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Quantifying the direct network effect for online platforms supporting industrial symbiosis: an agent-based simulation study

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Abstract

This paper explores the direct network effect for online platforms supporting industrial symbiosis (IS), which is a recommended strategy to support the transition towards the circular economy. Through IS, companies can use wastes produced by other companies as inputs to production processes. Online platforms supporting companies in operating IS relationships can play a critical role in developing the IS practice.

In this paper, an agent-based model is designed to simulate the emergence of IS relationships among companies located in a given geographical area. Companies can establish relationships traditionally (relying on face-to-face contacts) or by using a platform. Several scenarios, defined by different platform usage rates, are simulated. Results show that there is a minimum platform usage rate allowing companies to benefit from using the platform. If the platform usage rate is lower than this threshold, the platform does not contribute to generate further benefits for companies. When the platform usage rate is higher than the threshold, the individual benefits for users are higher the greater the number of other companies using the platform. Based on these results, implications on how to ensure a *win-win* approach for companies and platform owners can be provided, as well as implications for policymakers.

Keywords: self-organized industrial symbiosis networks, circular economy, online platforms, agent-based simulation, network effect.

1. Introduction

Nowadays, one of the key strategies that companies can adopt to support the transition towards the circular economy is industrial symbiosis (IS) (D'Amato et al., 2019; Diaz Lopez et al., 2019; Domenech et al., 2019; Domenech and Bahn-Walkowiak, 2017; European Commission, 2015). The IS practice engages different companies in physical exchanges of by-products. Accordingly, an IS relationship is established between two companies when the former replaces one production input with one waste produced by the latter. By implementing a symbiotic relationship, both companies can achieve direct environmental benefits to their advantage: in particular, the former reduces the amounts of primary inputs purchased from conventional suppliers while the latter reduces the amounts of wastes disposed of (Chertow, 2000; Lombardi and Laybourn, 2012). Accordingly, companies can enhance their production efficiency (Fraccascia et al., 2017a) and achieve economic benefits, which can be a source of competitive advantage on other companies not adopting IS, *ceteris paribus* (Esty and Porter, 1998; Yuan and Shi, 2009). In addition to the direct benefits created for the involved companies, indirect environmental benefits can be created for the overall society, for instance in form of CO_2 emissions reduction (e.g., Kim et al., 2018)[1]. Since IS is able to create environmental and economic benefits simultaneously, the implementation of this approach is strongly recommended by scholars (e.g., Chertow, 2007) and policymakers (European Commission, 2015). In this regard, several countries are endorsing IS by promoting the development of IS networks (ISNs), i.e., networks of firms involved in waste exchanges (Park et al., 2018; Simboli et al., 2015; Taddeo et al., 2017). The literature distinguishes two creation mechanisms for symbiotic networks: accordingly, ISNs can be designed by adopting a top-down approach or emerge spontaneously from the bottom. Examples of top-down ISNs are the Asian eco-industrial parks (Huang et al., 2019; Massard et al., 2018; Tiu and Cruz, 2017); examples of bottom-up ISNs are the so-called “self-organized ISNs” (e.g., Chertow and Ehrenfeld, 2012; Doménech and Davies, 2011; Morales et al., 2019).

This paper focuses on self-organized ISNs. These networks arise from the spontaneous evolution of single IS relationships created by independent couples of companies, which usually do not have the ambition to develop a network. The formation dynamics of self-organized ISNs have been extensively described in the literature, for example by Baas and Boons (2004), Chertow and Ehrenfeld (2012), and Doménech and Davies (2011).

Aimed at favor the development of self-organized ISNs, policymakers can stimulate companies to implement the IS practice and create symbiotic relationships. For example, they can design *ad hoc* regulations – e.g., forcing companies to reduce the amounts of wastes disposed of traditionally (e.g., Costa and Ferrão, 2010; Eckelman and Chertow, 2013) or explicitly allowing the use of specific wastes as input for production activities (e.g., Martin and Eklund, 2011; Wen et al., 2018) – or provide economic incentives to companies operating IS (e.g., Tao et al., 2019; Velenturf, 2016). Nevertheless, a useful strategy is providing companies with online tools supporting them in creating IS relationships, e.g., online platforms that act as facilitators of communication and distributors of knowledge among firms (Low et al., 2018; Maqbool et al., 2018; van Capelleveen et al., 2018a). In fact, in a given geographical area where there is availability of a given waste, potential waste users might be not aware of such availability because of the lack of information (e.g., Madsen et al., 2015). Similarly, in a given geographical area where there is demand for a given waste, companies producing this waste might have no awareness of such a demand. In this regard, online platforms allowing companies to share information on their production and demand of wastes – even only from the qualitative perspective – are claimed to play a critical role in supporting ISNs, since they are able to mitigate the mismatch between demand and supply of wastes (e.g., Fraccascia and Yazan, 2018; Mortensen and Kørnøv, 2019). In fact, using online platforms makes easy and quick discovering opportunities for IS and finding symbiotic partners able to ensure adequate supply or demand of wastes (e.g., van Capelleveen et al.,

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[1] These benefits can be computed through life-cycle assessment (e.g., Martin et al., 2015; Mattila et al., 2012) or input-output techniques at the enterprise level (e.g., Yazan, 2016).

2018a, 2018b). Furthermore, online platforms can be integrated with decision support tools able to identify the most profitable IS opportunities to each user (e.g., Yazdanpanah et al., 2019). A recent work by Fraccascia and Yazan (2018) highlights that companies operating IS relationships by relying on online platforms can achieve higher environmental benefits compared to those they would have gained by operating IS traditionally. However, so far few other studies have investigated the contribution provided by IS online platforms from a quantitative perspective.

Recently, some pilot projects aimed at designing online platforms and facilitation tools for IS have been carried out (e.g., Aid et al., 2015; Cutaia et al., 2015, 2014; Elabras Veiga and Magrini, 2009). These projects have highlighted an important drawback, i.e., that companies might prefer not using online platforms due to a low willingness to make their personal information available to other companies. In fact, from the company perspective, uploading information concerning types and amounts of wastes produced or required might be interpreted as the fact of disclosing sensitive data about the production processes of the company. Therefore, due to such a low propensity to information sharing, there is the risk that, although available to be used, online platforms for IS would be populated by a scant number of companies. Nevertheless, the number of users is recognized as one of the key factors contributing to the effectiveness of online platforms, according to the so-called “direct network effect” (e.g., Evans and Schmalensee, 2010; Lee et al., 2010). The direct network effect implies that the value of a service for the single user can increase as more participants use that service; for example, as more people use telephones, the telephone becomes more valuable to each user, since it allows him/her to connect with a higher number of other users. However, in the IS field it is unclear whether and how much the value of online platforms in promoting IS can be affected by the number of platform users.

This paper aims at quantifying the direct network effect in online platforms for IS, in particular by addressing the following two research questions:

(RQ1) Are the direct environmental benefits provided by IS platforms to each user (i.e., the reduction in the amounts of wastes disposed of and in the amounts of inputs used in production processes) affected by the number of other platform users?

(RQ2) Does the number of platform users impact on the efficacy of IS platforms in increasing the environmental benefits created by IS at the level of a given geographical area?

The paper investigates the above-mentioned research questions via adopting the agent-based modeling (ABM) approach. The use of this methodology is required because of lacking primary data coming from case studies concerning IS platforms. ABM is an effective technique to study complex systems made by different entities – i.e., the agents – that interact among each other autonomously, since it allows to discover new knowledge about some fundamental processes of these systems (e.g., Epstein and Axtell, 1996; Giannoccaro et al., 2018). One of the main advantages of ABM is the possibility to simulate the same system under different scenarios, defined by the combination of different values of selected variables, in order to highlight the impact of each variable on the system outputs. This is particularly useful to carry out analysis *ex-ante*, even before a given system has been created, aimed at supporting the design phase. Since ISNs have been recognized as complex adaptive systems (Côté and Hall, 1995; Liwarska-Bizukojc et al., 2009), the ABM approach is considered appropriate to analyze the dynamics of symbiotic cooperation among different companies (e.g., Batten, 2009; Cao et al., 2009; Demartini et al., 2018).

In this paper, an agent-based model is designed to simulate the emergence of an ISN involving companies located in a given geographical area. Companies can establish and operate IS relationships traditionally, i.e., relying on face-to-face contacts, or by using an online platform. Several scenarios are simulated, defined by different platform usage rates, i.e., the percentage of companies located in the considered area that are users of the online platform. A numerical case is used to conduct the simulations. For each simulated scenario, the amount of waste saved by each company belonging to the ISN is measured and compared with the base case, which is defined as the scenario where all companies operate IS traditionally. By comparing these scenarios, the network effect can be highlighted.

The rest of the paper is structured as follows. Section 2 presents the theoretical background of this paper by framing ISNs as complex adaptive systems. Section 3 describes the agent-based model. Section 4 presents the case example and the simulation results. Finally, the paper ends with discussion and conclusions in Section 5.

2. Theoretical background: ISNs as complex adaptive systems

Complex adaptive systems (CASs) are networks of agents that emerge from the bottom, through the interaction among agents. These systems can evolve over time in terms of new structures and patterns, driven by the self-organization of the agents, without any central control mechanism deliberately managing the overall system (e.g., Choi et al., 2001). Examples of CASs include natural ecosystems (e.g., Levin, 1998; Rammel et al., 2007), economic systems (e.g., Anderson, 2018; Holland and Miller, 1991), social systems (e.g., Dooley, 1997; Folke, 2006), supply chains (e.g., Choi et al., 2001; Surana et al., 2005), and industrial districts (e.g., Albino et al., 2005; Giannoccaro, 2015).

Self-organized ISNs are recognized as CASs (e.g., Côté and Hall, 1995; Liwarska-Bizukojc et al., 2009), since they are the result of a spontaneous and self-organized process, where waste producers (receivers) decide to establish IS relationships with other firms, driven by the willingness to reduce their waste disposal costs (input purchase costs)[2] (Esty and Porter, 1998; Yuan and Shi, 2009). When creating IS

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[2] Here the reader can read in parallel the role of waste users in the main sentence and the role of waste producers by following parentheses.

relationships, companies do not have the ambition to develop a network of symbiotic exchanges but rather the ISN spontaneously emerges as the evolution of single IS relationships (Boons et al., 2017; Chertow and Ehrenfeld, 2012).

Despite IS allows to reduce waste disposal and input purchase costs, two additional costs are required to operate IS exchanges: waste transportation costs and waste treatment costs. Waste transportation costs are required to move wastes from the producer to the receiver; they mainly depend on the geographic proximity among firms, as well on the type of exchanged waste. Waste treatment costs arise when the exchanged waste requires a treatment process (e.g., sorting or filtration) before being used as input. These additional costs can affect the economic feasibility of IS relationships. Hence, it may happen that a given IS relationship is fully feasible from the technical perspective but not economically convenient. For example, if the two companies are located far apart between them, the waste transportation costs might exceed the reduction in production costs for the involved companies. Furthermore, in some cases waste treatment processes can be technologically complex, thus requiring treatment costs so high as to make the IS relationship not economically convenient (e.g., Ueberschaar et al., 2017).

The above-mentioned additional costs arise at the level of the IS relationship; therefore, companies have to autonomously negotiate how to share them. Furthermore, companies need to arrange the contractual clauses related to the waste exchange, i.e., if: (1) the waste producer would pay additional compensation to the waste user; (2) the waste user would pay the waste producer to buy its waste; or (3) the waste exchange would be operated free of charges (Madsen et al., 2015; Yazan and Fraccascia, 2019). This negotiation process is critical for the establishment of the IS relationship because it affects the economic benefits that each company gains from the relationship. In particular, a minimum economic benefit exists motivating each company to operate IS, which is affected by idiosyncratic features of companies such as the desired return on investment. Hence, in order that an IS relationship is established between two companies, both of them must achieve at least their minimum benefit desired (e.g., Mirata, 2004). This economic logic also drives the spatial level of IS relationships. In fact, despite the geographic proximity is considered as a facilitator for IS relationships (e.g., Chertow, 2000; Jensen et al., 2011), empirical cases show that IS relationships may arise among firms distant from each other as far as there is economic convenience in operating them (e.g., Sterr and Ott, 2004).

Self-organized ISNs can evolve over time because of: (1) external companies create IS relationships with companies belonging to the ISN, thus entering into the network; (2) companies belonging to the ISN create new IS relationships among them; (3) companies belonging to the ISN interrupt existing IS relationships or abandon the network (e.g., Ashton et al., 2017). In fact, because of the dynamic business environment in which companies are involved, both types and amounts of produced wastes and required inputs might fluctuate over time (e.g., Fraccascia et al., 2017b; Wang et al., 2017). Such fluctuations might create a quantity mismatch between demand and supply of wastes, which can reduce the willingness of companies to keep their current IS relationships (Fraccascia, 2019). In this regard, let us consider an IS relationship operated between two companies. If the potential supply for waste becomes much lower than the demanded amount, the waste user could reduce its input purchase costs by a scant percentage, which may be not sufficient to motivate the company towards the symbiotic cooperation. Similarly, if the potential demand for waste becomes much lower than the produced amount, the reduction in waste disposal costs might be scant and not sufficient to motivate the company towards the cooperation. Therefore, one of the involved companies might decide to interrupt the IS relationship. However, this decision is also influenced by path dependence (Boons and Howard-Grenville, 2009). Path dependence theory explains that, when making decisions, agents are influenced by their past experiences (Arthur, 1994). For IS synergies, it is acknowledged that the existing relationships and the history of collaborations might affect the establishment of new IS relationships (e.g., Baas, 2011; Mortensen and Kørnøv, 2019).

3. Materials and Methods

This section presents the agent-based model used in this paper and it is divided into five sub-sections. Section 3.1 models companies as agents. Section 3.2 presents the main features of the ISN model used in this paper. Section 3.3 addresses the potential waste flows and economic benefits created by the IS relationships between two generic companies. Section 3.4 describes the actions undertaken by agents. Finally, Section 3.5 addresses the rules followed by agents when interacting among them.

3.1 The agents

In this model, agents are companies. Firms are modeled according to the Enterprise Input-Output approach, i.e., as entities that use materials and energy (inputs) to produce outputs and generate wastes as secondary products (Grubbstrom and Tang, 2000; Lin and Polenske, 1998). Companies purchase their production inputs from conventional suppliers, sell outputs on final markets, and dispose of wastes. It is assumed that each company operates a given number of production processes, each of them producing one main output, whose quantity is driven by the market demand.

According to their role in the ISN, two kinds of agents are distinguished: waste producers and waste receivers. The amounts of wastes produced and inputs required depend on the amounts of outputs produced, as well as on the production technologies. Accordingly, the overall amount of the generic k-th waste produced at time t by the $p(i)$ production processes of the generic waste producer i – i.e., $w_{ik}(t)$ – is computed as follows:

$$w_{ik}(t) = \sum_{p=1}^{p(i)} x_{ip}(t) \cdot W_{pk} \tag{1}$$

where $x_{ip}(t)$ denotes the amount of output produced by the *p*-th process of firm *i* at time *t* and W_{pk} is a technical coefficient denoting the production rate of the *k*-th waste per unit of output of the *p*-th process[3]. Similarly, the overall amount of the generic *l*-th input required at time *t* by the *p(j)* production processes of the generic waste user *j* – i.e., $r_{jl}(t)$ – is computed as follows:

$$r_{jl}(t) = \sum_{p=1}^{p(j)} x_{jp}(t) \cdot R_{pl} \tag{2}$$

where $x_{jp}(t)$ denotes the amount of output produced by the *p*-th process of company *j* at time *t* and R_{pl} is a technical coefficient denoting the usage rate of the *l*-th input per unit of output of the *p*-th process[4].

3.2 The industrial symbiosis network

It is considered that P waste producers and R waste receivers are located in a given geographical area. Furthermore, it is assumed that the *k*-th waste can replace the *l*-th input, instead of being disposed of in the landfill. Hence, each of the P waste producers can establish one IS relationship with each of the R waste receivers. For the sake of simplicity, it is assumed that each firm cannot exchange the same type of waste with more than one other company simultaneously. This assumption is consistent with the real behavior of companies, which usually prefer to implement one-to-one IS relationships (e.g., Chopra and Khanna, 2014). In fact, exchanging the same waste with more than one other company would increase the supply chain complexity and, as a consequence, the transaction costs for companies (Fraccascia et al., 2019).

3.3 The symbiotic relationship between companies: potential waste flows and economic benefits

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[3] The coefficient W is not time-dependent because it models the production technology of firm *i*. Accordingly, the value of this coefficient is assumed to be fixed in the short period and can change as the result of technological innovation (in particular, if firm *i* improves its production process so as it is able to generate lower amount of waste per unit of output produced).

[4] The coefficient R is not time-dependent because it models the production technology of firm *j*. Accordingly, the value of this coefficient is assumed to be fixed in the short period and can change as the result of technological innovation (in particular, if firm *j* improves its production process so as it is able to require lower amount of input per unit of output produced).

Let us consider the generic waste producer *i* and the generic waste user *j* that can exchange the waste *k* for the input *l*. The amount of waste that can be potentially exchanged between these companies at time *t* is described by the following equation:

$$e^{i\to j}(t) = min\left\{w_{ik}(t); \frac{r_{jl}(t)}{s^{k\to l}}\right\} \tag{3}$$

where $s^{k\to l}$ stands for a technical replacement coefficient denoting how many units of input *l* can be replaced by one unit of waste *k*. It is assumed that there is no lead time in moving wastes from *i* to *j*, since usually IS relationships are operated among companies geographically close-by (Jensen et al., 2011). The symbiotic cooperation at time *t* is able to create both direct and indirect environmental benefits. In this model, the direct environmental benefits are considered, i.e., (1) the amounts of wastes not disposed of in the landfill and (2) the amounts of primary inputs not used in production processes. In particular, $w_{ik}(t) - e^{i\to j}(t)$ units of waste are not disposed of in landfills and $r_{jl}(t) - s^{k\to l} \cdot e^{i\to j}(t)$ units of input are not used by company *j*. The economic benefits associated are the reduction in waste disposal costs for firm *i* – i.e., $RDC_i^{i\to j}\ (t)$ – and the reduction in input purchase costs for firm *j* – i.e., $RPC_j^{i\to j}\ (t)$. These benefits can be computed as follows:

$$RDC_i^{i\to j}\ (t) = udc_k \cdot e^{i\to j}(t) \tag{4}$$

$$RPC_j^{i\to j}\ (t) = upc_l \cdot s^{i\to j} \cdot e^{i\to j}(t) \tag{5}$$

where udc_k denotes the cost to dispose of one unit of waste *k* and upc_l denotes the cost to purchase one unit of input *l* from conventional suppliers.

Concerning the additional costs of IS, let $W\_TRA\_C^{i\to j}(t)$ and $W\_TRE\_C^{i\to j}(t)$ be the waste transportation costs and the waste treatment costs required to operate IS between *i* and *j* at time *t*, respectively. They can be computed as follows:

$$W\_TRA\_C^{i\to j}(t) = u\_tra\_c_k \cdot d^{i\to j} \cdot e^{i\to j}(t) \tag{6}$$

$$W\_TRE\_C^{i\to j}(t) = u\_tre\_c^{k\to l} \cdot e^{i\to j}(t) \tag{7}$$

where $u\_tra\_c_k$ is the transportation cost per Km of one unit of waste *k*, $d^{i\to j}$ is the distance between firms *i* and *j*, and $u\_tre\_c^{k\to l}$ is the treatment cost required to make one unit of waste *k* able to replace the input *l*. These additional costs are usually shared between the companies involved in the IS relationship. In this regard, let $\alpha^{i\to j}(t) \in [0,1]$ be the percentage of additional costs paid by firm *i* at time *t*. Of course, the percentage paid by firm *j* is $1 - \alpha^{i\to j}(t)$. Furthermore, let $ep^{i\to j}(t)$ be the waste exchange price paid by firm *i* to firm *j* per unit of exchanged waste. Accordingly, $ep^{i\to j}(t)$ is higher than zero when firm *i* pays additional compensation to firm *j*; alternatively it is lower than zero when firm *j* pays firm *i* to purchase the waste. Hence, according to the two above-mentioned parameters, five contractual clauses can support the symbiotic exchange: (1) additional costs of IS are shared among firms and the waste exchange is operated free of charges ($0 < \alpha^{i\to j} < 1$ and $ep^{i\to j} = 0$); (2) firm *i* pays all the additional costs of IS and the waste exchange is operated free of charges ($\alpha^{i\to j} = 1$ and $ep^{i\to j} = 0$); (3) firm *i* pays all the additional costs of IS and pays firm *j* to dispose of its waste ($\alpha^{i\to j} = 1$ and $ep^{i\to j} > 0$); (4) firm *j* pays all the additional costs of IS and the waste exchange is operated free of charges ($\alpha^{i\to j} = 0$ and $ep^{i\to j} = 0$); and (5) firm *j* pays all the additional costs of IS and pays firm *i* to purchase its waste ($\alpha^{i\to j} = 0$ and $ep^{i\to j} < 0$).

The economic benefit (EB) that firms *i* and *j* would achieve in case of symbiotic cooperation at time *t* can be computed as follows:

$$EB_i^{i\to j}(t) = RDC_i^{i\to j}(t) - \alpha^{i\to j}(t)\cdot\left[W\_TRA\_C^{i\to j}(t) + W\_TRE\_C^{i\to j}(t)\right] - ep^{i\to j}(t)\cdot e^{i\to j}(t) \tag{8}$$

$$EB_j^{i\to j}(t) = RPC_j^{i\to j}(t) - \left[1-\alpha^{i\to j}(t)\right]\cdot\left[W\_TRA\_C^{i\to j}(t) + W\_TRE\_C^{i\to j}(t)\right] + ep^{i\to j}(t)\cdot e^{i\to j}(t) \tag{9}$$

3.4 The actions undertaken by agents

Each agent can accomplish the following actions: (1) selecting a potential symbiotic partner; (2) evaluating a symbiotic relationship, deciding whether to cooperate or not; and (3) negotiating new contractual clauses. These actions are discussed in the following sections.

3.4.1 Selecting a potential symbiotic partner

Here, two cases can be distinguished, depending on whether the agent is a platform user. These cases are analyzed in the following subsections.

3.4.1.1. Firms using the online platform

For each period, each platform user is required to upload the following data: (1) the amount of produced or required wastes; (2) the geographic location of the plants producing or requiring the above-mentioned wastes; (3) economic information on waste disposal costs (for waste producers), input purchase costs (for waste users), and additional costs to operate IS. It is assumed that these data are not disclosed with other companies but they are visible only to the platform owner, in order to ensure their full confidentiality. By exploiting these data, the platform suggests to each user who is the best potential partner, according to the logic proposed by Yazdanpanah et al. (2019), which considers the quantity match between waste and input, as well as the distance between companies. It is supposed that companies choose the partner suggested by the platform.

3.4.1.2. Firms not using the online platform

In this case, all the other firms not using the platform can be potential symbiotic partners. However, according to the real world, each firm has no information concerning both the amounts of wastes required/produced by each of the other companies and their availability to start a new cooperation. Here, it is assumed that, when selecting a potential partner, the generic company *i* tries to establish a symbiotic cooperation with the company *j* with a given probability $P(i \rightarrow j)$. Such a probability depends on the geographic distance between companies (it is assumed that the closer the company *j* is to company *i*, the higher the probability that *j* is chosen as a potential partner) (Jensen et al., 2011), as well as on the social relationships between managers of the two companies (Hewes and Lyons, 2008). Of course, these probabilities are generated so that $\sum_j P(i \rightarrow j) = 1 \;\forall\, i$.

3.4.2 Evaluating a symbiotic relationship, deciding whether to cooperate or not

Companies decide whether to create a new IS relationship and to keep an existing IS relationship based on their “willingness to cooperate”. According to the model proposed by Fraccascia and Yazan (2018), the willingness of firm *i* to symbiotically cooperate with firm *j* at time *t* is measured by the function $WTC_i^{i\rightarrow j}(t)$, which is computed as follows:

$$WTC_i^{i\rightarrow j}(t) = \frac{1}{L^{i\rightarrow j}(t)+1} \cdot EB_i^{i\rightarrow j}(t) + \left[1 - \frac{1}{L^{i\rightarrow j}(t)+1}\right] \cdot WTC_i^{i\rightarrow j}(t-1) \qquad (10)$$

where $L^{i\rightarrow j}(t)$ is defined as the number of sequential time periods firms *i* and *j* are involved in the IS relationship. According to the literature, the higher the economic benefit potentially achievable from the cooperation – see Eq. (8) – the higher the willingness of firm *i* to cooperate with firm *j* will be, *ceteris paribus*. When the two companies did not cooperate at time *t*-1 (i.e., when $L^{i\rightarrow j}(t) = 0$), the willingness to cooperate of firm *i* depends only on the potential economic benefits achievable from the relationship with *j*: accordingly, $WTC_i^{i\rightarrow j}(t) = EB_i^{i\rightarrow j}(t)$. Alternatively, when the two companies cooperated at time *t*-1 (i.e., when $L^{i\rightarrow j}(t) > 0$), the willingness to cooperate of firm *i* is affected by the path dependence, i.e., the outcome coming from the previous relationships with *j*. In particular, the longer the time firms *i* and *j* are involved in an IS relationship, the higher the impact of the history of the relationship to motivate them towards the cooperation.

Firm *i* is willing to cooperate with firm *j* at time *t* only if $WTC_i^{i\to j}(t)$ is higher than or equal to a given threshold value T_i, which models the firms' propensity towards the symbiotic practice. In particular, the higher the threshold value, the higher the minimum amount of economic benefits required to motivate firms towards the cooperation will be. Here, the impact of path dependence can be easily highlighted. In fact, even if $EB_i^{i\to j}(t) < T_i$, it might happen that $WTC_i^{i\to j}(t) \geq T_i$ because of the positive outcome of the past interactions between companies *i* and *j*. Hence, in this case, company *i* would decide to still cooperate with company *j*.

3.4.3 Negotiating the contractual clauses

When its willingness to cooperate with firm *j* is lower than the threshold, firm *i* can renegotiate the contractual clauses in order to increase its willingness to cooperate. In particular, firm *i* proposes two new values of $\alpha^{i\to j}$ and $ep^{i\to j}$ so that $WTC_i^{i\to j}(t)$ becomes higher than the threshold T_i.

3.5 The dynamic interactions among agents

Let us consider two generic firms *i* and *j*, respectively waste producer and waste user, which were cooperating at time *t*-1. At time *t*, they assess their willingness to cooperate according to the contractual clauses previously adopted – i.e., $\alpha^{i\to j}(t) = \alpha^{i\to j}(t-1)$ and $ep^{i\to j}(t) = ep^{i\to j}(t-1)$ – aimed at deciding whether to cooperate or not (Section 3.4.2). Here, three cases can be considered: (1) both companies are willing to cooperate – i.e., $WTC_i^{i\to j}(t) \geq T_i$ and $WTC_j^{i\to j}(t) \geq T_j$ simultaneously – and the IS relationship is kept; (2) both companies are not willing to cooperate – i.e., $WTC_i^{i\to j}(t) < T_i$ and $WTC_j^{i\to j}(t) < T_j$ simultaneously – and the relationship is interrupted; (3) firm *i* would like to keep the IS relationship but firm *j* is not willing to cooperate with the existing contractual clauses – i.e., $WTC_i^{i\to j}(t) \geq T_i$ and $WTC_j^{i\to j}(t) < T_j$ – or *vice versa*. In this case, if firm *j* is not willing to cooperate under the current conditions, the company might try to renegotiate the contractual clauses (Section 3.4.3). However, this action is accomplished only if firm *j* has sufficient bargaining power in the relationship. According to Yazan et al. (2012), bargaining power in IS relationships concerns the dependency of a firm on its partner. The bargaining power of firm *j* related to firm *i* at time *t* – i.e., $BP_j^{i\to j}(t)$ – is defined and measured as the contribution of *j* to the economic benefits that *i* achieves from the relationship, i.e., $BP_j^{i\to j}(t) = EB_i^{i\to j}(t)$. Then firm *i* evaluates the new contractual clauses by computing its new willingness to cooperate: if this value is higher than or equal to the threshold, firm *i* agrees on the new contractual clauses and the IS relationship is kept, otherwise the IS relationship is interrupted.

Companies not involved in IS relationships at time *t* try to create a new relationship. Hence, the generic company *n* selects the potential symbiotic partner *q* (Section 3.4.1). If firm *q* is already involved in an IS relationship, firm *n* does not establish any IS relationship at time *t* and will select a new potential partner at time *t*+1. If *q* is not involved in other IS relationships, both companies evaluate the IS relationship (Section 3.4.2), where the values of $\alpha^{n \to q}(t)$ and $ep^{n \to q}(t)$ can be proposed by firm *n* or *q* with 50% of probability each[5]. Again, the outcome of this process depends on the values of the willingness to cooperate functions. If both companies have sufficient willingness to cooperate, the IS relationship is established. If both companies are not willing to cooperate, the relationship is not established. Finally, if firm *n* (*q*) would like to keep the IS relationship but firm *q* (*n*) is not willing to cooperate with the existing contractual clauses, two cases can be distinguished: (1) if firm *q* (*n*) does not have sufficient bargaining power, the IS relationship does not arise; (2) if firm *q* (*n*) has sufficient bargaining power, it negotiates new contractual clauses (Section 3.4.3). In this latter case, firm *n* (*q*) evaluates the new contractual clauses by computing its new willingness to cooperate: if firm *n* (*q*) agrees on the new contractual clauses, the IS relationship is established, otherwise it does not arise. Figure 1 shows the flow chart of the above-described interactions among agents.

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[5] This means that the contractual clauses are proposed by who play first and companies have the same probability to be the first mover.

Fraccascia L. (2020). Quantifying the direct network effect for online platforms supporting industrial symbiosis: an agent-based simulation study. *Ecological Economics*, *170*, 106587. doi:10.1016/J.ECOLECON.2019.106587

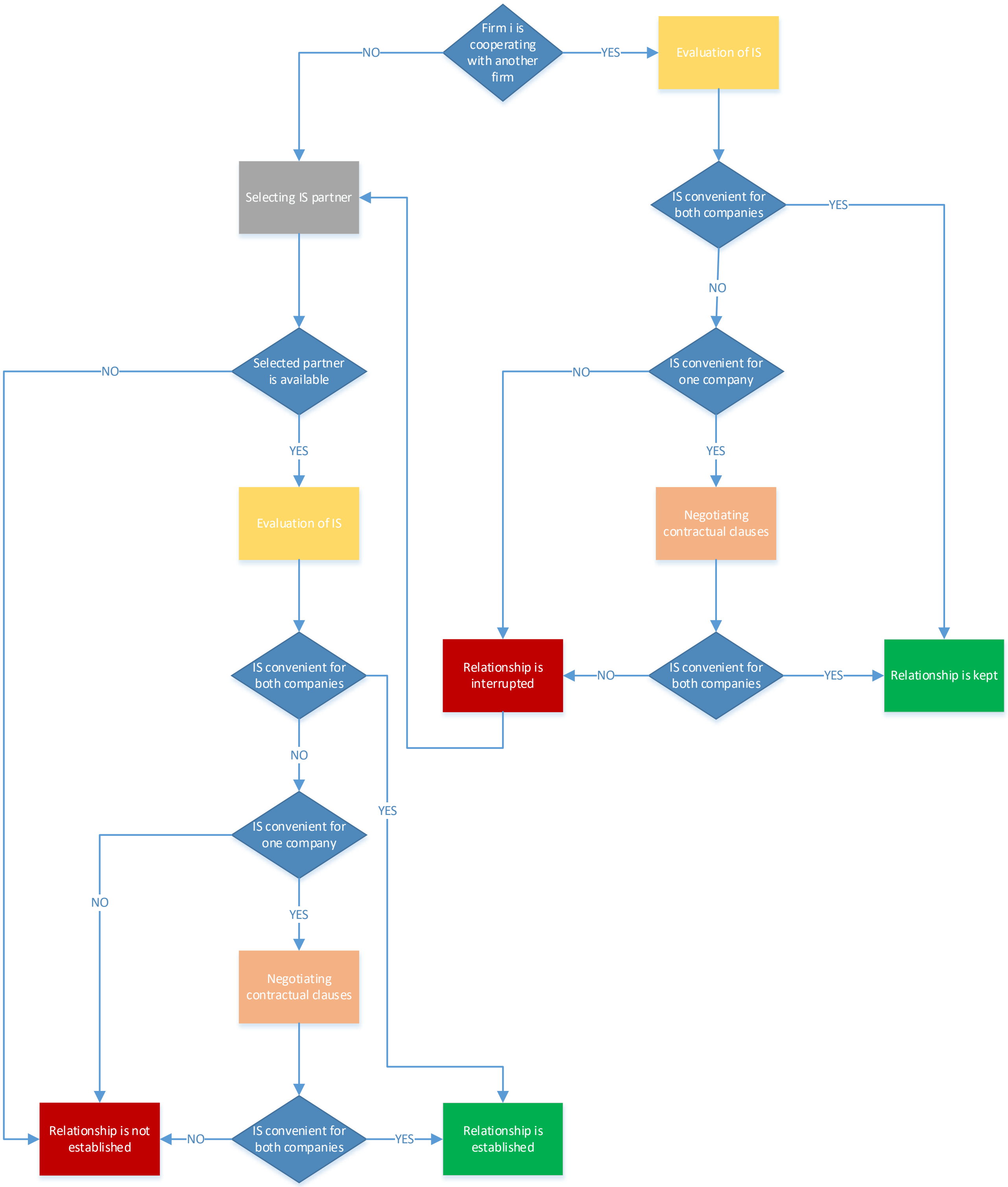

Figure 1. Flow chart of the dynamic interactions among agents.

4. Case Example and Results

This section is divided into two subsections: the former (Section 4.1) describes the case and presents the simulation settings, the latter (Section 4.2) presents the simulation results.

4.1. Case description and simulation settings

To run simulations, the data referring to the ISN described by Fraccascia and Yazan (2018) are used. Two types of waste producers (i.e., marble producers and concrete producers) and two types of waste users (i.e., alcohol producers and fertilizer producers) are assumed to be located in a given geographical area. For the sake of simplicity, it is assumed that each company operates one production process, whose output is the main product sold by the company – this assumption is also typical of other agent-based models (see, for example, Fraccascia et al., 2019). Marble producers generate marble residuals as waste, which could be used as an alternative aggregate by concrete producers, after receiving a treatment process (e.g., Hebhoub et al., 2011). Alcohol producers generate alcohol slops as waste, which could be used as input by fertilizer producers (e.g., Zhu et al., 2008). Hence, marble producers can establish IS relationships with concrete producers; alcohol producers can establish IS relationships with fertilizer producers. For both relationships, it is assumed that one unit of input can be replaced by one unit of waste.

In particular, it is considered that 400 companies (i.e., 100 marble producers, 100 concrete producers, 100 alcohol producers, and 100 fertilizer producers) are randomly spread in a square geographical area with 100 Km side (Euclidean distances among firms are considered). For each company, numerical data on the average amount of output produced, technical coefficients W and R (equations 1 and 2), waste disposal cost and input purchase cost are shown in Table 1. Each firm observes a stochastic demand for its main product over time, according to a normal distribution with mean μ and standard deviation σ. It is assumed that $\mu = x$ and that the value of σ ranges between 10% and 40% of the value of μ, according to a uniform distribution. Furthermore, according to Fraccascia and Yazan (2018), it is considered that the cost required to transport one ton of waste is 5 €/Km and that the waste treatment cost to operate marble-based exchanges is 0.66 €/t.

Table 1. Numerical data on average amount of output produced, technical coefficients, waste disposal costs, and input purchase costs.

	Marble producers	Alcohol producers	Concrete producers	Fertilizer producers
Average amount of output produced (*x*)	4000 m2/year	10000 t/year	9800 t/year	20000 t/year
Waste production technical coefficient (W)	$3.313\ \frac{\text{t marble residuals}}{\text{m2 marble}}$	$0.8\ \frac{\text{t alcohol slops}}{\text{t alcohol}}$	---	---

Waste disposal cost	$6 \frac{€}{\text{t marble residuals}}$	$30 \frac{€}{\text{t alcohol slops}}$	---	---
Input requirement technical coefficient (R)	---	---	$1.35 \frac{\text{t aggregate}}{\text{t concrete}}$	$0.4 \frac{\text{t alcohol slops}}{\text{t fertilizer}}$
Input purchase cost	---	---	$66 \frac{€}{\text{t aggregate}}$	$70 \frac{€}{\text{t alcohol slops}}$

Taking into account the idiosyncratic features of companies, it is assumed that each waste producer has a threshold value ranging from 0% to 50% of the average waste disposal costs, according to a uniform distribution. Similarly, it is assumed that each waste user has a threshold value ranging from 0% to 50% of the average input purchase costs, according to a uniform distribution. This variability models the different propensity of companies to establish IS relationships. In particular, the higher the threshold value of a given company, the lower the propensity of that company to implement IS.

At the beginning of the simulation, each company tries to establish one IS relationship with another company. A formal agreement, valid for one period, is created for each established relationship. 40 periods are simulated.

The case example is simulated for eleven scenarios defined by different values of the platform usage rate, i.e., the percentage of companies belonging to the considered area that are platform users. The scenario with a platform usage rate of 0% is considered the base case. At the end of each simulation, the following parameters are computed for each company: (1) the amounts of wastes exchanged, i.e., not disposed of thanks to the IS practice; (2) the amounts of wastes produced. As a performance measure, the ratio between the amount of waste exchanged and the amount of waste produced is used. Such a ratio ranges between zero and one: it is equal to zero when there are no waste exchanges within the ISN while is equal to one when the overall amount of wastes produced is recovered into the ISN. Each scenario is replicated 400 times. Results are averaged across replications.

4.2. Simulation results

Results are presented disaggregated for marble-based and alcohol-based IS exchanges, in order to highlight similarities or differences in patterns. Figure 2a and Figure 2b display the percentage of wastes exchanged by each of the companies using the platform (green lines) and not using the platform (red lines). Figure 2c and Figure 2d display the percentage of marble residuals and alcohol slops overall exchanged into the ISN. The procedure used to validate the simulation model is described in the Appendix.

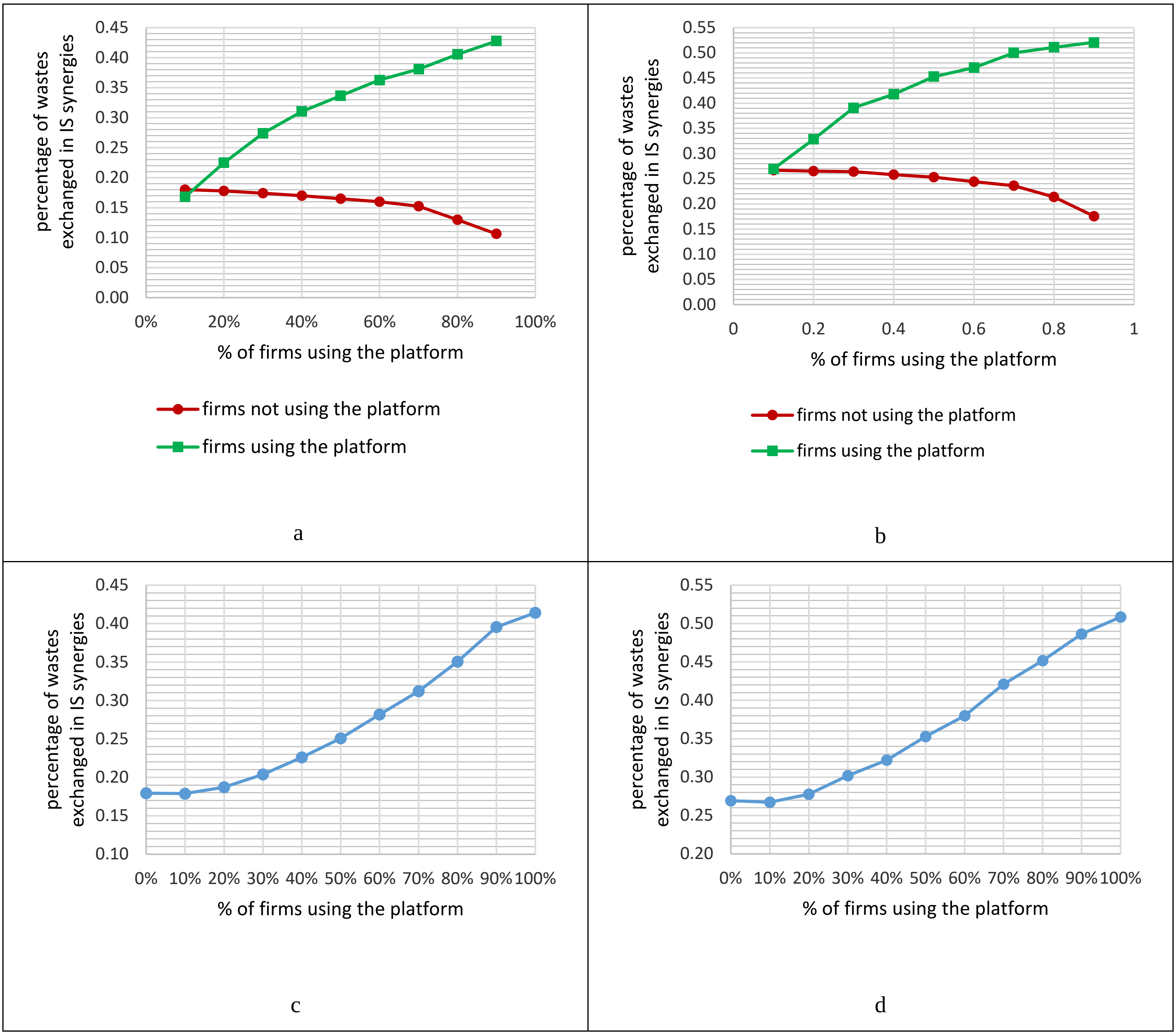

Figure 2. (a) Percentage of marble residuals saved by platform users (green line) and by companies not using the platform (red line); (b) Percentage of alcohol slops saved by platform users (green line) and by companies not using the platform (red line); (c) Percentage of marble residuals saved into the ISN; (d) Percentage of alcohol slops saved into the ISN.

First, it can be noted that, when none of the companies uses the online platform, the percentages of marble residuals and alcohol slops exchanged into the ISN are 17.94% (Figure 2c) and 26.91% (Figure 2d), respectively. These quite low values are not surprising, consistently with the operational problems that companies face when creating new IS relationships relying on face-to-face contacts, as well as when operating IS over time (Bansal and McNight, 2009; Herczeg et al., 2018).

Let us consider the scenario characterized by a platform usage rate of 10%. From Figure 2a and Figure 2b, it can be noted that the use of the platform does not result in advantages for companies (for marble-based IS relationships, the percentage of exchanged waste is even reduced by 1%). Two are the causes of this outcome. First, because of the low number of users, the platform can suggest few opportunities for IS to each user. Second, more convenient opportunities might exist than those suggested by the platform but the platform is not able to recognize these opportunities because they involve companies who are not platform users (hence, the platform does not have access to the data of these companies). For example, let us suppose that the platform suggests the cooperation with company *j*, which is *N* km far. However, *ceteris paribus* (e.g., the amounts of wastes to be exchanged, the input purchase cost, etc.), the user could gain more benefits by cooperating with company *k*, which is *M*<*N* Km far. In fact, exchanging wastes with firm *k* would be more profitable, since waste transportation costs are reduced. Nevertheless, since company *k* is not a platform user, the platform cannot suggest such cooperation[6]. No significant difference in performance can be noted for companies not using the platform. Hence, as a result, the introduction of the platform does not create any environmental benefit but, on the contrary, the amounts of wastes exchanged even decrease compared to the base scenario. In fact, from Figure 2c and Figure 2d, it can be noted that, when the platform usage rate is 10%, the percentage of exchanged wastes is reduced to 17.89% for marble-based exchanges (compared to 17.94% of the base case) and to 26.72% for alcohol-based IS exchanges (compared to 26.91% of the base case).

Let us consider the scenario characterized by a platform usage rate of 20%. Here, we can note that companies using the platform can increase the percentage of wastes exchanged compared to the base case. In fact, on average each marble producer using the platform exchanges 22.48% of marble residuals produced (Figure 2a) compared to 16.79% of the previous scenario and each alcohol producer exchanges 32.81% of alcohol slops produced (Figure 2b) compared to 26.95% of the previous scenario. It can also be noted that companies not using the platform do not suffer from any disadvantage from the reduction in the number of potential symbiotic partners. In fact, on average each marble producer not using the platform exchanges 17.78% of the marble residuals produced (compared to 18.01% of the previous scenario) and each alcohol producer not using the platform exchanges 26.49% of the alcohol slops produced (compared to 26.95% of the previous scenario). However, from Figure 2c and Figure 2d it can be noted that the low number of companies using the platform results in scant environmental benefits overall created in the ISN. In fact, the percentage of marble residuals exchanged increases to 18.72% (compared to 17.94% of the base case) and the percentage of alcohol slops exchanged increases to 27.75% (compared to 26.91% of the base case).

Figure 2a and Figure 2b show that the benefits that companies achieve by using the online platform further increase as the platform usage rate grows. This highlights the presence of a network effect for IS online platforms (RQ1). Accordingly, the higher the number of platform users, the better the IS

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[6] A similar observation can be raised for potential cooperation involving higher amount of wastes to be exchanged at the same distance.

opportunities suggested by the online platform are, *ceteris paribus*. On the other side, it can be observed that companies not using the platform still have no relevant disadvantages until the platform usage rate is lower than 60%, then their environmental performance starts to decrease. This happens because the number of potential symbiotic partners is reduced and a lower number of possible symbiotic opportunities exists for each company. At the ISN level, it can be observed that the number of platform users impacts positively on the environmental benefits created overall (RQ2). However, it can be noted that the percentages of wastes exchanged start to increase significantly only when the platform usage rate is at least 30% (Figure 2c and Figure 2d).

5. Discussion and conclusion

Online platforms supporting IS are claimed to play a key role in the development of self-organized ISNs but so far few studies have investigated their impact from the quantitative perspective. This paper contributes to such research issue by investigating the network effect characterizing these platforms, i.e., the extent to which the benefits created for each platform user (in terms of reduction in the amounts of wastes disposed of and primary inputs used in production processes) and at the ISN level depend on the overall number of users.

The direct network effect can be highlighted and quantified by green lines in Figure 2a and Figure 2b: accordingly, the value provided by the platform to the users – defined as the increase in the environmental performance compared to the base scenario – is much higher the greater the number of platform users, *ceteris paribus*. However, the results highlight that, in case of a low platform usage rate, the value that companies gain by using the platform is scarce and it might be even negative, i.e., using the platform to operate IS might be a disadvantage, since it reduces the environmental performance compared to the base scenario. Accordingly, firms might have a low willingness to become new users because of the scant benefits they can achieve by using the platform. This phenomenon can be strengthened by the fact that, for usage rates lower than 60%, companies not using the platform do not suffer from relevant disadvantages, since they are still able to create and operate IS relationships. Hence, when the platform usage rate is low, the platform is not able to promote effectively the adoption and operation of IS at the network level. This is in contrast with the mainframe of the literature, which highlights the benefits of using online platforms, without considering however the actual usage rate by companies. Therefore, the results of this paper shed light on the fact that simply developing online platforms might be not able to fully support the adoption of the IS practice. In fact, in order to ensure the high effectiveness of IS online platforms, it is critical that these tools are able to collect large numbers of users. From the firms perspective, the relevant benefits that they can achieve by using platforms populated by a high number of companies – highlighted by this paper – should motivate firms to adopt IS online platforms and to upload their (sensitive) data.

The number of potential platform users in a given geographical area may depend on the following three factors: (1) the presence of at least one online platform in the area of interest; (2) the number of companies implementing IS in that area; and (3) the platform usage rate. Both policymakers and platform owners can impact on the above-mentioned factors. The implications for them are discussed as follows.

The role of *policymakers* is crucial. In fact, policymakers should further incentivize companies to adopt the IS practice via two actions: (1) making companies aware of the potential benefits that they can achieve via implementing IS; and (2) developing effective policy measures to foster the development of IS strategies. Concerning the action (1), the literature recognizes that companies might have a low awareness on IS or, even in case of high awareness, they might have a low willingness to implement such a strategy (Corder et al., 2014; Fichtner et al., 2005; Golev et al., 2015; Promentilla et al., 2016). Concerning the action (2), it should be highlighted that the feasibility conditions for the emergence of IS relationships might be different according to different geographical areas and, even within the same geographical area, according to the wastes and resources involved (e.g., Yazan and Fraccascia, 2019). In this regard, the literature at the macroeconomic level highlights that a given policy measure might not be equally effective in different geographical areas or, even in the same area, might not be equally effective for all industries (e.g., Eickelpasch and Fritsch, 2005; Huberty and Zachmann, 2011; Pack and Saggi, 2006). In the IS field, this phenomenon is confirmed by Tao et al. (2019), who point out that the influence of policy instruments on the IS implementation can be different from case to case and from country to country. Therefore, policy measures aimed at supporting IS should be developed at the level of the single geographical area and single resource involved. Furthermore, policymakers should strongly promote the development of IS online platforms, for example via economic incentives or financing *ad-hoc* projects, because of the additional environmental benefits that IS platforms can create. In fact, currently the number of IS online platforms available in the market is limited – these platforms are mainly the result of pilot projects, in some cases interrupted – and even companies willing to use these tools are not able to do it.

Platform owners have a key role in reducing the barriers that companies face when deciding whether to become platform users, and therefore they can impact on the platform usage rate. First, as stated in the introduction, companies might be reluctant to use online platforms because they prefer not to share data considered sensitive. Here, a critical aspect may concern the reputation of the platform owners in managing personal data of companies. In this regard, companies should trust in the fact that the platform owner would not disclose their sensitive data to other companies. Furthermore, proper mechanisms to ensure the high confidentiality of data should be guaranteed by online platforms. For example, the platform's architecture should allow companies to manage the visibility of their data to other companies, for example by selecting which other companies can visualize the data uploaded to the platform. Second, the willingness of companies to use the online platform might be affected by the cost to use the platform.

In this paper, it is assumed that companies can use the platform free of charge. However, since online platforms can be developed and operated even by private companies, users might be required to pay a usage fee (e.g., Weinhardt et al., 2009). Nevertheless, depending on the willingness of companies to pay for using the platform, such a fee might limit the number of users, thus reducing the value generated for all the other users (e.g., Hoegg et al., 2006). Hence, the platform owners should carefully design business models able to ensure a *win-win* approach for both companies and the platform owner. A further assumption of this paper is that, through internal matchmaking algorithms that exploit the data uploaded by companies, the platform is able to suggest the best potential IS partner to each user. However, this role can be played by an IS facilitator. Facilitators could use an IS online platform to collect the data that currently are gathered manually – for instance through physical meetings with the managers of companies (e.g., Cutaia et al., 2015) – and use these data to support firms in creating IS relationships. In this sense, IS online platforms are not considered as a replacement of IS facilitators but, alternatively, as a support tool. Here, the network effect is a clear advantage to facilitators: in fact, the higher the number of platform users, the higher the potential IS opportunities that the facilitator can discover for each of them.

From the methodological perspective, this paper adopts the ABM approach to model the behavior of the single companies (in terms of decision rules) and simulate the interactions among different companies. The ABM approach could be used to carry out further studies aimed at supporting the application and the development of IS online platforms. For instance, agent-based models can be used to explore the potential benefits coming from adopting IS online platforms in a given industrial system, in particular by simulating IS strategies operated traditionally (i.e., without using the platform) and by using the platform, and finally comparing the two above-mentioned scenarios, in order to discover the additional benefits created by the online platform. Hence, the industrial systems where the platform is more able to provide additional benefits can be discovered *ex-ante*. Furthermore, the ABM approach can be used to test the effectiveness of different platform architectures. Similar analyses can be conducted aimed at highlighting the effectiveness of specific policy measures in different industrial systems.

Results of this paper call for future studies aimed at shedding light on the propensity of companies to use online platforms for IS, which is a field quite unexplored by the literature so far – to the best of the author’s knowledge. In this paper, several scenarios characterized by different platform usage rates have been investigated; however, companies cannot decide whether to become platform users or, alternatively, to cancel their subscription. In fact, the platform usage rate is fixed for each scenario. However, this issue calls for a detailed investigation, especially if the platform subscription is not free of charge. Related to this issue, the business models supporting the operations of IS platforms should be investigated. From the technical perspective, future studies could investigate how the IS platforms can ensure the full confidentiality of data uploaded by companies. In this sense, how the emerging role of other enabling digital technologies can be complementary to IS platforms and contribute to the development of self-organized ISNs is a matter for future research.

Two main limitations must be acknowledged. The former is related to the agent-based model proposed and concerns the fact that, according to the decision rules, companies cannot exchange the same type of waste with more than one company simultaneously. However, IS exchanges are mainly implemented between two companies, i.e., waste producers (users) exchange a given waste with only one waste user (producer) at a time. In this sense, IS synergies are characterized by low redundancy (e.g., Chopra and Khanna, 2014). In fact, exchanging the same waste with more symbiotic partners increases the complexity in implementing and managing the IS approach, which in turn poses a challenge for the firms (Fraccascia et al., 2019). Therefore, the proposed model can be representative of the great part of IS synergies. Furthermore, the above-mentioned assumption is also typical of other agent-based models in this field, mentioned in Section 2. The latter limitation is related to the numerical example and concerns the fact that each waste producer generates only one waste, as well each waste receiver uses only one input. Of course, this is a simplification of the real world, where companies usually produce more than one waste, as well as require more than one input. However, the proposed model can be used to simulate more complex scenarios of IS involving multiple wastes and input. In particular, the simulation model can be launched for each type of IS synergy and then the results can be analyzed both overall and separately. The design of more complex agent-based models able to simulate directly complex IS scenarios is a matter for future research.

Appendix: model validation

The model is validated through the following four steps: (1) micro-face validation; (2) macro-face validation; (3) input validation; and (4) output validation (Bianchi et al., 2008; Giannoccaro and Carbone, 2017; Manson, 2003; Rand and Rust, 2011).

The *micro-face validation criteria* are satisfied because the mechanisms and properties of the model, presented in Section 3, are defined consistently with the literature (e.g., the willingness to cooperate of firms depends on the potential economic benefits from the cooperation and the path dependence) and therefore they correspond to real-world mechanisms.

The *macro-face validation criteria* are satisfied because the dynamics of the model, presented in Section 3, are defined consistently with the literature (e.g., companies decide to start/keep an IS relationship only if the potential economic benefits are higher than a given threshold, standing for the minimum amount required to motivate them towards cooperation) and therefore they correspond to real-world dynamics.

Different strategies are adopted to satisfy the *input validation criteria*. First, the inputs that remain fixed across simulations (i.e., those reported in Table 1) are defined according to the values adopted by Fraccascia and Yazan (2018). Furthermore, results show a similar trend for both marble-based and alcohol-based IS relationships, which are characterized by different technical and economic data. This means that the outcome of the study does not depend on the value of these input data. Finally, further simulations have been conducted by considering that companies are spread into a geographical area of 50 Km side. Each scenario has been replicated 400 times. Simulation results are displayed in Table 1. Results show no differences in the outcome of the study.

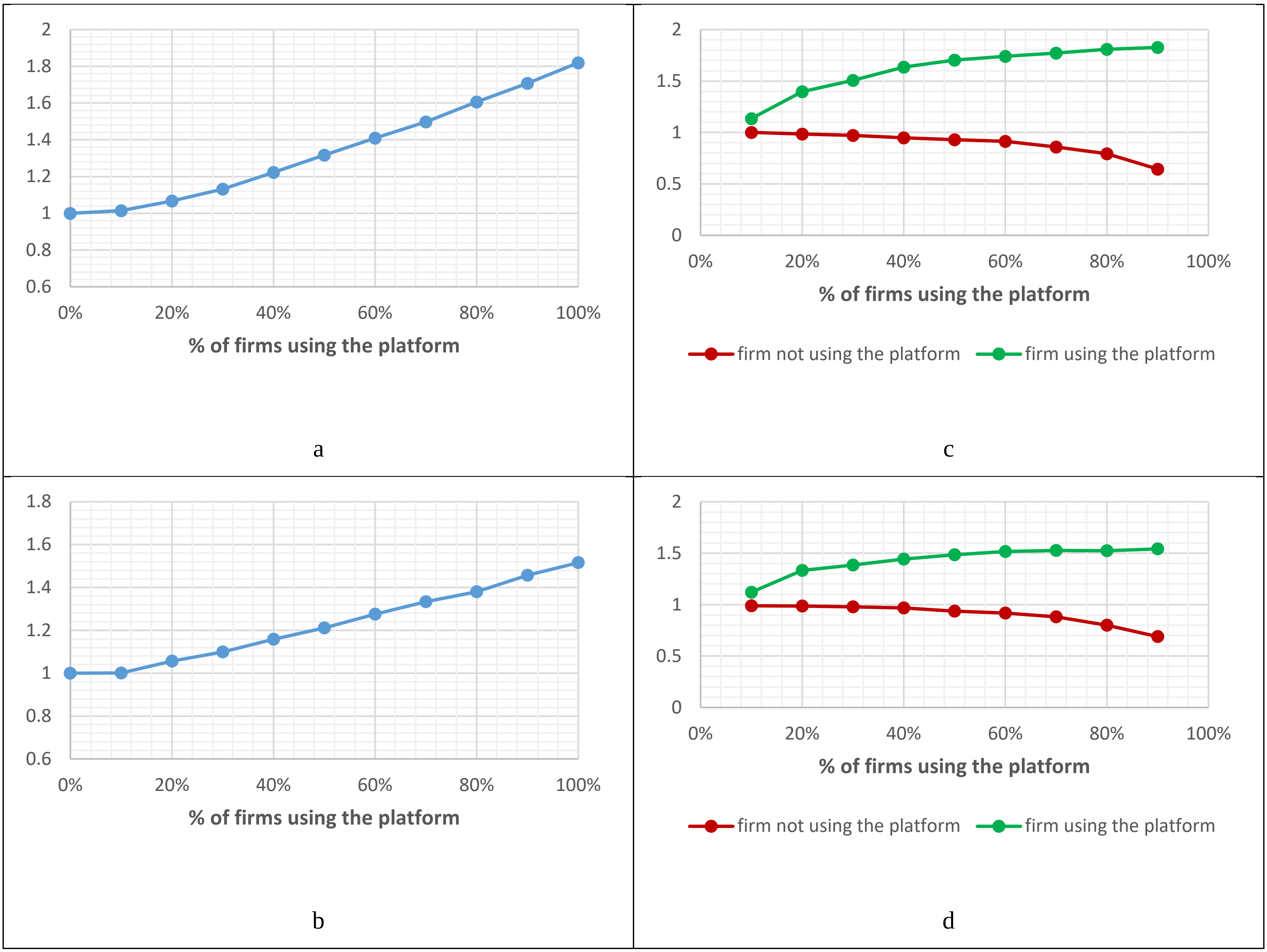

Figure 3. (a) Amount of saved marble residuals by marble producers, normalized according to the base case; (b) Amount of saved alcohol slops by alcohol producers, normalized according to the base case; (c) Amount of saved marble residuals by marble producers using the platform (green line) and by marble producers not using the platform (red line); (d) Amount of saved alcohol slops by alcohol producers using the platform (green line) and by alcohol producers not using the platform (red line)

Finally, output validation is provided via observing that, for all the simulated scenarios, companies using the platform perform better than similar companies operating IS traditionally (i.e., not using the platform). This is consistent with the hypothesis provided by the literature on the effectiveness of online platforms, as well as with the numerical results by Fraccascia and Yazan (2018).

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