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The role of online information-sharing platforms on the performance of industrial symbiosis networks

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ABSTRACT

From technical perspective, an important condition for developing industrial symbiosis (IS) is the match between waste supply and demand. Such a match is hampered by lack of information among companies, i.e., demand (supply) for waste exists but firms producing (requiring) that waste are not aware of such a demand (supply). Despite online information-sharing platforms are proposed to support the creation of industrial symbiosis networks (ISNs), related environmental and economic benefits are not in-depth investigated. This paper firstly aims to fill this gap.

Although up-to-date literature recognizes lack of information-sharing as an IS barrier, in-depth analysis about the impact of sensitive information-sharing on the operations of IS is not addressed. This paper secondly aims at filling this gap.

In this paper, we design an agent-based model to simulate the emergence and operations of self-organized ISNs in three scenarios: (1) no information-sharing platform; (2) a platform where companies provide information about their geographical location and the type and quantity of produced and required wastes; (3) a platform where companies provide sensitive information about the costs of operating IS. These scenarios are simulated in a numerical case study involving two kinds of IS businesses: (1) marble residuals used in concrete production; (2) alcohol slops used in fertilizer production.

Results show that online platforms increase the economic and environmental performance of ISNs. Findings help practitioners to understand the importance of information-sharing and to clarify whether the information they consider as 'sensitive' is really sensitive or it is non-sensitive information that facilitates business-making.

1. Introduction

Industrial symbiosis (IS) is a subfield of industrial ecology that engages separate industries in a collective approach to competitive advantage, involving physical exchange of materials, energy, and services (Chertow, 2000). In particular, wastes generated by one firm can be used by other firms to replace production inputs or be exploited to generate new products. By replacing inputs with wastes, firms can gain economic advantages because of enhancing production efficiency and, at the same time, create environmental and social benefits for the entire collectivity (Fraccascia et al., 2017a; Jacobsen, 2006; Yu et al., 2015; Yuan and Shi, 2009).

The European Commission explicitly recognizes the usefulness of the IS approach to boost resource use and production efficiency and recommends the implementation of such a practice (European Commission, 2015, 2011). Furthermore, several studies indicate that IS can be a useful approach for companies to reduce their CO_2 emissions (Hashimoto et al., 2010; Liu et al., 2017; Sun et al., 2017). As a result, policymakers of many countries have introduced the IS practice in their environmental agenda (Costa et al., 2010; Husgafvel et al., 2013; Mirata, 2004; Van Berkel et al., 2009).

An industrial symbiosis network (ISN) is a network of firms among which IS relationships exist (Fichtner et al., 2005). These networks can be designed by adopting a top-down approach, such as the eco-industrial park model (Heeres et al., 2004; Lambert and Boons, 2002), or emerge from the bottom as the result of a spontaneous and self-organized process undertaken by the involved firms (Chertow and Ehrenfeld, 2012; Doménech and Davies, 2011). Despite empirical cases show that both models can be successful, in recent years scholars seem to have converged in considering the self-organized approach as the most promising one. However, self-organized ISNs are underdeveloped in terms of practical applications compared to theoretical developments in the field. This is due to the low emergence rate of new ISNs and the low sustainability of existing ISNs over the long period (Chiu and Yong, 2004; Paquin et al., 2015). From the technical perspective, the most relevant condition for the development of sustainable IS relationships

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over the long period is the match between supply and demand of wastes (Yazan et al., 2016b). In fact, the lack of this match reduces the economic benefit that firms gain from the IS practice (Albino et al., 2016), which is the first driver attracting firms to adopt such a practice (Lyons, 2007). The mismatch between waste supply and demand quantities can be because of: (1) the lack of firms producing (requiring) a given waste for which demand (supply) exists (Alfaro and Miller, 2014; Eilering and Vermeulen, 2004; Fichtner et al., 2005); (2) the lack of information, i.e., demand (supply) for a given waste exists but firms producing (requiring) that waste are not aware of such a demand (supply) (Aid et al., 2017; Chertow, 2007; Golev et al., 2015; Sakr et al., 2011; Zhu and Cote, 2004). In addition, apart from potential savings from waste discharge costs (for the waste producer) and traditional resource purchasing cost (for the waste receiver) companies need to deal with additional costs to implement and operate IS. These costs are waste treatment costs, transportation costs, and transaction costs whose sum should be lower than the potential savings so that companies are motivated to initiate IS. Driven by the uncertainty on supply-demand match, also the costs and benefits of IS might fluctuate over time dynamically. This represents a barrier against implementing sustainable IS-based business and this paper aims to understand how such uncertainties can be reduced via adopting online information-sharing platforms.

Information communication technologies are claimed to play a critical role in solving both these problems (Heeres et al., 2004; Kincaid and Overcash, 2001). By using online platforms, firms can easily share information among themselves about their geographic location, the type and the amount of both produced and required resources, as well as their availability to start new IS relationships. Such a strategy can facilitate collaboration among firms helping them to discover IS opportunities (Park et al., 2016).

However, so far the extent to which online platforms can support IS relationships has been not in-depth investigated by the literature because assessing the real contribution of these tools is problematic (Grant et al., 2010). In fact, through observing the adoption of online platforms *a posteriori*, it is difficult or even impossible to understand which IS relationships took place thanks to the platform and which IS relationships would have been created even without the platform.

In IS-based business models, companies' willingness-to-share information with each other plays a critical role to launch the initial cooperation phase. Although information-sharing might intuitively increase the trust between companies, it might also be interpreted as the fact of revealing sensitive data about production recipe of products of the company. Furthermore, IS might require some basic information about the available/requested resource quantities, waste quality, details about the waste content such as chemical or physical characteristics, potential costs of treatment and transportation, etc. The sensitivity of such data is mainly decided by company managers who develop an information-sharing strategy in markets. However, as recognized in the IS literature (Ashton, 2008; Chertow, 2007; Sakr et al., 2011), information-sharing has a catalyzer role in facilitating the implementation of IS which has different dynamics than classical business models. Therefore, the questions pop up: 'What is sensitive information for a company?', 'Which type of information is non-sensitive for a company to implement IS-based cooperation?' and 'Is 'the sensitive information' really sensitive enough to motivate the limitation for its non-disclosure?'

In this paper, self-organized ISNs are studied from a complex system perspective approach to understand the role of (sensitive and non-sensitive) information-sharing via a communication platform on the performance of ISNs. In particular, we adopt the agent-based modeling, which is one of the most suited technique to study complex systems (Axelrod, 1997). In ABMs, each agent is characterized by a given set of goals and actions to accomplish and a given set of rules of social engagement, driving its interactions with other agents and the environment (Bonabeau, 2002; Weiss, 1999). Such an approach permits to investigate the system dynamics in a way that analytical models cannot do. In fact, the complex system behavior spontaneously emerges from the interactions among the agents and between the agents and the environment, rather than to be defined by the modeler (Macal and North, 2010). We design an agent-based model (ABM) which simulates the spontaneous creation and the operations of an ISN in three different scenarios: (1) basic scenario, where no communication platform is adopted; (2) a communication platform provides non-sensitive information about the geographical location of each firm and the type and quantity of produced and required wastes; and (3) a communication platform provides sensitive-information about the costs of operating IS, in addition to those provided by the second scenario. Physical and monetary flows among firms are assessed by adopting the Enterprise Input-Output (EIO) approach. These three scenarios are simulated in a numerical case study that concerns an ISN composed of marble, concrete, alcohol, and fertilizer producers. By comparing results from different scenarios, the paper quantitatively assesses the contribution of the adopted platform in supporting ISNs.

The paper is organized as follows. Section 2 presents the theoretical background on ISNs and role of information platforms to support IS-based businesses. The ABM for ISNs is developed in Section 3. Section 4 describes the scenario setting in the ISN case under investigation. Section 5 provides the simulation results. Findings are discussed in Section 6 and conclusions are presented in Section 7.

2. Theoretical background

This section is divided in two sub-sections. Sub-section 2.1 summarizes the Industrial Symbiosis Networks (ISNs) from a complex systems approach while Sub-section 2.2 focuses on the literature about the role of information platforms supporting the formation and operation of IS.

2.1. Studying self-organized ISNs: a complex systems approach

A wide part of the literature recognizes self-organized ISNs as complex adaptive systems (CASs) (Ashton, 2009; Côté and Hall, 1995; Liwarska-Bizukojc et al., 2009; Romero and Ruiz, 2013; Seuring, 2004). CASs are networks of agents that emerge over time into coherent forms through interaction, without any singular entity or central control mechanism deliberately managing the overall system (Dooley, 1997; Holland, 2002, 1995). The adaptiveness of these systems depends on their ability to change over time, creating new forms of emergent order consisting of new structures and patterns. These changes are not externally imposed on the system but they are due to the self-organization of the agents, which are able to autonomously interact among each other, in order to increase their fitness with the environment (Goldstein, 1999). The existence of interconnected agents with different attributes and actions, self-organization, adaptation, emergence, nonlinearity, and path dependence are recognized as the main properties of CASs (Arthur, 1994; David, 1994; Goldstein, 1999).

Framing the ISNs as CASs means that ISNs are the result of a self-organized process, where any generic firm autonomously makes the decision to establish IS relationships with other firms (i.e., to send/receive wastes to/from other firms) without any deliberate planning performed by a central entity, aimed at increasing its economic performance and gaining competitive advantage (Ashton, 2011; Esty and Porter, 1998; Lyons, 2007; Yuan and Shi, 2009). In fact, by exchanging wastes for primary inputs, firms can enhance their production efficiency (Fraccascia et al., 2017a), which allows them to reduce waste disposal costs and input purchase costs. However, these economic benefits are eroded by additional costs stemming from IS relationships, in particular waste treatment costs, waste transportation costs, and transaction costs (Esty and Porter, 1998; Sinding, 2000). Waste treatment costs depend on the technical substitutability between wastes and inputs. In fact, in some cases, additional processes can be required to make wastes suitable to be used as inputs (Fraccascia et al., 2017a). Waste transportation costs are dependent on the geographic proximity among firms. In this regard, the literature showed that IS relationships can arise at several spatial levels and the choice of such a level is dominated by the economic logic of the firms (Jensen et al., 2011; Lyons, 2007). Hence, IS relationships may also arise among firms very far from each other as far as they are evaluated as economically convenient (Sterr and Ott, 2004). Firms have to autonomously negotiate how to share both these costs (Giannoccaro and Pontrandolfo, 2009). Furthermore, since a waste market usually does not exist, they have to arrange waste exchange prices. Finally, transaction costs arise for each firm from searching the symbiotic partner, negotiating the economic clauses for the waste exchange, and monitoring the relationship (Chertow and Ehrenfeld, 2012; Sinding, 2000).

The match between demand and supply of wastes plays an important role in supporting the establishment of an IS relationship as well as its keeping over time. In fact, the higher such a match: (1) the higher the amount of economic benefits overall created by the IS practice will be, ceteris paribus; (2) the lower the probability that these economic benefits will be unfairly shared among the involved firms, ceteris paribus (Albino et al., 2016; Fraccascia et al., 2017a; Yazan et al., 2016b). This is extremely important because firms are willing to symbiotically cooperate only if they gain enough benefits from the symbiotic practice (Jacobsen, 2006; Mirata, 2004). In this regard, we assume firms characterized by an individual propensity to establish and keep IS relationships, which specifies the extent to which the relationship should be economically beneficial (Albino et al., 2016).

Since firms are involved in an external dynamic environment, in the long-period self-organized ISNs must constantly respond to external perturbations (Ashton et al., 2017; Chopra and Khanna, 2014; Fraccascia et al., 2017b; Wang et al., 2017). In particular, the more dynamic is the environment, the more frequent the fluctuations on the amounts of both produced wastes and required inputs over time, therefore making difficult the match between demand and supply of wastes (Lou et al., 2004). The lack of such a match deteriorates the economic benefits that firms gain from the IS practice: accordingly, firms may decide to interrupt IS relationships in which they are involved if they are assessed as not enough economically convenient (Mirata, 2004). However, in deciding if keeping or interrupting IS relationships, agents are also influenced by the path dependence (Boons and Howard-Grenville et al., 2009), which is one of the main features of CASs. Path dependence theory explains how "history matters", i.e., that agents are influenced by their past experiences when taking decisions (Arthur, 1994), which is also a driver of decision-making in cooperating with potential partners in IS-based businesses.

2.2. The role of online platforms in supporting IS relationships

A wide range of the literature agrees in considering online platforms as important facilitators for the establishment of IS relationships because such platforms can reveal IS opportunities for companies, helping the formation of potential markets for secondary resources (Ashton, 2008; Ashton et al., 2017; Bellantuono et al., 2017; Boons et al., 2017; Dong et al., 2014; Lehtoranta et al., 2011; Liu et al., 2016).

By using online platforms, firms can share their demand and/or potential supply of wastes with (a number of) other users. The use of online platforms provides firms with several advantages: (1) they support the identification, in a systematic way, of all the IS relationships technically feasible for each firm (Aid et al., 2015; van Capelleveen et al., 2018); (2) they make easy and fast finding IS partners because information are shared in real time. In such a way, transaction costs stemming from searching IS partners are reduced (Kincaid and Overcash, 2001); (3) each firm can choose, among all the potential partners, the firms allowing to maximize its economic benefits; and (4) even firms not in close geographic proximity but located in larger regional areas communicate among them. In particular, larger areas provide a greater variety of potential waste producers and users, which results in: (1) higher volume of exchangeable wastes, which helps to ensure the economic profitability of IS exchanges; (2) wider diversity of wastes, which increases the number of feasible IS relationship; and (3) greater possibility to exchange the same waste with more than one partner, thus reducing the firm's vulnerability to perturbations (Fraccascia et al., 2017b; Posch et al., 2004; Sterr and Ott, 2004).

Several tools are proposed by the literature to identify the potential IS partners able to ensure the best match between the amount of produced wastes and required inputs. These tools are mainly based on input-output (quantity) matching among wastes and inputs aimed at facilitating the initial phase of IS, i.e., identification of potential IS partners (Álvarez and Ruiz-Puente, 2016; Cecelja et al., 2015; Cutaia et al., 2015; Doyle and Pearce, 2009; Trokanas and Cecelja, 2016). Several projects where online platforms have been implemented with the aim of developing IS relationships are reported in the literature. The most popular case is the National Industrial Symbiosis Programme in UK, where feasible IS relationships are suggested to firms based on the information that they had voluntarily disclosed (Jensen et al., 2011; Mirata, 2004). Other projects have been carried on in Italy (Cutaia et al., 2014), Brazil (Elabras Veiga and Magrini et al., 2009), and Jamaica (Clayton et al., 2002).

However, there are no online platforms that assist the operational phase of IS taking into account the dynamic business environment. In this regard, if companies share additional information about their geographic locations and the additional costs required to carry out the IS relationships, such platforms can assist companies in the operational phase of IS. Hence, this paper studies the impact of two types of online platform on the performance of ISNs: (1) platform sharing non-sensitive information for the IS identification and (2) platform sharing sensitive information for IS operations.

3. The agent-based model

3.1. The industrial symbiotic network model: main features

We consider a given number of firms located in a generic geographic area. The firms can belong to different unrelated industries, which are defined as "firm type". Firms are modeled by using the Enterprise Input-Output approach: accordingly, each firm is modeled as a black box that procures materials and energy (inputs), transform them into outputs, and produce wastes, destined to be disposed of in the landfill (Grubbstrom and Tang, 2000). According to previous studies (Albino and Kühtz, 2004; Fraccascia et al., 2017a,c; Kuhtz et al., 2010; Lin and Polenske, 1998; Tan et al., 2016; Yazan, 2016; Yazan et al., 2016b), we consider that each firm produces a single main product sold on the final market, whose quantity is driven by an exogenous demand from the respective market. Each firm can require more than one inputs and generate more than one waste, which amount depends on the firm's output. For the sake of simplicity, in this model only the wastes which can replace inputs are considered, as well as only the inputs that can be replaced by wastes.

Let us assume that n(A) firms of type A and n(B) firms of type B belong to the ISN, and let us assume that one of the wastes produced by each on the n(A) firms can replace one of the inputs required by each of the n(B) firms. In particular, let us consider firms i and j belonging to the type A and B, respectively. The amount of waste which can be exchanged at time t between firms i and j is described by the following equation, under the assumption that one unit of waste is able to replace $s_{A\rightarrow B}$ units of input[1]:

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[1] We assume that such a parameter depends on the available technology, and therefore it is equal for each symbiotic exchange, not depending on the specific firms exchanging wastes.

$$e_{i\to j}(t) \le min\left\{w_i(t);\ \frac{r_j(t)}{s_{A\to B}}\right\} \tag{1}$$

where the equality holds if firm *i* exchanges wastes only with firm *j* and *vice versa*. In such an equation, $w_i(t)$ is the amount of waste produced by firm *i* at time *t* and$r_j(t)$ is the amount of input required by firm *j* at time *t*. These quantities result from the following equations:

$$w_i(t) = W_A \bullet x_i(t) \tag{2}$$

$$r_j(t) = R_B \bullet x_j(t) \tag{3}$$

where $x_i(t)$ and $x_j(t)$ are the final demand of products generated at time *t* by firms *i* and *j*, respectively, W_A is the amount of waste generated by firm *i* to produce one unit of its main product, and R_B is the amount of input required by firm *j* to produce one unit of its main product.[2]

The reduction in waste disposal costs that *i* gains by exchanging wastes with *j* (RD$C_{i\to j}$) at time *t* can be computed by the following equation:

$$RDC_{i\to j}\ (t) = udc_i \bullet e_{i\to j}(t) \tag{4}$$

where udc_i is the cost to dispose one unit of waste produced by *i*. Similarly, the reduction in input purchasing costs that *j* gains by using wastes produced by *i* (RP$C_{j\to i}$) at time *t* can be computed by the following equation:

$$RPC_{j\to i}\ (t) = upc_j \bullet s_{A\to B} \bullet e_{i\to j}(t) \tag{5}$$

upc_j is the cost to purchase one unit of input required by *j*.

However, three different additional costs associated with IS transactions these economic benefits: waste transportation cost, waste treatment cost, and transaction costs of cooperation.

Transportation costs are needed to deliver the waste from the waste producer to the waste user. Let $utc_{i\to j}$ be the cost to transport one unit of waste per kilometer [€/(unit*Km)] and d_{ij} be the distance between firms *i* and *j* [Km]. The total transportation costs (t$c_{i\to j}$) at time *t* is computed by the following equation:

$$tc_{i\to j}(t) = utc_{i\to j} \bullet d_{ij} \bullet e_{i\to j}(t) \tag{6}$$

Waste treatment costs arise when the waste needs to be treated before being used as input. Let $urc_{i\to j}$ be the cost to treat one unit of waste [€/unit]. The total treatment costs ($rc_{i\to j}$) at time *t* is computed by the following equation:

$$rc_{i\to j}(t) = urc_{i\to j} \bullet e_{i\to j}(t) \tag{7}$$

Finally, transaction costs arise in the form of search costs (*sc*), negotiation costs (*nc*), and enforcement costs (*ec*) (Chertow and Ehrenfeld, 2012). Let $cc_{i\to j}(t)$ ($cc_{j\to i}(t)$) be the overall transaction costs for firm *i* (*j*) due to the cooperation with firm *j* (*i*) at time *t* (Fig. 1). Since these costs do not depend on the amount of exchanged wastes, following Yazan et al., 2016a) we model the transaction costs for firm *i* (*j*) as a percentage *P* of total waste disposal (input purchase) costs payed by the firm:

$$cc_{i\to j}(t) = sc_{i\to j}(t) + nc_{i\to j}(t) + ec_{i\to j}(t) = P \bullet udc_i \bullet w_i(t) \tag{8}$$

$$cc_{j\to i}(t) = sc_{j\to i}(t) + nc_{j\to i}(t) + ec_{j\to i}(t) = P \bullet upc_j \bullet r_j(t) \tag{9}$$

Fig. 1 shows physical and monetary flows from, to, and between firms i and j

Five different contractual clauses can be associated with the waste exchange between *i* and *j,* ruling the cost sharing between firms. We model this contract by means the parameter $\alpha_{i\to j}$, which denotes the percentage of waste transportation and treatment costs payed by firm *i* (Table 1).

This contract can generate monetary flows between firms *i* and *j* (Fig. 2). Dotted lines in Fig. 2 show monetary flows from and to each firm: green lines denote ceasing costs (reduction in waste disposal and input purchasing costs) whereas red lines denote additional costs. Moreover, black lines denote monetary flows between firms (when a firm pays the other). The equations describing such flows are reported in Table 2.

3.2. The fitness function

A fitness function $F_{i\to j}(t)$ ($F_{j\to i}(t)$) is defined that measures the willingness of firm *i* (*j*) to symbiotically cooperate with firm *j* (*i*). Such a willingness depends on two factors: the net economic benefit achievable by the IS relationship and the path dependence.

The net economic benefit (NEB) that firm *i* (*j*) would achieve in case of IS cooperation with firm *j* (*i*) at time *t* can be computed as follows:

$$NEB_{i\to j}(t) = RDC_{i\to j}(t) - \alpha_{i\to j}(t) \bullet [utc_{i\to j}(t) \bullet d_{ij} + urc_{i\to j}(t)] \bullet e_{i\to j}(t) - cc_{i\to j}(t) \tag{10}$$

$$NEB_{j\to i}(t) = RPC_{j\to i}(t) - [1 - \alpha_{i\to j}(t)] \bullet [utc_{i\to j}(t) \bullet d_{ij} + urc_{i\to j}(t)] \bullet e_{i\to j}(t) - cc_{j\to i}(t) \tag{11}$$

The higher this benefit, the higher its availability to be involved in the IS will be, ceteris paribus. Furthermore, path dependence is introduced into the fitness function by assuming that the longer the time firms *i* and *j* are involved in an effective resource exchange, the lower the importance of the economic benefit gained at time *t* to motivate them to keep the IS relationship (Albino et al., 2016; Fraccascia et al., 2017c).

The fitness functions computed for agents *i* and *j* at period *t* are defined by the following equations:

$$F_{i\to j}(t) = \frac{1}{L_{i\to j}(t) + 1} \bullet NEB_{i\to j}(t) + \left[1 - \frac{1}{L_{i\to j}(t) + 1}\right] \bullet F_{i\to j}(t-1) \tag{12}$$

$$F_{j\to i}(t) = \frac{1}{L_{i\to j}(t) + 1} \bullet NEB_{j\to i}(t) + \left[1 - \frac{1}{L_{i\to j}(t) + 1}\right] \bullet F_{j\to i}(t-1) \tag{13}$$

where $L_{i\to j}(t)$ is defined as the number of sequential time periods firms *i* and *j* are involved in an effective resource exchange. Accordingly, $L_{i\to j}(t)$ is equal to zero if agents *i* and *j* did not cooperate at time (*t*-1). If at time *t*, agents *i* and *j* are continuously cooperating for *n* time periods (i.e., the cooperation started at time *t-n*), it results $L_{i\to j}(t) = n$.

We assume that firm *i* (*j*) agrees to cooperate with firm *j* (*i*) only if the fitness value associated with the symbiotic relationship is higher than or equal to a given threshold value $T_i(T_j)$. Such a threshold models the firms' propensity to implement the symbiotic approach: the higher the threshold value, the higher the amount of economic benefits necessary to motivate firms to cooperate will be.

3.3. The agent-based model dynamics

Each firm can accomplish the following actions: (1) seeking a new IS partner with which trying to establish an IS relationship; (2) creating a new IS relationship; (3) evaluating an existing IS relationship, deciding if keeping or interrupting it. These actions are presented in the following sections.

3.3.1. Seeking a new IS partner

A generic firm *i* (*j*) can seek a new IS partner: (1) at the start of the simulation ($t = 1$); (2) at generic time *t*, when the IS relationship in which it was previously involved has been interrupted at time *t*-1. Actually, this process is affected by how firms can share information among them. As stated in the introduction, three different scenarios are considered: (1) no information platform; (2) platform sharing non-sensitive information; (3) platform sharing sensitive information. These

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[2] W_A and R_B depend on the production technology, which is the same for each of the n (A) firms and for each of the n(B) firms, respectively.

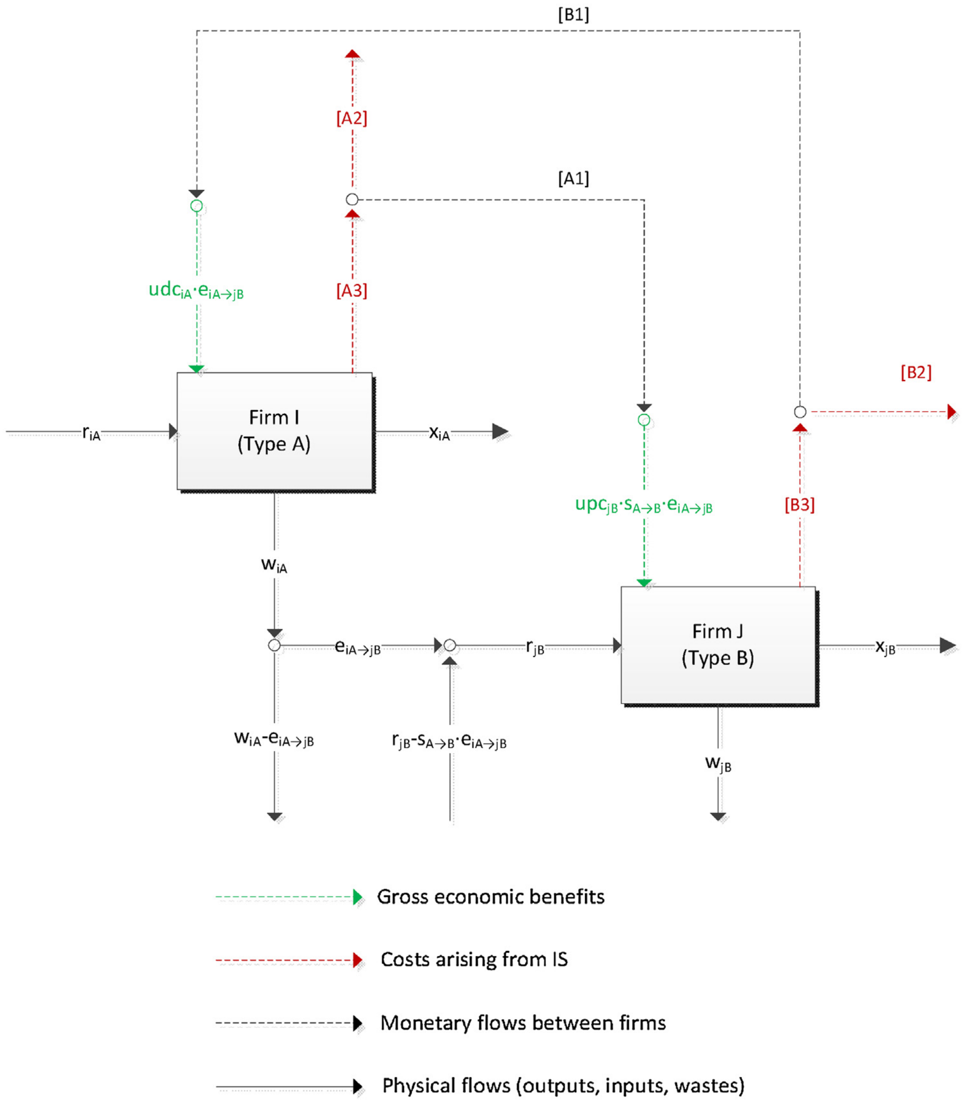

Fig. 1. Physical and monetary flows from, to, and between two firms exchanging wastes (from Fraccascia, 2017).

Table 1
Different contractual clauses that firm can use in exchanging wastes.

Case	Costs sharing	Monetary flows between firms
$0 < \alpha_{i\to j} < 1$	Costs arising from IS are shared among firms	The waste exchange[a] is for free
$\alpha_{i\to j} = 1$	Firm *i* pays all the costs arising from IS	The waste exchange is for free
$\alpha_{i\to j} > 1$	Firm *i* pays all the costs arising from IS	Firm *i* pays firm *j* to dispose of its waste
$\alpha_{i\to j} = 0$	Firm *j* pays all the costs arising from IS	The waste exchange is for free
$\alpha_{i\to j} < 0$	Firm *j* pays all the costs arising from IS	Firm *j* pays firm *i* to purchase its waste

[a] Here, we refer to firm *i* that is sending wastes to firm *j*.

cases are analyzed below.

3.3.1.1. No platform. All the n(B) (n(A)) firms of type B (A) can be potential partners. About these possible partners, firm *i* (*j*) has no information concerning neither the amount of required (produced) wastes nor its availability of establishing an IS relationship, i.e., if it is currently involved in another symbiotic relationship or not. Hence, each firm randomly chooses the partner *k* with which trying to establish an IS relationship. If firm *k* is currently involved in an IS relationship with another firm, firm *i* (*j*) remains unlinked at time *t* and will repeat such a procedure at time *t* + 1. Alternatively, if firm *k* is not currently involved in an IS relationship with another firm, firms *i* (*j*) and *k* try to establish an IS relationship by following the rules described in Section 3.3.2. In both cases, firm *i* (*j*) pays search costs.

3.3.1.2. Platform sharing non-sensitive information. An online platform shares among firms the following information: (1) the amount of produced and required wastes for each firm; (2) the firm's current status, i.e., if it is currently available to start an IS relationship or it is yet involved in an IS exchange. In such a case, firm *i* (*j*) chooses as a symbiotic partner, among all the available firms, the firm allowing it to maximize the match between demand and supply of wastes. We assume that search costs are saved by the firm thanks to using the platform.

3.3.1.3. Platform sharing sensitive information. In addition to the information mentioned above, in such a case each firm is required to upload economic information concerning waste disposal costs, input purchasing costs, and additional costs to treat the produced waste. The platform suggests to each firm the partner allowing to maximize the economic benefits from the symbiotic relationship. Also in this case, we assume that search costs are saved by the firm thanks to using the

Table 2
Equations for monetary flows among firms.

Code	Description	Firm *i*
[A1]	Flows to the firm *j*	$[\max\{0, \alpha_{iA\to jB}(t)\}-\max\{0, \min[\alpha_{iA\to jB}(t), 1]\}]\bullet[utc_{iA\to jB}(t)\bullet d_{ij} + urc_{iA\to jB}(t)]\bullet e_{iA\to jB}$
[A2]	Flows to the external environment	$\max\{0, \min[\alpha_{iA\to jB}(t), 1]\}\bullet[utc_{iA\to jB}(t)\bullet d_{ij} + urc_{iA\to jB}(t)]\bullet e_{iA\to jB} + cc_{iA\to jB}(t)$
[A3]	Total monetary flows	$\max\{0, \alpha_{iA\to jB}(t)\}\bullet[utc_{iA\to jB}(t)\bullet d_{ij} + urc_{iA\to jB}(t)]\bullet e_{iA\to jB} + cc_{iA\to jB}(t)$

Code	Description	Firm *j*
[B1]	Flows to the firm *i*	$[\max\{0,1-\alpha_{iA\to jB}(t)\}-\max\{0, \min[1-\alpha_{iA\to jB}(t), 1]\}]\bullet[utc_{iA\to jB}(t)\bullet d_{ij} + urc_{iA\to jB}(t)]\bullet e_{iA\to jB}$
[B2]	Flows to the external environment	$\max\{0, \min[1-\alpha_{iA\to jB}(t), 1]\}\bullet[utc_{iA\to jB}(t)\bullet d_{ij} + urc_{iA\to jB}(t)]\bullet e_{iA\to jB} + cc_{jB\to iA}(t)$
[B3]	Total monetary flows	$\max\{0,1-\alpha_{iA\to jB}(t)\}\bullet[utc_{iA\to jB}(t)\bullet d_{ij} + urc_{iA\to jB}(t)]\bullet e_{iA\to jB} + cc_{jB\to iA}(t)$

platform.

3.3.2. Creating new IS relationship

Let us consider firms *i* and *j* that were not cooperating at time *t*-1. When they try to establish an IS relationship at time *t*, they compute their fitness values (Eqs. (12) and (13)), where $\alpha_{i\to j}(t)$ is randomly assigned (Table 1). If $F_{i\to j}(t) \geq T_i$ and $F_{j\to i}(t) \geq T_j$ simultaneously, the relationship between *i* and *j* arises. Otherwise, if results that $F_{i\to j}(t) < T_i$ and $F_{j\to i}(t) < T_j$ simultaneously, the relationship does not arise. Finally, if $F_{i\to j}(t) < T_i(F_{j\to i}(t) < T_j)$, firm *i* (*j*) tries to increase its fitness by renegotiating the current cost-sharing policy. In particular, firm *i* (*j*) computes the value of alpha so that its new fitness $F'_{i\to j}(t)(F'_{j\to i}(t))$ would be at least equal to the threshold $T_i(T_j)$. However, such a renegotiating process is affected by bargaining power (BP) of firms. According to Yazan et al. (2012), BP is representative for the dependency of a given firm on its partner. It is defined and measured by the contribution of each firm to the economic benefits of its partner. For the symbiotic relationship between firms *i* and *j*, BP is computed by the following equations:

$$BP_{i\to j}(t) = NEB_{j\to i}(t) \tag{14}$$

$$BP_{j\to i}(t) = NEB_{i\to j}(t) \tag{15}$$

The new cost-sharing policy is proposed to firm *j* (*i*) only if firm *i* (*j*) has enough bargaining power, i.e., if $BP_{i\to j}(t) > BP_{j\to i}(t)$ ($BP_{j\to i}(t) > BP_{i\to j}(t)$). Hence, if $F'_{j\to i}(t) \geq T_j$ ($F'_{i\to j}(t) \geq T_i$), firm *j* (*i*) evaluates the new cost sharing policy as a convenient one for itself and the IS relationship between *i* and *j* arises, otherwise the IS relationship does not arise. In the case that firm *i* (*j*) has not enough bargaining power to renegotiate the cost-sharing policy, the IS relationship does not arise. In all cases, the involved firms pay negotiation costs.

3.3.3. Evaluating an existing IS relationship

Let us consider firms *i* and *j* that were cooperating at time *t*-1. At time *t*, they compute their fitness values (Eqs. (12) and (13)), where $\alpha_{i\to j}(t) = \alpha_{i\to j}(t-1)$. If $F_{i\to j}(t) \geq T_i$ and $F_{j\to i}(t) \geq T_j$ simultaneously, the relationship between *i* and *j* is kept. Otherwise, if it results that $F_{i\to j}(t) < T_i$ and $F_{j\to i}(t) < T_j$ simultaneously, the relationship is interrupted. Finally, if $F_{i\to j}(t) < T_i(F_{j\to i}(t) < T_j)$, firm *i* (*j*) tries to increase its fitness by renegotiating the current cost-sharing policy, following the rule presented in previous section. Hence, both firms compute their new fitness value: if $F'_{j\to i}(t) \geq T_j$ ($F'_{i\to j}(t) \geq T_i$), firm *j* (*i*) evaluates the new cost sharing policy as a convenient one for itself and the IS relationship between *i* and *j* is kept, otherwise it is interrupted. In the case that firm *i* (*j*) has not enough bargaining power to renegotiate the cost-sharing policy, the IS relationship is interrupted. In all cases, the involved firms pay monitoring end enforcement costs.

4. Case example

4.1. Main features

To run simulations, we use data referring to a potential ISN made by four kinds of firms: marble producers, concrete producers, alcohol producers, and fertilizer producers. Marble residuals from marble producers are usually not treated but discharged to municipal incinerators or disposed of in the landfill, causing high discharge costs and environmental impacts. However, marble residuals could be used by concrete producers as an alternative aggregate in concrete production, after receiving a treatment process (Yazan et al., 2010). Furthermore, an effective case of IS discussed in the literature is the use of alcohol slops, generated as waste by alcohol producers, as input for fertilizer production processes (Yang and Feng, 2008; Zhu et al., 2008). We consider 50 marble producers, 50 concrete producers, 50 alcohol producers, and 50 fertilizer producers randomly spread in a square geographic area with 50 Km side (Euclidean distances among firms are considered). Each firm observes a stochastic final customer demand over time for its main product, distributed according to a normal distribution with mean μ and standard deviation σ. Numerical data on the average main product demand, raw material requirements, waste produced, marble residuals disposal cost, aggregate purchasing cost, waste transportation cost, and waste treatment cost, obtained from cases studied, are shown in Table 3.

At the beginning of the simulation, each marble producer tries to establish symbiotic relationships with concrete producers, as well as each alcohol producer tries to establish symbiotic relationships with fertilizer producers. For each established relationship, a formal agreement is created, valid for 3 months (time period). Every three months, firms interact with each other, following behavioral rules presented in Section 3.3.

4.2. Simulated scenarios

As stated in the Introduction, we simulated the case example for three settings: (1) no information platform; (2) platform sharing non-sensitive information; (3) platform sharing sensitive information.

For all these strategies, the simulation scenarios are defined by varying the waste market dynamicity and weight of transaction costs on the economic benefits generated. The market dynamicity is modeled through the standard deviation σ of the final customer demand μ compared to the mean value (σ/μ): the higher such a ratio, the higher the dynamicity will be. The weight of transaction costs is modeled by varying P in Eqs. (8) and (9). The higher the P, the higher the weight of transaction costs will be. Both these parameters are recognized by the literature playing a negative role on the emergence of ISNs. We simulate four values of waste market dynamicity and five values of transaction costs.

Summarizing, the simulation plan consists of 20 scenarios (4 × 5)

Table 3
Numerical data on main products demand, raw material requirements, wastes produced, waste disposal costs, input purchase costs, waste transportation and treatment costs.

	Marble producers	Concrete producers	Alcohol producers	Fertilizer producers
Main product demand (x)	4000 m^2/year	9800 t/year	10000 t/year	20,000 t/year
Waste produced (w_A)	13,252 t marble/year $\left(W = 3.313 \frac{\text{t marble residuals}}{\text{m2 marble}}\right)$	–	8000 t alcohol slops/year $\left(W = 0.8 \frac{\text{t alcohol slops}}{\text{t alcohol}}\right)$	
Input required (r_B)	–	13,252 t concrete/year $\left(R = 1.35 \frac{\text{t aggregate}}{\text{t concrete}}\right)$		8000 t alcohol slops/year $\left(R = 0.4 \frac{\text{t alcohol slops}}{\text{t fertilizer}}\right)$
Waste disposal cost	$6 \frac{€}{\text{t marble residuals}}$	–	$30 \frac{€}{\text{t alcohol slops}}$	–
Input purchase cost	–	$66 \frac{€}{\text{t aggregate}}$	–	$70 \frac{€}{\text{t alcohol slops}}$
Waste transportation cost	$5 \frac{€}{\text{t marble residuals} \bullet \text{Km}}$		$5 \frac{€}{\text{t alcohol slops} \bullet \text{Km}}$	
Waste treatment cost	$0.66 \frac{€}{\text{t marble residuals}}$		$0 \frac{€}{\text{t alcohol slops} \bullet}$	

Table 4
Values of market dynamicity and transaction costs for simulated scenarios.

Variable	Modelling variable	Values
Market dynamicity (MD)	Standard deviation of the main product demand	σ/μ = 0.1, 0.2, 0.3, 0.4
Transaction costs (TC)	Percentage of transaction cost over waste disposal cost or input purchase cost	P = 0, 0.025, 0.05, 0.075, 0.1

(Table 4). We simulate each scenario for a simulation run of 40 time periods (corresponding to 10 years) and replicate 1000 times to give statistical significance to the results. Moreover, for each scenario, we assume that $T_i = T_j = 0.1 \bullet \text{production costs} \ \forall \ i, \ j$, and one unit of waste is able to replace one unit of the respective input.

4.3. Performance measures

We adopted two indicators to assess the economic and environmental performance of the ISN.

The economic performance indicator (ECO_P) is computed as the ratio between the economic benefits created by the IS approach (ECO_B) and the production costs of the involved firms (PC) during all the simulation time:

$$ECOP = \frac{\sum_t ECOB(t)}{\sum_t PC(t)} \tag{16}$$

where

$$ECOB(t) = \sum_i \sum_j \{[udc_i(t) + upc_j(t) \bullet s_{A \to B} - utc_{i \to j}(t) \bullet d_{ij} - urc_{i \to j}(t)] \bullet e_{i \to j}(t) - [cc_{i \to j}(t) + cc_{j \to i}(t)]\} \tag{17}$$

$$PC(t) = \sum_i udc_i(t) \bullet w_i(t) + \sum_j upc_j(t) \bullet r_j(t) \tag{18}$$

ECO_P ranges between 0 and 1 and refers to the percentage reduction in production costs thanks to IS. For instance, ECO_P = 0.6 means that IS has reduced the 60% of the production costs for firms within the ISN. The higher the percentage of production costs reduced by IS, the greater the economic sustainability will be, ceteris paribus.

The environmental performance measure (ENV_P) is computed as the ratio between the total amount of wastes not disposed of in the landfill and primary inputs saved and the total amount of produced wastes and required primary inputs during all the simulation time:

$$ENVP = \frac{\sum_{t=1}^{40} \left[2 \sum_{i=1}^{50} \sum_{j=1}^{50} e_{i \to j}(t)\right]}{\sum_{t=1}^{40} \left[\sum_{i=1}^{50} w_i(t) + \sum_{j=1}^{50} r_j(t)\right]} \tag{19}$$

ENV_P ranges between 0 and 1 and refers to the reduction in

Table 5
Economic performance (ECO_P) for marble-based IS exchanges.

			WASTE-MARKET DYNAMICITY				COMPARED WITH NO PLATFORM CASE WASTE-MARKET DYNAMICITY				COMPARED WITH NON SENSITIVE PLATFORM CASE WASTE-MARKET DYNAMICITY			
			0.1	**0.2**	**0.3**	**0.4**	**0.1**	**0.2**	**0.3**	**0.4**	**0.1**	**0.2**	**0.3**	**0.4**
NO PLATFORM	**TRANSACTION COSTS**	**0**	0.2389	0.2251	0.2107	0.1849								
		0.025	0.2305	0.2168	0.2001	0.1719								
		0.05	0.2195	0.2068	0.1898	0.1602								
		0.075	0.2115	0.1947	0.1773	0.1471								
		0.1	0.1997	0.1834	0.1665	0.1333								
NON-SENSITIVE PLATFORM	**TRANSACTION COSTS**	**0**	0.2874	0.2723	0.2561	0.2339	*20.13%*	*20.77%*	*21.34%*	*26.21%*				
		0.025	0.2834	0.2664	0.2482	0.2253	*22.93%*	*22.69%*	*23.99%*	*30.99%*				
		0.05	0.2773	0.2564	0.2399	0.2130	*26.00%*	*23.95%*	*26.32%*	*32.81%*				
		0.075	0.2688	0.2501	0.2321	0.2045	*27.14%*	*28.30%*	*30.85%*	*38.88%*				
		0.1	0.2614	0.2412	0.2198	0.1907	*30.69%*	*31.35%*	*31.82%*	*42.41%*				
SENSITIVE-PLATFORM	**TRANSACTION COSTS**	**0**	0.4938	0.4647	0.4324	0.3586	*106.70%*	*106.42%*	*105.21%*	*93.98%*	*72.06%*	*70.92%*	*69.12%*	*53.69%*
		0.025	0.4853	0.4562	0.4229	0.3452	*110.50%*	*110.38%*	*111.40%*	*100.80%*	*71.23%*	*71.48%*	*70.50%*	*53.29%*
		0.05	0.4766	0.4463	0.4132	0.3312	*117.10%*	*115.81%*	*117.69%*	*106.80%*	*72.30%*	*74.11%*	*72.33%*	*55.71%*
		0.075	0.4664	0.4367	0.4022	0.3176	*120.50%*	*124.34%*	*126.77%*	*115.87%*	*73.43%*	*74.86%*	*73.30%*	*55.44%*
		0.1	0.4570	0.4272	0.3898	0.3034	*128.86%*	*132.96%*	*134.09%*	*127.65%*	*75.12%*	*77.36%*	*77.59%*	*59.85%*

Table 6
Economic performance (ECO_P) for alcohol slops-based IS exchanges.

			WASTE-MARKET DYNAMICITY				*COMPARED WITH NO PLATFORM CASE* WASTE-MARKET DYNAMICITY				*COMPARED WITH NON SENSITIVE PLATFORM CASE* WASTE-MARKET DYNAMICITY			
			0.1	0.2	0.3	0.4	0.1	0.2	0.3	0.4	0.1	0.2	0.3	0.4
NO PLATFORM	TRANSACTION COSTS	0	0.3290	0.3140	0.2953	0.2612								
		0.025	0.3256	0.3095	0.2909	0.2535								
		0.05	0.3203	0.3035	0.2839	0.2465								
		0.075	0.3151	0.2987	0.2777	0.2376								
		0.1	0.3112	0.2913	0.2705	0.2272								
NON-SENSITIVE PLATFORM	TRANSACTION COSTS	0	0.3614	0.3410	0.3241	0.3016	*9.83%*	*8.61%*	*9.75%*	*15.46%*				
		0.025	0.3579	0.3400	0.3202	0.2967	*9.91%*	*9.86%*	*10.09%*	*17.04%*				
		0.05	0.3565	0.3377	0.3160	0.2909	*11.31%*	*11.26%*	*11.34%*	*18.02%*				
		0.075	0.3526	0.3316	0.3104	0.2852	*11.88%*	*11.01%*	*11.79%*	*20.05%*				
		0.1	0.3487	0.3287	0.3060	0.2784	*12.05%*	*12.85%*	*13.13%*	*22.52%*				
SENSITIVE-PLATFORM	TRANSACTION COSTS	0	0.5842	0.5503	0.5140	0.4457	*61.67%*	*61.35%*	*58.56%*	*47.81%*	*77.56%*	*75.24%*	*74.02%*	*70.67%*
		0.025	0.5758	0.5416	0.5050	0.4360	*60.88%*	*59.31%*	*57.71%*	*46.93%*	*76.83%*	*75.01%*	*73.62%*	*71.97%*
		0.05	0.5666	0.5324	0.4952	0.4221	*58.92%*	*57.63%*	*56.70%*	*45.11%*	*76.89%*	*75.39%*	*74.46%*	*71.27%*
		0.075	0.5574	0.5235	0.4863	0.4091	*58.08%*	*57.89%*	*56.66%*	*43.43%*	*76.86%*	*75.27%*	*75.12%*	*72.19%*
		0.1	0.5487	0.5137	0.4755	0.3971	*57.35%*	*56.28%*	*55.39%*	*42.64%*	*76.31%*	*76.35%*	*75.79%*	*74.77%*

Table 7
Environmental performance (ENV_P) for marble-based IS exchanges.

			WASTE-MARKET DYNAMICITY				*COMPARED WITH NO PLATFORM CASE* WASTE-MARKET DYNAMICITY				*COMPARED WITH NON SENSITIVE PLATFORM CASE* WASTE-MARKET DYNAMICITY			
			0.1	0.2	0.3	0.4	0.1	0.2	0.3	0.4	0.1	0.2	0.3	0.4
NO PLATFORM	TRANSACTION COSTS	0	0.5250	0.489	0.4516	0.3926								
		0.025	0.5142	0.4778	0.4386	0.3771								
		0.05	0.5002	0.4658	0.4261	0.3657								
		0.075	0.4899	0.4525	0.4121	0.3528								
		0.1	0.4768	0.4404	0.3997	0.3394								
NON-SENSITIVE PLATFORM	TRANSACTION COSTS	0	0.6718	0.6271	0.5834	0.526	*27.84%*	*27.94%*	*29.05%*	*33.76%*				
		0.025	0.6593	0.6156	0.5696	0.5134	*28.14%*	*28.67%*	*29.72%*	*36.06%*				
		0.05	0.6467	0.5994	0.5562	0.4957	*29.09%*	*28.61%*	*30.38%*	*35.45%*				
		0.075	0.6279	0.5851	0.5427	0.4830	*28.09%*	*29.09%*	*31.64%*	*36.76%*				
		0.1	0.6132	0.5689	0.5219	0.4638	*28.50%*	*28.89%*	*30.38%*	*36.23%*				
SENSITIVE-PLATFORM	TRANSACTION COSTS	0	0.7822	0.7339	0.6793	0.5606	*48.99%*	*50.07%*	*50.42%*	*42.78%*	*16.55%*	*17.29%*	*16.56%*	*6.75%*
		0.025	0.7764	0.7271	0.6709	0.5474	*51.00%*	*52.17%*	*52.96%*	*45.18%*	*17.84%*	*18.27%*	*17.92%*	*6.70%*
		0.05	0.7690	0.7182	0.6629	0.5343	*53.75%*	*54.19%*	*55.59%*	*46.12%*	*19.10%*	*19.89%*	*19.34%*	*7.88%*
		0.075	0.7588	0.7096	0.6515	0.5199	*54.88%*	*56.83%*	*58.09%*	*47.38%*	*20.92%*	*21.49%*	*20.09%*	*7.76%*
		0.1	0.7503	0.7004	0.6396	0.5065	*57.37%*	*59.04%*	*60.00%*	*49.22%*	*22.47%*	*23.39%*	*22.71%*	*9.54%*

material flows from and to the ISN compared to the case of no symbiotic relationships. For instance, ENV_P = 0.4 means that IS is reducing waste flows from the ISN and input flows to the ISN by 40% compared to the case of no symbiosis. The higher the percentage of material flows reduced by IS, the greater the environmental sustainability will be, ceteris paribus.

Each of these indicators is separately computed for marble-based exchanges and alcohol slops-based exchanges, in order to discuss the effect of the platforms on different kinds of symbiotic exchanges.

5. Results

In this section, simulation results for all scenarios are presented. The economic and environmental performance of marble-based IS exchanges are shown in Tables 5 and 7, respectively. The economic and environmental performance of alcohol slops-based IS exchanges are shown in Tables 6 and 8, respectively. Furthermore, Fig. 2 graphically highlights the average impact, computed on all the simulated scenarios, of the investigated platforms.

First, let us consider the case where no platform is adopted. Depending on the considered scenario, ECO_P (ENV_P) ranges between 0.1333 and 0.2389 (0.3394 and 0.5250) for marble-based IS exchanges and between 0.2272 and 0.3290 (0.4820 and 0.6959) for alcohol slops-based IS exchanges. Notice the negative effect of MD and TC on both the economic and environmental performance, ceteris paribus. In fact, when MD rises from 0.1 to 0.4, ECO_P (ENV_P) decreases between 22.60% and 33.25% (25.21% and 28.81%) for marble-based exchanges and between 20.62% and 26.98% (24.08% and 27.08%) for alcohol slops-based IS exchanges. Moreover, when TC rises from 0 to 0.1, ECO_P (ENV_P) decreases between 16.42% and 27.91% (9.19% and 13.55%) for marble-based exchanges and between 1.78% and 3.93% (5.02% and 8.76%) for alcohol slops-based IS exchanges. Hence, these results validate our simulation model, which indeed is able to reproduce the empirical observations and the dynamics identified in the literature.

Let us consider the adoption of a non-sensitive platform. Since such a platform is supposed to enhance the match between demand and supply of wastes, the environmental sustainability is expected to be higher compared to the previous case. Results confirm such an expectation: on average, ENV_P rises by 31.51% (between 27.84% and 36.76%, depending on the scenario) for marble-based exchanges and by 12.57% (between 8.61% and 22.52%, depending on the scenario) for alcohol slops-based exchanges. Also ECO_P is observed to be higher than the previous case: on average, it rises by 27.98% (between 20.77%

Table 8
Environmental performance (ENV_P) for alcohol slops-based IS exchanges.

							COMPARED WITH NO PLATFORM CASE				*COMPARED WITH NON SENSITIVE PLATFORM CASE*			
			WASTE-MARKET DYNAMICITY				**WASTE-MARKET DYNAMICITY**				**WASTE-MARKET DYNAMICITY**			
			0.1	**0.2**	**0.3**	**0.4**	**0.1**	**0.2**	**0.3**	**0.4**	**0.1**	**0.2**	**0.3**	**0.4**
NO PLATFORM	**TRANSACTION COSTS**	**0**	0.6959	0.6537	0.6063	0.5283								
		0.025	0.6860	0.6454	0.5960	0.5172								
		0.05	0.6771	0.6336	0.5853	0.5073								
		0.075	0.6694	0.6243	0.5749	0.4946								
		0.1	0.6609	0.6145	0.5629	0.4820								
NON-SENSITIVE PLATFORM	**TRANSACTION COSTS**	**0**	0.7901	0.7432	0.6953	0.6421	*13.55%*	*13.70%*	*14.69%*	*21.55%*				
		0.025	0.7831	0.7345	0.6876	0.6351	*14.14%*	*13.81%*	*15.38%*	*22.81%*				
		0.05	0.7732	0.7281	0.6790	0.6263	*14.20%*	*14.92%*	*16.00%*	*23.47%*				
		0.075	0.7642	0.7171	0.6666	0.6140	*14.16%*	*14.86%*	*15.94%*	*24.13%*				
		0.1	0.7509	0.7093	0.6589	0.6024	*13.62%*	*15.42%*	*17.05%*	*24.99%*				
SENSITIVE-PLATFORM	**TRANSACTION COSTS**	**0**	0.8414	0.7911	0.7383	0.6501	*6.49%*	*6.44%*	*6.18%*	*1.25%*	*20.92%*	*21.02%*	*21.78%*	*23.07%*
		0.025	0.8377	0.7860	0.7325	0.6414	*6.98%*	*7.00%*	*6.53%*	*0.99%*	*22.11%*	*21.77%*	*22.92%*	*24.02%*
		0.05	0.8316	0.7803	0.7267	0.6285	*7.55%*	*7.17%*	*7.02%*	*0.35%*	*22.82%*	*23.16%*	*24.14%*	*23.90%*
		0.075	0.8255	0.7754	0.7209	0.6152	*8.03%*	*8.13%*	*8.15%*	*0.20%*	*23.32%*	*24.20%*	*25.39%*	*24.38%*
		0.1	0.8192	0.7673	0.7118	0.6047	*9.09%*	*8.19%*	*8.04%*	*0.38%*	*23.95%*	*24.87%*	*26.46%*	*25.46%*

and 42.41%, depending on the scenario) for marble-based exchanges and by 16.53% (between 13.55% and 24.99%, depending on the scenario) for alcohol slops-based exchanges. Such an increase is mainly due to the lower amount of wastes disposed of in the landfill and inputs not purchased from outside, which reduce the firms' production costs. For both the performance measures, we can note that the positive effect of the platform is much higher the greater the MD and the TC are, ceteris paribus. In fact, this kind of platform allows to reduce the negative role that the environmental dynamicity plays on the match between demand and supply of wastes, ceteris paribus.

Let us consider the adoption of a sensitive platform. The positive effect of such a platform compared to the absence of a platform is evident: on average, ECO_P rises by 115.07% (between 93.98% and 134.09%, depending on the scenario) for marble-based exchanges and by 74.94% (between 70.67% and 77.56%, depending on the scenario) for alcohol slops-based exchanges. ENV_P rises on average by 52.46% (between 42.78% and 60%, depending on the scenario) for marble-based exchanges and by 23.39% (between 20.92% and 26.46%, depending on the scenario) for alcohol slops-based exchanges. These results are better compared to the adoption of a non-sensitive platform. In fact, in addition to providing a better match between demand and supply of wastes, the sensitive-platform computes the additional costs for operating IS such as waste treatment and transportation costs and it is therefore able to recommend an IS partner that minimizes such costs. As a result, since the costs stemming from IS exchanges are reduced the willingness to cooperate of firms increases.

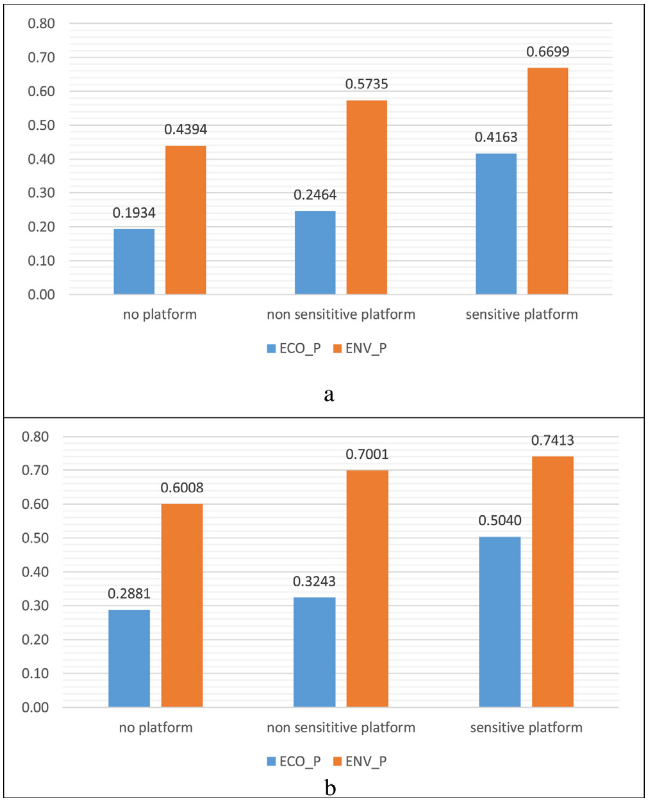

Fig. 2. Average values of economic and environmental performance for marble-based (a) and alcohol slops-based (b) exchanges computed on all the scenarios.

6. Discussion

Findings show that sharing information via online platforms increases economic and environmental performance of the ISN. It is observed that sharing non-sensitive information regarding geographic locations and quantities has less positive impact than sharing sensitive information about costs in both performance measures. Findings are strongly influenced by the operational conditions of IS, shaped by transaction costs (TC) and waste market dynamicity (MD) embedded in the proposed Agent-based Model (ABM).

In fact, the ABM proposed in this paper helps companies not only to evaluate the static impact of information-sharing but also to assess the economic and environmental benefits shaped by dynamic conditions. Hence, the ABM serves also as a decision-support tool for companies to evaluate an existing IS relationship, to interrupt an existing IS and seek for a new partner and to create a new IS-based business. This is in line with high dynamic character of ISNs. Furthermore, in case an IS relationship is interrupted, firms have higher possibilities to easily and quickly find a new symbiotic partner by adopting an online platform, thereby reducing transaction costs related to searching the new partner. Generally, ISNs are observed to arise and be sustainable over the long period in low-dynamic environments. In this regard, our results are interesting because they show that the adoption of an online information-sharing platform may allow ISNs to have good performance even in more dynamic environments.

This paper takes further several studies (Ashton, 2011; Esty and Porter, 1998; Lyons, 2007; Yuan and Shi, 2009) in the domain of IS by showing the utility of additional information-sharing on improving the performance of ISNs. Furthermore, it specifies the typology of information facilitating better match-making in terms of economic performance. Differently from above-mentioned papers approaching ISNs as self-emergent networks, the model presented in this paper can attribute to the information-sharing platform the role of 'facilitator' as well as the role of 'single managing entity' in case the platform is largely recognized by multiple companies as a performance optimizer.

In addition, although several studies address the economic performance dominant approach of companies in IS (Jensen et al., 2011; Lyons, 2007), the use of operational parameters influencing the economic performance in network modeling is limited. Indeed, parameters influencing supply-demand mismatch (e.g. quantity), transportation costs (e.g., geographic locations of firms), and potential cost savings (e.g., discharge cost, primary input purchasing cost) are specifically included in the ABM under three different scenarios so that the utility of each information is emphasized comparatively. This is both a theoretical and modeling contribution of this paper.

Specifically in the ISN case presented in this paper, companies are suggested to share information to reach better economic and environmental performance. However, IS-based businesses are case- and site-specific. Therefore, some IS-based businesses might not be economically profitable because of operational conditions or the risk of high-level perturbations. However, this does not influence the replicability of our findings on the positive contribution of information-sharing in implementing IS.

In the context of information disclosure, there are several factors influencing the data revelation to potential IS partners. These factors can be specifically related to the market conditions of the sectors in which companies operate, strategy-making process of company managers, concerns about the reactions of traditional business partners to IS, dynamicity level of the potential IS-business, or to the reasoning of decision-makers based on the tacit knowledge they have about their competitors. However, by nature of IS, companies which have potential to implement IS are traditionally non-engaged and possibly located in different sectors which do not directly compete for the same markets. Companies should be aware of the fact that potential IS partners are 'friends' and look for win-win solutions. In this sense, information-sharing is useful to reduce uncertainties and implement a trustful business.

However, for a vast range of reasons, companies might find information-sharing risky. In fact, in the scenario implementation of the ISN presented in this paper, both waste producers and waste receivers provide the data to the platform. Therefore, they do not reveal their data to each other but to the platform, which makes automatic computations for the best cooperation strategies. Thus, if companies consider a type of data to be sensitive and not to be shared with others, then they can only provide the data input to the platform and make computations. Indeed, the online platform investigated in this paper has the role of 'facilitator' for IS. In order for the facilitator to gather information to match companies, the companies must trust the facilitator not to reveal or exploit sensitive or confidential information received (Madsen et al., 2015).

However, there might be a wide range of factors that might defect companies from IS, not included in the ABM proposed in this paper. These factors can be ranked as the quality of waste, presence of regulations about the discharge or reuse of waste, quality constraints of the main products in which waste is used, etc. Then, a complete automatization of the platform using the input data given by companies might not always be a good idea. Hence, the online platform should allow companies to operate a part of decision-making process manually. This also stems from the fact that the question of information sensitivity is a highly subjective issue and it might differ from sector to sector, company to company, and manager to manager.

Obviously, developing an idea about the sensitivity of information is an evolutionary process for decision-makers. A company might try to implement IS with limited information about its potential partner(s) in the initial stage which could be followed by a trust-developing phase in which more information is shared. Such issues are to be observed once more online platforms emerge providing case-based data about the evolution of IS-based businesses over time.

The available literature on information systems facilitating IS proposes tools mainly based on input-output (quantity) matching among wastes and inputs in the initial phase of IS, i.e., the identification of potential IS partners (Álvarez and Ruiz-Puente, 2016; Cecelja et al., 2015; Cutaia et al., 2015; Doyle and Pearce, 2009; Trokanas and Cecelja, 2016). The platform considered in this paper does not limit to identify the potential IS partners but it can be used by companies as a decision-support tool for the implementation of IS. In fact, the platform suggests to each company the IS partner allowing to maximize the match between waste supply and demand (non-sensitive platform) and the economic benefits that the company can achieve through the symbiotic cooperation (sensitive platform). In this sense, the match-making technique is not limited to the use of the name and quantity of wastes, but it can involve additional information on the geographic location of companies as well as waste transportation and treatment costs. Hence, the approach offered in this paper is innovative as it builds on a future business-making perspective in terms of sustainability, which automatically involves strategic management of the IS relationship.

Another observation is about the cost of implementing the online information-sharing platforms, for which companies might pay a fee. Alternatively, governments might pay for the costs of such a platform to encourage companies to get engaged with IS practice (Cutaia et al., 2014; Luciano et al., 2016). Up to the authors' knowledge, literature does not provide an average cost estimate of developing and operating an online platform. Obviously, the cost of using such a platform should be paid off by the economic benefits gained from the IS practice implemented thanks to the platform.

Findings of the paper indicate policy implications for (local) governments. Governments are concerned with the adoption of IS because the environmental and social costs of production activities should not remain as externalities and be taken into account in implementing IS (Dong et al., 2017; Fraccascia et al., 2017c; Jiao and Boons, 2014; Liu et al., 2018). Thus, governments might receive help from the accumulated data in such online platforms and better visualize which sectors successfully implement IS or in which sectors there are barriers against IS. Accordingly, governments might distribute incentives based on sector-specific requirements, change/update environmental regulations, or provide subsidies for IS cases that are environmentally and socially promising but economically challenging. Thus, the bottom-up operational approach proposed in this paper can assist governments to design the framework of top-down environmental and economic policies taking into account the individual needs of each specific sector.

7. Conclusions

This paper proposes an Agent-based Model (ABM) to assist company managers in decision-making to implement industrial symbiosis (IS) in a dynamic environment and investigates the role of information-sharing to foster the IS practice between companies via online information-sharing platforms. Three scenarios are simulated to measure the environmental and economic contribution of information-sharing platform to the implementation of IS-based businesses in the ISN case example. Findings show a noticeable increase on performance measures when non-sensitive information is shared while a sharp performance increase is observed when sensitive information is additionally shared.

Although the lack of information-sharing is well recognized as a barrier to IS practice in the literature, limited studies concerning the net contribution of online platforms are conducted. Hence, this paper is a seminal theoretical contribution for IS literature highlighting the importance of online information-sharing platforms and measuring the environmental and economic performance of ISNs.

In addition, the paper has practical and managerial contributions for companies operating or willing to operate in IS environments. First, it provides decision support for practitioners taking into account the dynamic nature of ISNs. Second, it provides managerial insights about what information to share with potential partners and the related consequences. Accordingly, company managers are encouraged to share information with such a facilitator online platform or even with other companies. In fact, this is driven by the capability of proposed ABM to count on the combined impact of dynamic operational variables of IS with the epistemic dimensions of IS on the ISN performance. The ABM proposed in this paper can be useful and easily be adopted by other studies analyzing IS cases from operational and business-making perspectives. Because the model is a generic one which contains generic potential decisions of companies involved in IS, e.g., seek for a (new) partner, interrupt IS, or implement IS. Although the investigated IS cases might vary due to different sectors or geographic locations, the decision-making rules are mostly driven by the economic reasoning of companies, which makes the proposed model adoptable for such specific IS cases.

One might also think for ABM that operates on the basis of environmental performance. In such a case, the generic decision rules might be ‘implement IS with a company so that IS relationship produces minimum CO_2’ or ‘interrupt IS when the total CO_2 emission is higher than a threshold value’ etc. Accordingly, the ABM might run for different types of environmental performance indicators instead of operating based on economic parameters. In this way, companies might comparatively evaluate the economic and environmental performance and ask for support from governments if their best economic scenario does not correspond to their best environmental scenario. Such an ABM could be very useful for governments to map potential environmental impacts on air, soil, water, energy, or space and implement future policies for process industries. Furthermore, governments aimed at reducing the environmental impact of industrial activities thorough IS might also support online platforms that operate to maximize the different environmental performance indicators.

This paper indicates future directions for the interdisciplinary research on IS, combining operations management research with information science research. Several research questions related to this research stream can be ranked as follows. How can the online platforms be used in the IS identification, e.g., via recommender systems? What type of information is commonly perceived to be sensitive or non-sensitive? What is the human factor in decision-making about sharing information? How can such platforms enforce their roles as facilitators of IS? Answering such questions would accelerate the diffusion of IS practices and strengthen its catalyzer role in supporting the transition from linear economy to circular economy.

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