cost savings thanks to IS, (2) economic value created by IS synergies, and (3) comprehensive economic feasibility of IS synergies.

Cost savings refer to the *reduction in the waste disposal costs and input purchasing costs* thanks to IS implementation (e.g., Tan et al., 2016). However, simply quantifying these costs highlights the "gross economic benefits", but it does not provide information on the additional costs required to operate IS, as well as on the additional benefits achieved. Therefore, a category of indicators is proposed to measure the *economic value created by IS*. These consider, in addition to the above-mentioned avoided costs, the operational costs (e.g., waste transportation costs, waste treatment costs, transaction costs of IS cooperation), additional costs or revenues coming from selling/buying wastes to/from the symbiotic partner(s), the additional gains generated by selling new products generated thanks to using wastes, etc. (Fraccascia et al., 2019a; Yazan and Fraccascia, 2020). These indicators have a short period perspective – e.g., one year – and, therefore, do not consider the investments required to implement (e.g., building new infrastructures or new plants) and operate IS synergies (e.g., the maintenance costs for the new infrastructures). The indicators concerning the *comprehensive economic feasibility of IS* adopt the traditional approach of investment analysis, which considers the cash flow generated by the investment in IS (e.g., Cao et al., 2017; Ng et al., 2014; Røyne et al., 2018). They permit comparing the profitability of IS investments with traditional investments.

Both the environmental and economic benefits can be measured from the absolute or the relative point of view. For the sake of clarity, let us consider the amounts of a given waste not disposed of in the landfill thanks to IS. While the absolute perspective is limited to provide the numerical value of this benefit (e.g., the IS synergy allows to reduce the amounts of waste landfilled by x units), the relative perspective compares the benefit with the highest possible achievable (e.g., the IS synergy allows to reduce the amounts of waste landfilled by x units; however the company produces $y \geq x$ units of wastes, hence the IS synergy allows to reduce the waste disposal by x/y percent). The relative perspective provides additional information than the absolute perspective, which can be useful to design the evolution of IS synergies

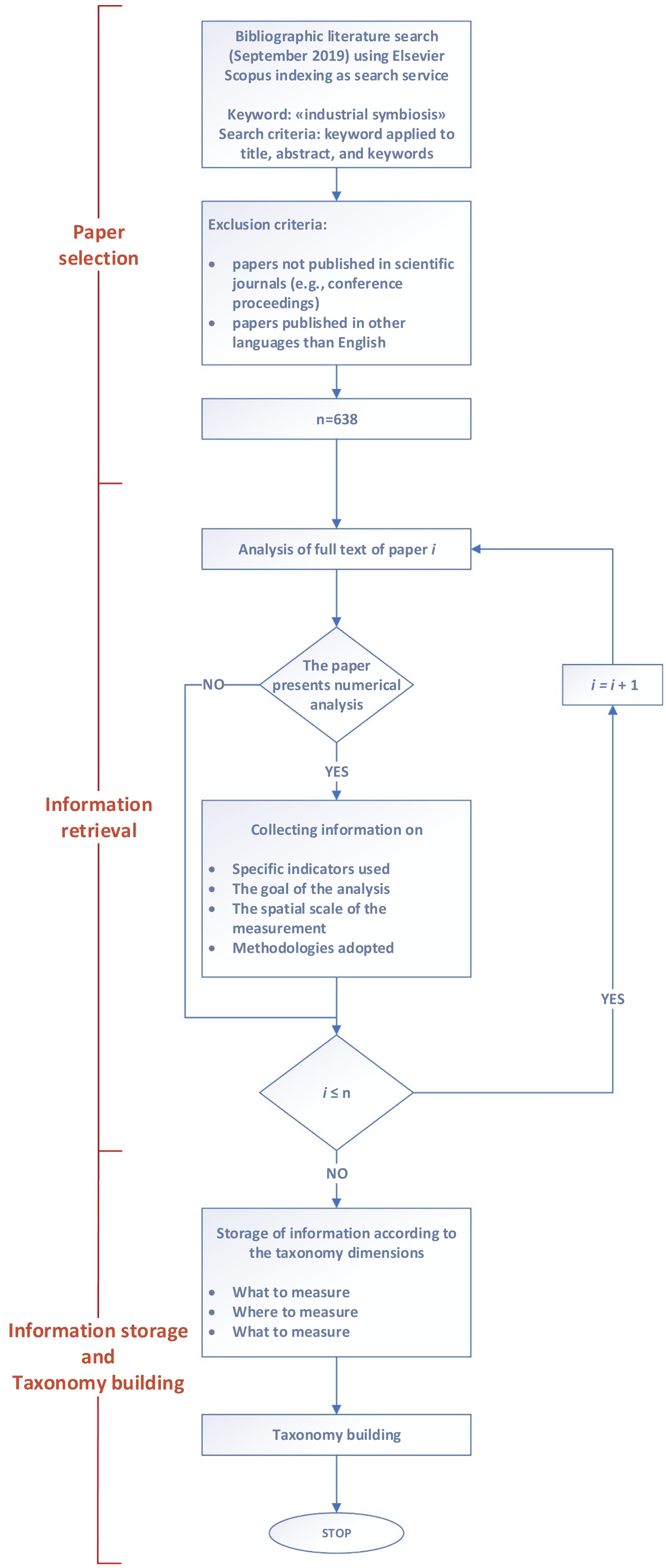

Fig. 3. Flow chart of the methodology used to conduct the research.

currently applied or to implement additional IS relationships.

Contrary to the environmental and economic benefits, the assessment of the social benefits is scantly addressed by the analyzed papers. In this regard, only two indicators have been used in the literature, i.e., job creation (e.g., Domenech et al., 2019; Santos and Magrini, 2018) and job retention (e.g., Martin and Harris, 2018).

Finally, some hybrid indicators, which consider more than one of the above-mentioned perspectives simultaneously, have been developed. For instance, eco-efficiency indicators and resource productivity indicators are able to consider the economic and environmental dimensions simultaneously (e.g., Park and Behera, 2014; Rosano and Schianetz, 2014; Wen and Meng, 2015). In fact, they assess the raw material consumption and the waste disposal per unit of economic output of the system. A hybrid indicator that considers both quantitative (i.e., the amounts of wastes exchanged) and qualitative (i.e., legislation, class of waste, use of waste, destination of waste, and problems/risks) criteria is proposed by Felicio et al. (2016). Trokanas et al. (2015) proposed a single indicator measuring the overall environmental impact of IS, which transforms the environmental impact indicators into cost performances and considers a weighted average of their values.

Structural features of IS. Indicators concerning the following several features of ISN have been mainly developed in the literature: (1) the quantity match between demand and supply for the waste, (2) the spatial scale of IS relationships, (3) the redundancy of the IS exchange, and (4) the network properties of ISNs.

Quantifying the supply-demand match is important in order to investigate whether IS synergies can be characterized by incentive misalignment problems; in particular, the higher the quantity match, the lower the chance of a misalignment incentive problem among the involved companies. Furthermore, measuring the quantity match can provide suggestions on how to further implement the IS practice, for instance by creating new IS relationships and/or evolving the existing ones (e.g., Fraccascia et al., 2017a). The spatial scale of IS relationships is determined by the distance among the involved companies (e.g., Jensen et al., 2011; Velenturf, 2017). IS synergies can arise at several spatial levels (e.g., Chertow, 2000), whose choice is dominated by the economic logic of the firms involved (Lyons, 2007). Finally, the redundancy of the IS synergy is measured as the number of symbiotic partners involved in supplying or receiving the waste (e.g., Fraccascia et al., 2019b; Wu et al., 2017a). This parameter is related to the strategic behavior of companies in terms of multiple partnerships. *Ceteris paribus*, the redundancy is positively related to the resilience of IS synergies to disruptive events and therefore can be considered as one of the drivers of stability of ISNs over the long period (Ashton et al., 2017; Chopra and Khanna, 2014; Fraccascia et al., 2017b; Li et al., 2017; Wang et al., 2017; Wu et al., 2017b).

Concerning the ISNs, several structural indicators of ISNs have been proposed, many of them via network analysis methodologies (for details see Section 4.3.4) (e.g., Doménech and Davies, 2011; Song et al., 2018) or material flow analysis (e.g., Fraccascia et al., 2017b) (for details see Section 4.3.1). Such kind of analysis is mainly aimed at identifying the most important companies in a given ISN, in terms of their contribution to the IS synergies, as well as companies mostly able to impact on the ISN performance in case they abandon the network.

4.2. Where to measure

This section concerns the different levels considered when measuring IS. In this regard, we distinguish five levels: (1) company, (2) IS relationship, (3) ISN, (4) geographic area, and (5) overall environment.

The level of *company* concerns the IS synergies implemented within the company boundaries, i.e., among different production processes belonging to the same company (e.g., Zhu et al., 2008). Usually, wastes are produced and exploited in the same production plant, thus not requiring transportation activities. The level of *IS relationship* concerns two companies between which at least one IS synergy exists. The involved companies can be located close-by or far from each other, as much as the waste exchange is convenient enough from the economic perspective. The level of *ISN* concerns more than two companies exchanging at least two different wastes, according to the definition provided by Chertow et al. (2007). The ISN can involve companies located in close proximity – such as the case of eco-industrial parks (e.g., Zhang et al., 2015b) or the case of Kalundborg (Jacobsen, 2006) – or be developed in a larger area (e.g., Taddeo et al., 2017b). For the three above-mentioned levels, the indicators measuring the economic, environmental, and social benefits can be used. These indicators are mainly adopted to several purposes: (1) supporting company and network managers in the operations management of IS synergies, (2) providing decision-support to managers when designing the implementation and further evolution of IS synergies, (3) communicating to external actors (e.g., customers, suppliers, policymakers) the companies' efforts towards the environmentally sustainable industrial activity, (4) supporting policymakers in designing incentives aimed at (further) developing the IS practice. Benefits coming from IS can be measured via flow analysis methodologies (see Section 4.3.1), methods focused on thermodynamic analyses (see Section 4.3.2), and LCA (see Section 4.3.3). Furthermore, at the level of ISN, the structural features of the network are also measured via network analysis methodologies (see Section 4.3.4). Assessing the structural features permits to study the complex patters of relationships among companies belonging to the network, as well as to investigate the extent to which ISNs can be resilient to disruptive events (e.g., Chopra and Khanna, 2014).

The level of *geographic area* corresponds to a region or a country, where several IS relationships and ISNs are implemented. At this level, the benefits generated by the IS approach can be computed as the sum of the benefits generated by single IS relationships and/or single ISNs (e.g., Huang et al., 2019b; Park et al., 2019, 2016). These indicators are mainly adopted to support regional planning and to quantify the efficacy of regional policies in supporting IS implementation. Finally, the broader perspective of indicators concerns the measure of the impact assessment of IS on a global scale, i.e., on the *overall environment.* These indicators are not limited to quantify the direct benefits created by IS, but also include the impacts along the upstream and downstream supply chains of the companies involved. Such an assessment can be supported by EIO approach (e.g., Yazan, 2016) and LCA (e.g., Martin, 2019) (for details see Sections 4.3.1 and 4.3.3). These indicators are successfully used to support policymakers in the management of top-down IS projects – see, for instance, the eco-town program in Japan (Van Berkel et al., 2009).

4.3. How to measure

This section concerns the methodologies used when measuring IS. Analysis of IS can be conducted via several methodologies, which can be classified into four groups: flow analysis (Section 4.3.1), thermodynamics (Section 4.3.2), LCA (Section 4.3.3), and network analysis (Section 4.3.4).

4.3.1. Flow analysis

Three methodologies belong to this category: *Material Flow Analysis* (MFA), *Substance Flow Analysis* (SFA), and *Enterprise Input-Output* (EIO) *approach*.

Material Flow Analysis (MFA) is considered as the basic method to map the physical material flows and stocks through a given system. This methodology is useful to assessing the environmental load to the system and revealing how economic activities can impact on the environmental performance of the system considered (e.g., Brunner and Rechberger, 2016). This is the basic methodology that can be adopted to analyze ISNs, in terms of data required and computations, since it only requires to map the material and energy flows, without performing any conversion (e.g., Sendra et al., 2007). It is used to measure the environmental benefits thanks to IS, in terms of reductions in the amounts of input used, wastes discharged, and greenhouse gas (GHG) emitted, as well as to evaluate the economic benefits for companies belonging to the ISN (Li et al., 2016; Ohnishi et al., 2017; Sun et al., 2017). MFA can be used also to map energy flows among companies or processes (e.g., Zhang et al., 2013b).

Substance Flow Analysis (SFA) allows monitoring flows of individual substances, i.e., chemical elements (atoms) or chemical compounds (molecules), into a given system. This methodology is useful to analyze substances that raise particular alarms concerning both the environmental perspective and health issues (e.g., Huang et al., 2012). In the IS field, SFA is used to map the carbon flows among companies and production processes involved in IS synergies, in order to assess the reduction in carbon emissions thanks to IS (e.g., Zhang et al., 2013a, 2013b).

Enterprise Input-Output (EIO) models are a subset of Input-Output (IO) models, accounting for single production units instead of sectors of national economies. EIO models can be used as an accounting tool, aimed at mapping both the physical (i.e., materials, energy, water) and monetary flows among production processes belonging to a single company or among different companies (e.g., Grubbstrom and Tang, 2000; Lin and Polenske, 1998). In fact, EIO models are useful to analyze logistics flows among different companies, as well as to support coordination policies (e.g., Albino and Kuhtz, 2004). Moreover, the environmental impacts – both direct and indirect – of production processes, companies, and even supply chains can be assessed by using EIO models. The EIO approach is adopted to model both IS relationships and ISNs. The system analyzed is modeled as made by several production processes that absorb inputs (i.e., materials and energy), transform them into outputs, and produce wastes. The outputs generated by production processes can be intermediate goods, destined to be inputs for other processes, or final goods, destined to be sold on external markets. Conversely than the MFA approach, the EIO approach allows to model input requirement and waste production as a function of the outputs of each production process; therefore, this is a useful methodology to analyze dynamic scenarios characterized by market dynamics, as well as by disruptive events (Fraccascia, 2019). By adopting the EIO approach, several indicators have been proposed. First, the direct and indirect benefits thanks to adopting IS can be easily accounted, both from the environmental and the economic perspective (Yazan, 2016; Yazan et al., 2016a). The direct benefits are those created by companies involved in IS relationships, while the indirect benefits are created by other companies along the supply chains of companies exchanging wastes (see Section 4.2). As environmental benefits, the reduction in the amounts of wastes discharged and in the amounts of inputs used by production processes, thanks to adopting IS, are considered. As economic benefits, the reductions in production costs and the increase in revenues are considered. Furthermore, the EIO approach can be used to assess some structural features of IS, at the level of IS relationship (Fraccascia, 2019) and ISN (Fraccascia et al., 2017a).

4.3.2. Thermodynamics

Two methodologies belong to this category: *emergy analysis* and *exergy analysis*.

Emergy analysis has been developed as a tool for resource quality evaluation and environmental policy within the assessment of complex system dynamics. Emergy analysis has conceptual basis grounded in thermodynamics and systems theory. “Emergy is defined as the sum of all inputs of available energy directly or indirectly required by a process to provide a given product or flow when the inputs are expressed in the same form (or type) of energy, usually solar energy” (Geng et al., 2010, p. 5274). Emergy analysis considers a given system as a network of energy flows and determines the emergy value of each stream and the overall system. Hence, this method allows to assess both the quantity and the quality of the energy required to produce a given product or service, as well as provides information concerning how much efficiently the energy has been used. In this regard, such an approach for resource-consumption accounting is useful to assess the eco-efficiency of given system and compare similar systems among them (e.g., Ulgiati et al., 2011). The emergy analysis allows computing indicators at the system level. Brown and Ulgiati (1997) propose five emergy indicators to assess the sustainability of a system: (1) *percent renewable*, which measures the percent of the total energy driving a process coming from renewable sources. In the long run, only processes with high value of this indicator are sustainable; (2) *nonrenewable to renewable ratio*, is computed as the ratio between the nonrenewable energy contribution and the renewable contribution to a process; (3) *emergy yield ratio*, which is computed as the ratio between the emergy of the output of the system and the emergy of those inputs to the system that are fed back from outside the system. It measures the ability of the system to exploit local resources; (4) *environmental loading ratio*, which measures the pressure of the process on the local ecosystem. Such an indicator can be considered a measure of the environmental stress due to production activities; and (5) *emergy investment ratio*, which measures if the system is a good user of the emergy that is invested, compared to other alternatives.

The benefits thanks to the IS approach are computed by measuring emergy-based indicators of the same system for two different scenarios, i.e., when IS occurs and when IS does not occur, and comparing the values of the same indicator for the two above-mentioned scenarios (e.g., Geng et al., 2014). Several contributions have been provided, aimed at adapting this approach to assessing the comprehensive performance of ISNs. For instance, Pan et al. (2016) propose the following indicators for an ISN: (1) *emergy yield rate*, which measures how much industrial processes are capable to exploit local resources; (2) *unit emergy value of economic output*, which measures the production efficiency of the system; (3) *improved environmental loading ratio*, which measures the pressure of industrial activities on the local environment; (4) *emergy loss percent*, which measures the cleaner production level of the system and the press on the environment indirectly; (5) *recycling and reuse benefit ratio*, which measures the systematic perspective of recycling and resource conservation in the system under investigation; and (6) *improved emergy sustainable index*, which reflects the ecological sustainability of the industrial activity in the long term. Readers interested to explore further specific indicators are referred, for example, to the following papers (Dong et al., 2018; Fan et al., 2017; Geng et al., 2014, 2010; Liu et al., 2016; Ohnishi et al., 2017; Sun et al., 2017).

The concept of *exergy* is based on the second law of thermodynamics. Exergy measures the maximum work that a system might produce while interacting with the environment, or, from the opposite perspective, the minimum work needed to produce the outputs of the system considered (e.g., Szargut, 2005). Exergy provides a rigorous way to represent and compare flows of material and energy, as well as provides information on the environmental impact of these streams. In fact, the exergy associated with the use of non-renewable resources and wastes produced to the environment can be considered as a potential for environmental losses (e.g., Dincer, 2000). In this regard, exergy analysis can be useful to identify the energetic inefficiencies in a process and to highlight their sources (e.g., Rosen et al., 2008).

In the IS field, exergy analysis has been adopted to assess the environmental benefits thanks to adopting IS. In particular, by recovering wastes into the ISN, IS synergies can reduce the energy losses of the ISN, thus contributing to enhancing the exergy efficiency of the system, i.e., the ratio between the exergy of outputs and the exergy of inputs (e.g., Wu et al., 2016). Wu et al. (2018) propose the exergetic sustainability index, which is an inverse measure of the environmental impact of the ISN. Uson et al. (2012) integrate environmental and economic analysis by computing the exergy costs of all the flows into a given ISN.

4.3.3. Life cycle assessment (LCA)

Life cycle assessment (LCA) is a methodology aimed at assessing the (potential) environmental impacts of a product, service, and technology throughout a life-cycle extending "from cradle to grave", i.e., from raw material extraction to final disposal (ISO, 2006). Analyses based on the LCA methodology are carried out through four steps: goal and scope definition, inventory analysis, impact assessment, and interpretation of the results.

The LCA methodology has been largely used to measure the environmental benefits thanks to the IS practice. The environmental benefits are evaluated at three different spatial levels: single company, single IS relationship, and ISN (e.g., Daddi et al., 2017; Hossain et al., 2019; Martin, 2019; Røyne et al., 2018). Martin et al. (2015) and Kim et al. (2018b) discuss methodological considerations and propose practical approaches to assess the environmental benefits at the level of IS relationship or ISN and then allocating these benefits to the involved companies. In general, the environmental benefits are measured by computing the environmental impacts of a given system associated with the following two scenarios: (1) when IS is implemented, and (2) when IS is not implemented. By comparing the impacts of the two above-mentioned scenarios, the environmental benefits thanks to the IS practice can be easily highlighted. Three settings are used for the analysis, depending whether IS is currently implemented into the system considered: (1) currently there is no IS and the current scenario is compared to a hypothetical scenario where IS is implemented; (2) currently IS is implemented into the system and the current scenario is compared to a hypothetical scenario where IS does not occur; and (3) currently IS is implemented into the system and the current scenario is compared to a hypothetical scenario where IS is further developed into the system, in terms of new IS synergies. While scenarios (1) and (3) are used to provide evaluations *ex-ante*, scenario (2) is used to provide evaluation *ex-post*. For a detailed review of the reference scenarios adopted, readers are referred to a recent work by Aissani et al. (2019).

4.3.4. Network analysis

Network analysis is a methodology that uses quantitative methods to analyze physical and social interactions among entities belonging to a system (e.g., Borgatti et al., 2009). The system is conceptualized as a network made by nodes and links: each node represents a given entity and a relationship between two entities as a link between the corresponding nodes. Various types of links can be modeled via network analysis, e.g., material and energy flows, information, financial transactions, and even social interactions.

In the IS field, four methodologies related to this approach have been used: *social network analysis, stakeholder value network approach, ecological network analysis*, and *food web analysis*.

Social network analysis has been adopted mainly to measure structural features of ISNs. Here, companies belonging to the network are represented as nodes within and a link between two nodes represents a waste flow between the respective companies. By adopting this approach, several indicators describing the network structure have been proposed, such as density measures and centrality measures (e.g., Song et al., 2018; Zhang and Chai, 2019; Zhang et al., 2016, 2015b). Furthermore, centrality measures computed at the level of nodes are used to identify the most important nodes for the ISN in case of disruptions, according to a resilience perspective (e.g., Chopra and Khanna, 2014; Li and Shi, 2015; Wang et al., 2018).

Stakeholder value network approach is used to model the value flows among companies into ISNs (e.g., Hein et al., 2017). A value flow represents a transfer of utility between two companies. Here, utility depends on two factors: urgency and importance score. Urgency is related to how quickly a resource is needed by the user company. The importance score is related to the specific company which supplies a resource: *ceteris paribus*, this score is much higher the more the supply of the resource is dependent on a specific source company. According to the utility flows, the relative power can be computed for each company, as well as the most important wastes for the ISN can be highlighted.

Ecological network analysis concerns the integrated assessment of the utility resulting from exchanges of wastes among companies into a given ISN (e.g., Wu et al., 2019; Zhang et al., 2015a). Such an analysis can reflect the ecological relationships among companies belonging to the ISN. Accordingly, four types of relationships can be identified: exploitation, control, competition, and mutualism. According to these ecological relationships, companies belonging to the ISN can be divided in the following three clusters: producers, primary consumers, and secondary consumers.

Finally, *food web analysis* is a methodology based on biomimicry that is traditionally used to investigate the interactions among organisms in an ecosystem. Here, energy flows among organisms are represented via food chains. A food web matrix shows the materials and energy flow in a natural ecosystem and is useful to assess the prey-predator relations between species. In the IS field, a food web matrix describes the waste flows between companies belonging to the ISN, where companies are distinguished between predators and prey (e.g., Genc et al., 2019; Hardy and Graedel, 2002). Specific indices based on this matrix have been computed, such as the pray to predator ratio (i.e., the ratio between the amounts of waste producers and waste users), the generalization (i.e., the number of waste producers interacted per waste receiver), and the connectance (i.e., the number of waste flows implemented compared to the theoretically possible flows).

5. Discussion and conclusion

Industrial Symbiosis (IS) is recognized as one of the most promising strategies to pursue circular economy and achieve sustainable development. Therefore, both companies and policymakers are largely interested to identify proper ways aimed at supporting and implementing IS in practice. The literature has highlighted that one of the main gaps concerning the creation, development, and implementation of IS is the lack of proper indicators to measure the phenomenon. Thus, measuring IS has become an important research issue and many studies have been proposed by the literature in this regard. Measuring the performance of IS is useful for two purposes: communication and management. From the former perspective, the (potential) benefits associated with IS can be communicated to stakeholders, policymakers, citizens, and customers, for example aimed at enforcing the green reputation of the involved companies. From the latter perspective, knowing the (potential) benefits associated with IS can help company managers to implement further activities towards the sustainability practice.

To date, a growing number of different indicators has been proposed, while a clear map of the available tools is still lacking (Domenech et al., 2019). Too many indicators without critical analysis and classification create confusion, which in turn limits their diffusion and implementation in practice. To overcome this problem, a taxonomic exercise, which can guide decision-makers both in companies and policy institutions to select the right indicators to adopt, is required.

We addressed this call by proposing a taxonomy of IS indicators with the aim of answering three main questions: (1) what to measure, (2) where to measure, and (3) how to measure. This contributes to giving a clearer picture of available indicators in terms of purpose, context, and methodology, respectively.

As to purpose, it is widely recognized that IS provides economic, environmental, and social benefits. We classified indicators based on the nature of performance to measure. While in the past the evaluation of ISNs performance has been identified as scarce, in particular concerning the measurement of environmental performance (Eckelman and Chertow, 2009), we found that the effort in measuring the economic and environmental performance is increased. In particular, proper environmental indicators have been provided to quantify the beneficial impact of IS on the environment in terms of both reduction of inputs used and reduction of waste and greenhouse gas emissions generated. The economic benefits associated with IS have been also clearly identified by clarifying the cost reductions and the new value generated, for example thanks to the premium price received by customers. However, an important gap we found concerns the availability of indicators measuring social performance, which are still lacking. Assessing the social performance of IS is important, in order to highlight in a comprehensive way the benefits provided by the symbiotic practice to human health.

Furthermore, we noted that specific indicators have been developed to characterize the IS structural features, including the quantity match between demand and supply for the waste, the redundancy of the IS exchange, and several network properties of ISNs. Such indicators are useful to compare different models of ISN, which are spread across countries (Boons et al., 2017). Coupled with the economic, environmental, and social performance indicators, they can provide strategic implications for the effective design of IS in practice.

In our analysis, we showed that the IS indicators have been developed at different spatial levels (i.e., context). These refer to five different units of analysis: the company, the relationship, the network, the geographical area, and the overall environment, which in turn correspond to the diverse implementation scales of IS. While the literature often classifies IS indicators distinguishing between *micro, meso*, and *macro* scales, we specified the context of application, thus overcoming a limit very recently highlighted by Moraga et al. (2019), which concerns the unclear and inconsistent definition of micro, macro, and meso across studies.

We noted that the economic and environmental indicators can be applied at multiple scales by simply summing the benefits of the corresponding actors involved. However, specific indicators have been developed at the network, geographical area, and overall environment levels, to capture their specific nature. In such a case, more complex and systemic approaches and methodologies are used, as emerged in the analysis of the "*how to measure*" dimension of our taxonomy.

Finally, we analyzed the methodologies used to develop the IS indicators. We classified them into four groups: flow analysis, thermodynamics, LCA, and network analysis. In the first category, we included indicators using the material flow analysis, the substance flow analysis, and the enterprise Input-Output approach. The indicators in the thermodynamics category adopt two main methodologies, i.e., the emergy and exergy analysis. The LCA category includes all the indicators adopting this tool. Finally, indicators belonging to the network analysis category are based on social network analysis, stakeholder value network approach, ecological network analysis, and food web analysis. The four categories differ in terms of data and information required and computational effort. In fact, they provide complementary information and require different competencies to be computed. This confirms the increasing complexity of the IS literature that has grown including more disciplines compared to the past.

It can be highlighted that the above-mentioned methodologies can be used in an exclusive manner or combined among them. For instance, some papers (e.g., Ohnishi et al., 2017; Sun et al., 2017) combine MFA and emergy analysis: first, MFA is used to map the material flows among companies and then data coming from MFA are multiplied by the relevant transformities to obtain emergy values. Other papers (e.g., Dong et al., 2017) combine LCA and input-output analysis, aimed at providing a better assessment of the environmental benefits created by IS.

Our analysis also permits to identify promising future research directions. First, indicators measuring the social benefits of IS should be developed. Furthermore, hybrid indicators capturing all the three performance dimensions should be identified. Increasing attention should be also paid especially at developing indicators at the firm and overall environment levels. The development of indicators at the firm level, able to quantify the benefits of IS for a company, are in fact fundamental to motivate firms to adopt the IS practice. Indicators at the environment level would help assess the global impact of IS so that the IS benefits can be totally exploited. Furthermore, we believe that, given the increasing importance of IS in urban and rural areas (Kim et al., 2018a; Yazan et al., 2018), indicators specific to these contexts should be designed. As to the methodological perspective, tools based on a combination of the different methodologies should be proposed so that a clear assessment of IS from multiple points of view can be provided. This will also help to improve planning or designing of IS in practice.

Our paper presents some limits. It proposes a taxonomy of IS indicators that, even though is based on a systematic literature review, is not intended to be exhaustive. Moreover, our analysis provides an updated picture of the current available indicators but does not show how analytically to compute them in specific contexts.

Author statement

Both the authors equally contributed to the research

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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