Ecological Economics 230 (2025) 108502

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

What drives the success of online platforms for industrial symbiosis? An agent-based model

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ARTICLE INFO

Keywords:
Industrial symbiosis
Circular economy
Agent based model
Online platform

ABSTRACT

This paper aims to investigate which factors affect companies' choice of subscription to an online platform designed to support the creation of industrial symbiosis (IS) relationships, and the effectiveness of such platform from the economic and environmental perspectives. The analyzed platform finds optimal symbiotic partners by pursuing an economic objective and proposes the fair sharing of the additional costs of IS, enabling subscribers to avoid search and negotiation costs at the expense of a subscription fee. An agent-based model is developed where the companies' choice of subscription is dependent on potential savings in transaction costs, future expectations, and past experience. The main results highlight that (1) it is possible to attract subscribers with moderate fees by enhancing trust in the platform's usage widespread; (2) trust ensures hedging from waste demand and supply fluctuations; (3) the number of subscribers has a greater impact on the economic rather than on the environmental performance of the system.

1. Introduction

IS has been recognized as one of the most promising strategic approaches toward the circular economy (CE) and has increasingly drawn the attention of researchers and practitioners (Neves et al., 2020; Domenech and Bahn-Walkowiak, 2019; D'Amato et al., 2019). IS allows companies to exchange materials, energy, and by-products, providing them with long-term competitiveness (Chertow, 2000) and simultaneously reducing the environmental burden of the industrial system. In simple words, a waste producer and a waste receiver establish an industrial symbiosis relationship (ISR) when the waste receiver replaces its primary input with the waste provided by the waste producer.[1] Both the waste producer and the waste receiver obtain economic advantages from the ISR, i.e., reduced waste disposal costs for the waste producer, and reduced input purchase costs for the waste user (Fraccascia et al., 2017; Jacobsen, 2006). Moreover, environmental advantages arise due to the reduced amount of virgin primary inputs required and because of landfill diversion of wastes and by-products (Lombardi and Laybourn, 2012).

Despite these benefits, several barriers from the technical, legal, and organizational perspectives hamper the widespread of IS (Golev et al., 2015; Neves et al., 2019; Tudor et al., 2007). Among the others, information gaps, lack of mutual trust, and improper communication among firms play a major role. Since waste is not produced upon demand, but is generated by the waste producer as a consequence of the production of the main output, uncertainties or unawareness about waste availability – in terms of quantity, quality, and timing – can hold back promising ISRs from being realized (Taddeo et al., 2017). In fact, in absence of social ties derived from well-established and consolidated relationships, it is challenging for firms to exchange such information (Chertow, 2007; Golev et al., 2015).

Information and communication technology (ICT) tools (e.g., online platforms) are claimed to be effective to support the outgrowth of ISRs (Grant et al., 2010; van Capelleveen et al., 2018; Silva et al., 2022). Indeed, different digital tools might be employed to provide companies interested in implementing IS with clear information about (1) suitable partners and their geographic location, (2) quantity, quality, and timing of waste available for (or required by) the company, and (3) expected benefits and costs deriving from cooperation — trying to tackle some of the above-mentioned barriers. In the literature of IS the challenge of designing, implementing, and analyzing the effects of these tools has been widely addressed (e.g., Akrivou et al. (2021), Chen and Ma (2015), Lütje et al. (2019), Maqbool et al. (2018) and

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[1] Note that other forms of symbiotic relationships can arise. However, the most commonly referred to is the cooperation among separated companies where the input of one company is replaced with waste from the other company.

https://doi.org/10.1016/j.ecolecon.2024.108502
Received 15 July 2024; Received in revised form 30 October 2024; Accepted 12 December 2024
Available online 26 December 2024

Aid et al. (2015)), and theoretical findings support the economic and environmental advantages derived from their adoption (Fraccascia, 2020; Fraccascia and Yazan, 2018). However, starting from the earliest platforms employed in real contexts, e.g., WasteX (Clayton et al., 2002), or the Facility Synergy Tool (FaST) of the DIET toolkit (Dubester, 2000), such tools experienced some issues. For instance, when WasteX was created by The University of West Indies with the support of The Environmental Action Program, it encountered discouraging results: the Canadian International Development Agency had to recognize that the platform was not able to achieve the critical mass of users, despite its functionalities (Grant et al., 2010). A similar negative fate was encountered by FaST, which was claimed to have costly usability concerns to overcome (Grant et al., 2010). Later attempts to use this kind of platforms to support IS facilitated programs were still not successful. By way of example, during the project of development of the first Italian platform for IS – promoted by the Italian Agency for new Technologies, Energy and Sustainable Economic Development (ENEA) –, despite more than 690 potential matches among companies were found by the platform, several barriers hampered the actual implementation of those ISRs: environmental regulation, lack of cooperation and trust between industries in the area, economic barriers, and lack of information sharing (Cutaia et al., 2014). Also Fortuna and Diyamandoglu (2015), analyzing the performance of the NYC WasteMatch – a publically owned online facilitated materials exchange platform operated in New York City – found out that it did not contribute significantly to waste diversion in NYC, mainly because of lack of business awareness and integration into the local economy. Basically, these platforms encountered companies' resistance to subscription and unwillingness to share information (Yeo et al., 2019b; van Capelleveen et al., 2018). In the last years, several new platforms have been developed and tested in different regional contexts and industrial areas (King et al., 2020; Grimmel et al., 2024; Patricio et al., 2022). These tools are claimed to be effective just because they succeeded in finding a large number of potential advantageous matches among waste streams or because they address limitations previously detected in the literature, but without considering and reporting whether they actually determined the creation of ISRs. Moreover, no information is given regarding companies' evaluation and attitude toward such platforms over time. Only (Krom et al., 2022) addressed the problem by interviewing some platform providers, who confirmed that most companies are still unwilling to subscribe and commit to this kind of platforms in the long run. Hence, digital platforms supporting IS actually have a high chance of failure in achieving their goals and to fall in disuse after a really short time span (Benedict et al., 2018). Therefore, their effectiveness is hampered, but the literature of IS devoted scant attention in investigating how to drive companies' subscription and commitment to them.

This paper is aimed at addressing this research gap in the literature of ICT tools for IS by building a theoretical model to study the behavior of companies when deciding whether to subscribe to an OP aimed at supporting the creation of ISRs, and the effect of their choices from the economic and environmental perspectives. In particular, the methodological framework of this study is rooted in the well-know field of agent-based modeling (ABM). This is a modeling approach particularly suited to represent systems made of independent and heterogeneous agents interacting freely with each other (Giannoccaro and Pontrandolfo, 2009). Hence, its effectiveness in studying the dynamics of IS – especially the birth-stage, i.e., the cooperation decision-making process – has been widely recognized (Demartini et al., 2022; Batten, 2009). Several agent-based (AB) models have been proposed in the literature of IS, in which the cooperation decision of companies is modeled under different setting environments — with the aim of analyzing how these settings can influence the development of ISRs (Albino et al., 2016; Fraccascia et al., 2019). In this paper, other than exploiting ABM to model the companies' choice of cooperation, this methodology is employed to simulate the subscription decision-making process to the IS online platform, too. Therefore, the proposed AB model introduces a double decision-stage for companies, which represents a novelty in the literature, as the setting environment in which companies have to decide whether to cooperate is no longer imposed *from above* but it is shaped by companies' own decisions.

In addition to these literature streams related to IS, i.e., ICT tools to support IS and ABM to study the dynamics behind the development of IS, this work relates to the wider research field of business-to-business (B2B) digital platforms. Specifically, it is linked to the digital platforms' subscription-decision problem and builds on the economic theory of two-sided markets.

Indeed, the IS platform considered in this study – just like any traditional two-sided platform – enables the interaction between two groups of users (i.e., waste producers and waste receivers) — thus creating a two-sided market, i.e., a market where the benefits of the members of one group depend on the number of users belonging to the other group (Rochet and Tirole, 2004; Rysman, 2009; Fraccascia, 2020). Such phenomenon, known as cross-side (or indirect) network effect, is responsible of peculiar dynamics that occur when potential users have to choose whether to adopt a platform, which is no more dependent solely on the price.

Specifically, the online platform investigated in this paper aims at finding optimal symbiotic partners among subscribed agents, i.e., companies. The objective of the platform is to maximize the economic benefit achievable by the system — made of the agents subscribed to the platform. Subscription requires the agents to pay a subscription fee, but determines a number of benefits, which might result in economic advantages compared to companies not using the platform. In particular, subscribed agents are not in charge of searching their partner from their own nor to negotiate the terms of the ISR (i.e., they can reduce transaction costs), and they can be sure that the platform will provide them the optimal solution, restricted to the subsystem of subscribers.

The AB model is developed to simulate the dynamics behind the reasoning and the choices undertaken by companies when deciding whether to adopt the platform . In particular, the agents can choose whether and when to enter and/or leave the platform according to a rational economic reasoning dependent on (1) potential savings in transaction costs, (2) future expectations, and (3) past experience.

The present study aims at answering to the following research questions:

- (RQ1): Which are the main drivers of companies' choice of subscription to an online platform designed to support the creation of ISRs, assuming they act as rational economic agents?
- (RQ2): How does the strategic choice of subscription impact the environmental and economic benefits achievable through IS by the overall system?

To answer these research questions the developed AB model has been employed to analyze the average number of subscribers and the related overall economic and environmental benefits achieved by the system. Specifically, the influence of three main factors has been studied: (1) market dynamicity, (2) subscription fee, and (3) average level of trust in the usage widespread of the platform by other companies.

This paper provides a novel contribution to the literature of IS in terms of both content and methodology. Indeed, it is the first study to consider the issue of subscription from the companies' decision-making perspective in the research stream of ICT tools for IS. Furthermore, from the methodological perspective, this paper introduces a double decision-stage in the AB model, where the former decision-stage influences the setting environment of the latter, i.e., the subscription decision shapes the setting environment in which companies make their cooperation decisions.

The remainder of this paper is structured as follows. Section 2 provides the theoretical background of the paper. The AB model is developed in Section 3, while the logic, the setting and the metrics employed in the simulations is provided in Section 4. Section 5 contains the results and Section 6 the discussion. Conclusions are reported in Section 7.

2. Theoretical background

This Section develops the theoretical background of the manuscript and it comprehends three subsections.

Section 2.1 addresses the existing literature on ICT tools for enabling IS with a two-folded aim: (1) introducing the empirical context in which our model is rooted, and (2) recalling the main contributions of the literature to the topic — thus highlighting the research gap we are going to address.

There is a wide variety of tools discussed and available in the literature of IS, but we will focus on a specific one, i.e., an online platform to support the creation of ISRs. An overview of the literature on B2B digital platforms in a broader context is proposed in Section 2.2 to emphasize the relevance of the subscription decision problem in the literature of platforms and to provide a deeper understanding of the main related issues.

Finally, Section 2.3 shortly describes the foundations of ABM and elucidates the methodological approach proposed in the paper. Specifically, we will discuss how this methodology has been extensively used and recognized as a proper technique to study the development of IS – thus justifying its employment in this study – and highlight the novelty of the proposed AB model, i.e., the introduction of the double decision-stage.

2.1. ICT tools for IS

The potential of ICT to support the creation and the development of IS is a matter of fact and has been soon recognized (Grant et al., 2010). Indeed, it was even before the year 2000 that the earliest tools to support the creation of ISRs were developed (Brown, 2002; Boyle and Baetz, 1998). Given the expected potential of these tools, many efforts have been made to leverage them and promote the widespread of IS (e.g., Chen et al. (2006), Mirata (2004) and Young (1999)). However, most did not fulfill the expectations. As Grant et al. (2010) posed the attention on the high failure rate of these attempts, increasing interest in the issue has risen in the literature of IS (e.g., Dietrich et al. (2014), Dhanorkar et al. (2015), Chen and Ma (2015) and Ghali et al. (2016)).

Specifically, researchers have focused on three related research streams: (1) overview, classification, and evaluation of existing tools, (2) conceptualization and design of new tools, and (3) theoretical studies on these tools effectiveness.

Regarding the first research stream, van Capelleveen et al. (2018) classified ICT tools aimed at facilitating the identification of IS into six main typologies characterized by the type of support provided, the openness of information, and the technologies and techniques adopted. The aim of the authors was to propose future directions to enhance these tools' effectiveness: product and service development, data integration and adoption of intelligent learning have been recommended. Benedict et al. (2018) analyzed existing ICT tools for IS against the background of platform ecosystems theory to underline the main limits of existing platforms. Specifically, (1) the lack of standardized data and interoperability between different systems, (2) the scarce attention to the social component, (3) the need for integration of different methods, and (4) the non-accessibility or the low level of awareness of such tools have been recognized as the major ones. Later on, Yeo et al. (2019b) analyzed IS tools available in the literature with respect to each step of the IS creation process, i.e., (1) preliminary assessment, (2) businesses engagement, (3) synergy opportunities identification, (3) business feasibility assessment, (4) implementation of transactions, and (5) documentation and reinforcement. Through a systematic literature review, the paper investigated the specific techniques and approaches used, the tools' main requirements, and their application contexts. Results highlighted that relevant tools mainly focus on performance evaluation in order to identify proper synergy opportunities and make use of process input–output stream-based matching techniques coupled with a corresponding IS facilitation program. Recently, Krom et al. (2022) addressed the way in which digital platforms can overcome the barriers of IS through qualitative, semi-structured interviews conducted with some platform providers. According to the authors, platforms should be easily accessible and user-friendly, ensure compatibility with the systems already in use, and provide clear information about the financial benefit derived from joining.

Strictly connected with the suggestions proposed by the above-mentioned studies, the second research stream of the literature of ICT tools for IS is concerned with designing new tools that might overcome the identified barriers. For instance, Kerdlap et al. (2019) proposed the introduction of an Industrial Symbiosis-Life Cycle Analysis (IS-LCA) Engine to assess the environmental performance of IS through process-based LCA using a matrix-based model. Hsien et al. (2019) presented a web-based graph database engine for companies to find out how to convert their wastes into resource, and then extended the database query processor to identify such eco-efficient pathways according to user's preferences (Hsien et al., 2020). Yeo et al. (2019a) proposed a method for creating a self-learning waste-to-resource database (W2RDB) to minimize time and effort required in the long-term maintenance of IS knowledge repositories.

As the third main research stream, the literature of IS addressed the issue of platforms to support the creation of ISRs from the theoretical perspective, too. In particular, Fraccascia and Yazan (2018) employed an AB model to compare the economic and environmental performances of a self-organized industrial symbiosis network (ISN) in the presence of an information-sharing platform with those of a baseline scenario (i.e., without the platform), showing the positive role of the platform from both perspectives. Later on, Fraccascia (2020) highlighted the importance for these kind of platforms of reaching a large number of subscribed companies, to exploit the benefits deriving from the network effects. Indeed, the higher the platform usage rate, the higher the individual benefits for users will be, *ceteris paribus*. Moreover, the higher the usage rate, the higher the economic and environmental advantages obtained by the ISN, *ceteris paribus*.

Despite the literature detecting several key issues concerning different existing ICT tools for IS and trying to propose solutions (first research stream), the analysis overlooked the identification of the strategic drivers for companies' subscription and commitment to them. Moreover, while the improvement of these tools' functionalities and the fine-tuning of technological issues are critical for them to be successful (second research stream), these efforts take the risk of being in vain if companies are not willing to use them. In the existing theoretical studies (third research stream), companies are not allowed to choose whether to use or not to use the platform, thus the decision-making of companies is disregarded once again. Therefore, there is a gap in the literature of ICT tools for IS concerning the strategic decision-making of companies toward these tools' subscription and commitment, and this paper is aimed at filling this research gap.

2.2. B2B digital platforms

The digital transition is markedly transforming traditional B2B relationships. In particular, B2B - or industrial[2]- digital platforms are gaining an increasingly prominent role in the industrial landscape. The meaning of the word "platform" itself is source of considerable confusion in the literature (De Reuver et al., 2018). Indeed, different types of industrial digital platforms exist, varying from those internal to the single company (e.g., internally connected systems providing basic services) to the ultimate platform ecosystems (Jovanovic et al., 2022; Hein et al., 2019). A recent studied by Madanaguli et al. (2023) raised the issue of the need for a more appropriate and concrete definition of the concept and revised the existing literature of industrial digital

[2] In the following, the terms *B2B digital platform* and *industrial digital platform* will be considered interchangeable.

platforms from a business model perspective. The authors distinguished the different types of industrial digital platforms according to their level of (1) data integration, i.e., to which extent they create, deliver and capture value from data, and (2) ecosystem integration, i.e., how much different ecosystem partners are integrated into the platform. To the aim of our study, we may focus on those platforms defined by Madanaguli et al. (2023) as *industrial transaction platforms*, i.e., platforms that create value by reducing searching and transaction costs and act as intermediaries among companies. The most frequently studied in the literature are the electronic marketplaces (e.g., Johnson and Johnson (2005) and Yoon et al. (2021)), but these kind of platforms can have different shapes. According to Shree et al. (2021, p.354), they can be defined as *"internet-based aggregators of buyers and sellers"*. Typically, they are designed to efficiently match demand and supply to increase the transactions' number and to provide a value-adding service for subscribed companies.

The issue of driving users' subscription decisions to such platforms has been widely addressed (Ruutu et al., 2017; Casey and Töyli, 2012), especially in the business-to-consumer (B2C) context.[3] Bichraoui et al. (2013) assessed that when the platform is in the initial stages, adopters' willingness to pay for subscribing primarily depends on stand-alone features, while the decision-making in the following stages of the platform considers both stand-alone features and participation of users on the other side of the platform. According to Haurand and Stummer (2018), the decision to adopt the platform is determined by buying conditions (e.g. fees), perceptions of the future platform's success (in terms of number of participants on the other side of the platform), prior experiences and also individual preferences. Actually, a consistent stream of the literature on platforms focused on the issue of platforms' adoption in their initial stages, when they have to deal with the so-called *chicken-and-egg dilemma*, i.e., which side to *take on board* first and how. Several launching strategies have been suggested to overcome this initial coordination problem. Stummer et al. (2018) listed six main strategies available for platforms, i.e., (1) single target group, (2) platform staging, (3) subsidizing, (4) platform envelopment, (5) exclusivity agreement, and (6) side switching. Later on, Schirrmacher et al. (2017) distinguished these strategies between sequential and simultaneous entry strategies and highlighted that the latters can be employed in the case of switching user sides, i.e., if users can switch side in the platform. Recent efforts have been made to understand the difference between B2B and B2C digital platforms and how these differences can impact the success of their launching strategies. In particular, Anderson et al. (2022) proposed a value-creation framework tailored to B2B digital platforms according to which the total value for users on either side can be separated into three components: stand-alone value, cross-side value and same-side value. The authors pointed out that it is more likely for a B2B platform to leverage on stand-alone functionality at the launching stage. However, over time, B2B platforms' value propositions might shift emphasis from stand-alone value to a cross-side value. Also, Shree et al. (2021) argued that the technological, organizational and environmental context are key in determining companies' the attitude toward platforms' adoption.

While the literature on platforms has shown considerable interest in understanding the dynamics underlying users' subscription decisions and has deepened the issue until deriving proper strategies to enhance their chances of success in the long run – both in the B2C and B2B context –, the topic has remained completely unspoiled in the field of IS. Therefore, this paper provides the first contribution to the literature of IS in this context.

2.3. Agent-based models for IS

ABM is a methodological framework to model systems made of independent and heterogeneous agents — interacting with each other. Agents are provided with specific sets of rules to follow and objectives to achieve. They make choices and adjust their behavior according to the actions of other agents and to fit with the environment. As a result, the system evolves over time, showing the emergence of patterns, structures, and properties.

It has been argued that ABM is particularly effective to model complex adaptive systems (CASs), i.e., networks in which agents interact freely without the presence of any central entity or control mechanism (Dooley, 1997; Holland, 2002). Indeed, CASs are characterized by adaptiveness, non-linearity, and path dependence (Arthur, 1994; David, 1994; Rammel et al., 2007): all mechanisms which analytical models fail to address, but that can be properly modeled through ABM.

The literature of IS has soon recognized self-organized industrial symbiosis networks (ISNs)[4] as CASs (Chertow and Ehrenfeld, 2012; Cote and Hall, 1995). Therefore, several studies in the field of IS have been conducted relying on the ABM approach (Demartini et al., 2022). For instance, Cao et al. (2009) employed ABM to show the economic and environmental advantages deriving from building a hypothetical Eco-Industrial Park (EIP)[5] in the Sichuan Province in China to exploit the natural gas and halite resources available in the area and to support its economic development in a sustainable way. Later on, Bichraoui et al. (2013) stressed the important role of ABM as a tool for shaping the behavioral characteristics of companies to study the emergence of IS. In the paper, the authors proposed an AB model to explore how cooperation level and learning conditions can affect the development of an ISN. Albino et al. (2016) studied the effect of contractual mechanisms in the creation of ISRs through ABM and showed how these contracts should guarantee benefits for all parties in order to facilitate the establishment of symbiotic synergies. Ghali et al. (2017) proposed an AB model of a self-organized ISN to show how trust and social factors can be included in the processes of knowledge diffusion and synergy creation. Zheng and Jia (2017) used ABM to investigate the influence of promoting strategies – associated with various dimensions of institutional capabilities – on the identification of IS opportunities, while Fraccascia et al. (2020) investigated the role of different redundancy strategies on the development of an ISN. Lately, Saghafi and Roshandel (2024) integrated the technological feasibility of the symbiotic exchanges into an AB model aimed at simulating the development of an EIP in a region at the south of Tehran, Iran.

Basically, AB models have been employed in the literature of IS either to simulate and predict the feasibility of potential EIPs in some specific areas, or to investigate which factors might affect the cooperation decision of companies. Specifically, in this latter stream of the literature, the cooperation decision process of companies is typically modeled under different setting environments, e.g., with different contractual schemes (Albino et al., 2016), with different social structures (Ghali et al., 2017), with different promoting strategies (Zheng and Jia, 2017), and with different redundancy strategies (Fraccascia et al., 2020). These settings are not affected by the agents' own choices but are imposed *from above* and kept stable for the entire simulation time. Similarly, in the AB model developed in this paper, companies undergo the cooperation decision-making process. However, companies have to deal with a former decision-stage, which shapes the setting environment in which they will decide to cooperate in ISRs, i.e., the subscription decision to the online platform. Hence, this study represents a novelty for the literature of AB models for IS, since it is the first to introduce a double decision-stage.

[3] B2C platforms enable transactions between businesses and consumers, differently from B2B platforms where transactions are only between businesses.

[4] ISN arises when at least three firms exchange at least two wastes. ISNs can arise spontaneously from the bottom-up: in this case, they are called self-organized ISNs.

[5] An EIP is a term commonly used as synonymous with ISN in the context of facilitated IS programs or top-down approaches to IS.

3. The agent-based model

This section will provide the theoretical development of the AB model. It is divided into four main subsections: Section 3.1 describes the agents; Section 3.2 models how the agents behave; Section 3.3 provides the functioning of the platform; finally, Section 3.4 describes the dynamics of the model.

3.1. Agents description

Let us consider two groups of agents: agents of type A (e.g., $i \in \{1,\dots,n\}$) and agents of type B (e.g., $j \in \{1,\dots,m\}$).

Each agent represents a company. For the sake of simplicity, each agent produces one main output, requiring one input and generating one waste. The generic agent x (either of type A or B) is characterized by a certain mean output demand $\bar{d}_x$ and standard deviation σ_{d_x}.

The same technology characterizes agents of the same type. Hence, for any given amount $q_i(t)$ of main output to produce at time t, agent i of type A will require an amount of primary input $r_i(t)$ and generate an amount of waste $w_i(t)$, which can be computed as follows:

$$\begin{aligned} r_i(t) &= R_A \cdot q_i(t) \\ w_i(t) &= W_A \cdot q_i(t) \end{aligned} \tag{1}$$

Conversely, for any given amount $q_j(t)$ of main output to produce at time t, agent j of type B will require an amount of input $r_j(t)$ and generate an amount of waste $w_j(t)$, which can be computed as follows:

$$\begin{aligned} r_j(t) &= R_B \cdot q_j(t) \\ w_j(t) &= W_B \cdot q_j(t) \end{aligned} \tag{2}$$

where R_A, W_A, R_B, and W_B are technical substitution coefficients. Specifically, R_A and R_B denote how many units of primary input are required by agents of type A and B, respectively, to produce one unit of output; similarly, W_A and W_B denote how many units of waste are generated by agents of type A and B, respectively, when producing one unit of output.

Let us assume that agents of type B can replace their primary input with waste generated by agents of type A, after the waste has received some treatment. Hence, any couple made by an agent i of type A and an agent j of type B can establish an ISR, in which agent i is the waste producer and agent j is the waste receiver. In particular, let us assume that s_{AB} units of input can be replaced by one unit of waste; moreover, let the efficiency of the treatment process, i.e., the percentage of waste that can be used as input after having received the treatment, be equal to β.

Being $q_i(t)$ and $q_j(t)$ the amount of output to be produced by agent i and agent j at time t, respectively, the amount of waste that can be exchanged in an ISR between these two agents at time t - denoted as $e_{i\to j}(t)$ - is defined as the minimum between the amount of waste produced by agent i and the amount of waste required by agent j. According to the literature (Fraccascia, 2019), it can be computed as follows:

$$e_{i\to j}(t) = min\left\{ W_A \cdot q_i(t); \frac{R_B \cdot q_j(t)}{\beta \cdot s_{AB}} \right\} \tag{3}$$

Let d_{ij} be the distance in km between i and j, udc the unit waste disposal cost, upc the unit input purchase cost, $utrec$ the unit waste treatment cost, and $utrac$ the unit waste transportation cost per km. Then, for each unit of waste exchanged at time t:

- agent i, i.e., the waste producer, obtains savings in waste disposal costs $SAV_i(t) = udc \cdot e_{i\to j}(t)$;
- agent j, i.e., the waste receiver, obtains savings in input purchase costs $SAV_j(t) = upc \cdot e_{i\to j}(t)$;
- additional costs arise for the treatment and the transportation of the waste $AC_{ij}(t) = (utrec + utrac \cdot d_{ij}) \cdot e_{i\to j}(t)$;

The above-mentioned additional costs can be shared between agent i and agent j. Specifically, the share of additional costs of IS ($AC_{ij}(t)$) paid by agent i is α_{ij}, while the share of additional costs of IS paid by agent j is $1-\alpha_{ij}$ (Fraccascia and Yazan, 2018). If $\alpha_{ij} \in [0,1]$, the additional costs of IS are shared between agent i and agent j and the waste is exchanged free of charge. If $\alpha_{ij} > 1$, agent i, i.e., the waste producer, bears the overall additional costs of IS and further pays agent j, i.e., the waste receiver, to dispose of its waste. Conversely, if $\alpha_{ij} < 0$, agent j, i.e., the waste receiver, bears the overall additional costs of IS and further pays agent i, i.e., the waste producer, to buy its waste (Fraccascia et al., 2020).

3.2. Agent's decisional rules

In the following, the agents' behavior will be analyzed with respect to the actions they can undertake — specifically, the choices of cooperation and platform subscription.

3.2.1. Evaluation of industrial symbiosis relationships

The establishment of the ISR implies transaction costs to be paid by both agents. Let x be the generic agent (either of type A or B), according to the literature, we can model the transaction costs paid by agent x as made of three components (Hobbs, 1996; Williamson, 1981; Rindfleisch and Heide, 1997): (1) costs for searching a suitable partner, i.e., search costs sc_x, (2) costs for negotiating the parameter a_{ij}, i.e., negotiation costs nc_x, and (3) costs for monitoring the partner performance and the quality of the waste exchanged, i.e., enforcement costs ec_x. In particular, the following condition holds:

$$TC_x = sc_x + nc_x + ec_x \tag{4}$$

The gross economic benefit stemming from the establishment of the ISR for the waste producer i and the waste receiver j at time t, respectively, can be computed as follows:

$$\begin{aligned} GEB_i^{IS}(t) &= SAV_i(t) - \alpha_{ij} \cdot AC_{ij}(t) - ec_i \\ GEB_j^{IS}(t) &= SAV_j(t) - (1-\alpha_{ij}) \cdot AC_{ij}(t) - ec_j \end{aligned} \tag{5}$$

Note that search costs ($sc_x, x = \{i,j\}$) and negotiation costs ($nc_x, x = \{i,j\}$) are sunk costs for both agent i and agent j. Indeed, these costs contribute to the net economic benefit deriving from IS but are not considered when evaluating whether to establish the ISR. Hence, the willingness to cooperate for the generic agent x - being x either i or j - at time t can be computed as follows (Albino et al., 2016; Fraccascia and Yazan, 2018; Fraccascia, 2020; Fraccascia et al., 2020):

$$WTC_x^{i\to j}(t) = \frac{1}{L_x^{i\to j}(t)+1} \cdot \frac{GEB_x^{IS}(t)}{utc \cdot e_{i\to j}(t)} + [1 - \frac{1}{L_x^{i\to j}(t)+1}] \cdot WTC_x^{i\to j}(t-1) \tag{6}$$

where $L_x^{i\to j}(t)$ is the number of sequential periods in which agent i and agent j have been cooperating until time t and utc is the unit traditional cost that would be paid by agent x if IS was not implemented, i.e., $utc = udc$ if agent x is a waste producer and $utc = upc$ if agent x is a waste receiver. An ISR between agent i of type A and agent j of type B arises at time t when their willingness to cooperate ($WTC_x^{i\to j}(t)$) is simultaneously higher than their respective minimum benefit expected ($T_x^{IS} < 1$). The willingness to cooperate between i and j depends on (1) the gross economic benefit stemming from the cooperation and (2) the history of the agent, i.e., the willingness to cooperate between i and j is path-dependent (Boons and Howard-Grenville, 2009; Chertow, 2007).

The net economic benefit deriving from IS for the waste producer i and the waste receiver j at time t is, respectively:

$$\begin{aligned} NEB_i^{IS}(t) &= GEB_i^{IS}(t) - sc_i - nc_i \\ NEB_j^{IS}(t) &= GEB_j^{IS}(t) - sc_j - nc_j \end{aligned} \tag{7}$$

3.2.2. Evaluation of subscription to the online platform

Let us assume that an OP exists and is available for agents to (1) find the optimal partner, i.e., the partner that maximizes the total economic benefit stemming from the ISR according to the distance between the plants and the match between demand and supply, and (2) share equally and fairly the emerging costs of IS.

Subscription to the OP is subjected to a fixed fee F to be paid in each period t. Moreover, enforcement costs (ec_x) are still to be paid, but the OP allows the generic agent x to avoid search (sc_x) and negotiation costs (nc_x).

The OP creates a two-sided market. Indeed, each agent of type A benefits from the increase in subscriptions to the OP of agents of type B and *viceversa*, as the chance to find a more suitable partner increases with the number of potential partners subscribed (Rochet and Tirole, 2004; Rysman, 2009).

Each agent x willing to establish an ISR has a specific willingness to subscribe to the OP at time t, i.e., $WTS_x^{OP}(t) \in [0,1]$. The willingness to subscribe to the OP is modeled as a utility function depending on three components: (1) the percentage of savings in transaction costs, (2) the indirect network effect, and (3) the path dependence.[6] It can be computed as follows:

$$
\begin{aligned}
WTS_x^{OP}(t) = a_x^1 \cdot \frac{sc_x + nc_x - F}{TC_x} + a_x^2 \cdot \frac{E[s_T(t)]_x}{N_T} + a_x^3 \cdot \Delta(WTC) \\
s.t. \quad a_x^1 + a_x^2 + a_x^3 = 1 \\
0 \le a_x^1 \le 1 \\
0 \le a_x^2 \le 1 \\
0 \le a_x^3 \le 1
\end{aligned} \tag{8}
$$

The coefficients a_x^1, a_x^2, and a_x^3 are meant to weight each addendum of the willingness to subscribe to the OP - aimed at assessing its percentage effect on the overall utility.

The subscript T is such that:

$$
\begin{cases} T = B & \text{, if } x \text{ is of type A} \\ T = A & \text{, if } x \text{ is of type B} \end{cases} \tag{9}
$$

The first addendum of Eq. (8) ($\frac{sc_x+nc_x-F}{TC_x}$) represents the percentage of transaction costs saved by using the OP: the lower the platform subscription fee compared to the transaction costs, the higher the willingness to subscribe, *ceteris paribus*. Conversely, if the fee is higher than the search and negotiation costs, such addendum is lower than zero: accordingly, the willingness to subscribe of agent x is reduced, *ceteris paribus*.

The second addendum of Eq. (8) ($\frac{E[s_T(t)]_x}{N_T}$) stands for the indirect network effect derived from subscribing to the OP. It represents – for agents of type A (B) – the percentage of agents of type B (A) expected to be subscribed to the OP at time t. Indeed, the higher the expected number of agents of type T subscribed to the OP, the higher the benefit that agent x is expected to achieve from adopting the OP, *ceteris paribus*. The expected number of agents of type T subscribed to the OP at time t according to agent x ($E[s_T(t)]_x$) can be computed as follows:

$$
\begin{cases} E[s_T(t)]_x = max\{\,0, rand \cdot N_T + \psi_x\,\} & \text{, if } t = 1 \\ E[s_T(t)]_x = max\{\,0,\ s_T(t-1) + \psi_x + \Delta_x(t)\} & \text{, if } t > 1 \end{cases} \tag{10}
$$

According to Eq. (10):

- At time $t = 1$ the expected number of agents of type T subscribed to the OP is defined randomly and corrected with a variable ψ_x, which can be positive or negative. The variable ψ_x is specific to each agent and represents the optimism (if positive) or the pessimism (if negative) of the agent toward the widespread of the OP. In the following, ψ will be referred to as *"trust level in the OP"*.[7]
- At the generic time t the expected number of subscriptions to the OP of agents of type T according to agent x is equal to the effective number of subscription observed at time $t-1$ ($s_T(t-1)$), corrected by the ψ_x and by a second factor $\Delta_x(t)$. This factor ($\Delta_x(t)$) is a random variable such that:

$$
\begin{cases} \Delta_x(t) > 0 & \text{, if } E[s_T(t-1)]_x < s_T(t-1) \\ \Delta_x(t) < 0 & \text{, if } E[s_T(t-1)]_x > s_T(t-1) \end{cases} \tag{11}
$$

  Namely, if agent x underestimated the number of subscriptions at time $t-1$, the expectation at time t will be increased. In contrast, if the agent overestimated the number of subscriptions at time $t-1$, the expectation at time t will be reduced.

The third addendum of Eq. (8) ($\Delta(WTC)$) is related to the path-dependence phenomenon. In particular, it can be computed as follows:

$$
\begin{cases} \Delta(WTC) = 0 & \text{, if } t = 1 \\ \Delta(WTC) = \frac{WTC_x^{x\to k}(t-1) - WTC_x^{x\to q}(t-1)}{WTC_x^{x\to q}(t-1)} & \text{, if } t > 1 \end{cases} \tag{12}
$$

where k is the partner suggested to agent x by the OP at time $t-1$ - if agent x was subscribed and an optimal partner for agent x was found by the OP - and q is the previous partner of agent x - if agent x was cooperating with another partner (different from agent k) at time $t-2$. Such construction allows us to model the following mechanism:

- The higher the benefits obtained from an ISR suggested by the OP in the previous periods, the higher the willingness to subscribe again to the OP will be, *ceteris paribus*.
- The higher the benefits obtained from an ISR not suggested by the OP, the lower the willingness to subscribe to the OP will be, *ceteris paribus*.

Whether the willingness to subscribe to the OP of agent x is higher than a given threshold (T_x^{OP}), agent x will decide to subscribe.

3.2.3. Evaluation of industrial symbiosis relationships suggested by the online platform

Each couple made of a waste producer i and a waste receiver j suggested by the OP will be keen to establish an ISR whether the willingness to cooperate (computed as described in Eq. (8)) of both agents is higher than their respective minimum expected benefit from IS, i.e., T_i^{IS} and T_j^{IS}.

The net economic benefit deriving from an ISR established at time t with the aid of the OP for the waste producer i and the waste receiver j, respectively, is:

$$
\begin{aligned}
NEB_i^{IS}(t) = GEB_i^{IS}(t) - F \\
NEB_j^{IS}(t) = GEB_j^{IS}(t) - F
\end{aligned} \tag{13}
$$

[6] The construction of the $WTS_x^{OP}(t)$ is consistent with the model proposed by Zhu and Iansiti (2012). Indeed, the authors defined the consumer's utility to join the platform as made of three components: (1) a fixed parameter dependent on the specific consumer j, (2) the quality level of the platform, and (3) the indirect network effect.

[7] Note that, in this paper, the term *"trust"* is related to users' beliefs in the platform's usage widespread in future period, and it is not related to the disclosure of sensible information. Indeed, to the aim of our study, we have excluded this already well argued variable (i.e., trust in the platform not disclosing information) from the analysis to focus on other effects currently disregarded in the literature. Readers interested in the topic are referred to the (non-exhaustive) list of following papers: Fraccascia and Yazan (2018), Benedict et al. (2018), and Patricio et al. (2022).

3.3. Online platform functioning

The OP aims at finding optimal partners among subscribed agents. To do so, the OP solves a matching problem on a bipartite graph, also known as *assignment* problem (Asratian et al., 1998). Indeed, subscribed agents can be modeled as the nodes of a complete bipartite graph, in which each agent of one group (waste producers or waste receivers) can be assigned to any agent of the other group.

The optimization problem can be written as follows:

$$\begin{aligned} & max \sum_{i=1}^{n}\sum_{j=1}^{m} c_{ij}(t)\cdot x_{ij}(t) \\ s.t. & \sum_{j=1}^{m} x_{ij}(t) \le 1 \quad , \ i = 1..n \\ & \sum_{i=1}^{n} x_{ij}(t) \le 1 \quad , \ j = 1..m \\ & x_{ij}(t) \in \{0,1\} \end{aligned} \tag{14}$$

where $x_{ij}(t)$ is a binary variable such that $x_{ij}(t) = 1$, if agent i and agent j are optimal partners at time t, and $x_{ij}(t) = 0$ otherwise. The coefficients $c_{ij}(t)$ in the objective function represent the total economic benefit stemming from the ISR between agent i and agent j at time t and are computed as follows:

$$c_{ij}(t) = (udc + upc - utrec - utrac \cdot d_{ij}) \cdot e_{ij}(t) \tag{15}$$

Specifically, these coefficients can be defined as the sum of savings that would be obtained (by both the waste producer and the waste receiver) minus the overall arising costs from the potential symbiotic relationship. Note that this measure is aggregate, i.e., it does not consider how the benefits will be shared between the parts. This is because the aim of the platform is to maximize the overall economic benefit achievable by the system. Moreover, in the computation of $c_{ij}(t)$, the coefficient $(udc + upc - utrec - utrac \cdot d_{ij})$ is constant for the specific couple ij, while $e_{ij}(t)$ is defined according to Eq. (3) and, therefore, it depends on the specific time period. Hence, the platform can suggest to a specific agent i different optimal partners at different times.

The two sets of capacity constraints ensure that each agent can be the optimal partner for only one agent of the opposite type at best. Note that a generic agent x can remain without an optimal partner if:

1. The number of agents of type A and type B is different;
2. The total economic benefit deriving from the most convenient IS for agent x is negative.

The OP has the additional role of suggesting how to share the additional costs of IS between agent i and agent j, i.e., to define the parameter α_{ij}. In order to promote a fair cost-sharing policy, the OP computes α_{ij} such that each partner would incur a cost equal to its Shapley Value (Yazan et al., 2020).

3.4. Behavioral dynamics

The algorithm of the AB simulation can be divided into four main processes, as shown in the flowchart reported in Fig. 1.

1. **First Process: Platform Adoption**
At the beginning of each period, each agent x either of type A and B decides whether to subscribe to the OP, which is done by comparing the willingness to subscribe of agent x at time t with its minimum expected benefit from the subscription.
2. **Second Process: Matching First Round**
For each optimal couple of subscribed agents $(i,j)^*$ suggested by the OP, both agents i and j should decide whether to cooperate with the suggested partner. If i and j were already partners at time $t-1$, or none of them had a previous different partner, the choice only depends on the willingness to cooperate, i.e., they will cooperate if and only if $WTC_i^{i\to j}(t) \ge T_i^{IS}$ and $WTC_j^{i\to j}(t) \ge T_j^{IS}$ simultaneously. However, whether agent i and/or j were cooperating with another partner at time $t-1$, i.e., the OP suggested to agent i and/or j to change their partner, the agent should decide whether to follow the suggestion of the OP or to continue its previous ISR. This is made by comparing the willingness to cooperate with the new suggested partner and with the old partner.
3. **Third Process: Matching Second Round**
Since some subscribed agents might not follow the suggestion of the OP, a second round of the matching algorithm performed by the OP is executed in each period to provide a further suggestion for those subscribed agents still not involved in IS at time t.
4. **Fourth Process: Non-Subscribed Agents**
Once all subscribed agents have chosen whether to cooperate and their partners, non-subscribed agents have to make their decisions, too. First, ISRs established in previous periods are considered. Whether old ISR are interrupted, non-subscribed agents search for a new partner randomly. If a non-busy partner is found, a negotiation about how to share the additional costs of IS takes place: the potential partners negotiate the value α_{ij} and must find an agreement in a maximum of three proposals, after which the ISR is abandoned.

4. The simulation study

This section provides the logic, the setting, and the metrics adopted in the simulations.

4.1. Simulation setting and investigated scenarios

The proposed AB model has been implemented in MATLAB, while the matching algorithm performed by the OP has been implemented in Visual Studio Code and solved with the Gurobi Solver. Each run considered a total number of 100 agents (i.e., 50 agents of type A and 50 agents of type B) randomly distributed in a square of 50 km^2 and interacting for 40 periods (i.e., ten years considering each period equal to a trimester).

To ensure the consistency of the simulation input dataset, we have decided to refer to the IS that can be established between alcohol producers and fertilizer producers exchanging alcohol slops. Indeed, the use of alcohol slops as input for fertilizer production processes is a case of perfect[8] symbiosis well-known in the literature (Yang and Feng, 2008; Zhu et al., 2007). Therefore, it has been often used as an exemplification of theoretical and simulation models (Fraccascia and Yazan, 2018; Albino et al., 2016).

Let us assume agents of type A are alcohol producers and agents of type B are fertilizer producers. The following inputs have been used as simulation setting, in compliance with Fraccascia (2020):

For the sake of simplicity, it is assumed that one unit of waste can replace one unit of primary input: accordingly, both s_{AB} and β are equal to one. The mean demand of output of each company of type T (i.e., A or B) is distributed according to a normal distribution with mean $\overline{d_T}$ and coefficient of variation equal to 0.1. A normal distribution is also assumed for the output demand of each agent over time. Note that the mean demand of output for both types of agents is such as to ensure the match between the overall demand and supply of waste.

The developed model has been employed to analyze (1) the average number of agents subscribed to the OP, and (2) the economic and environmental performance of the agents in presence of the OP.

[8] When there is no need of additional treatments to be performed on the waste before it enters the new production process, the IS is called “perfect”; otherwise it is called “imperfect”.

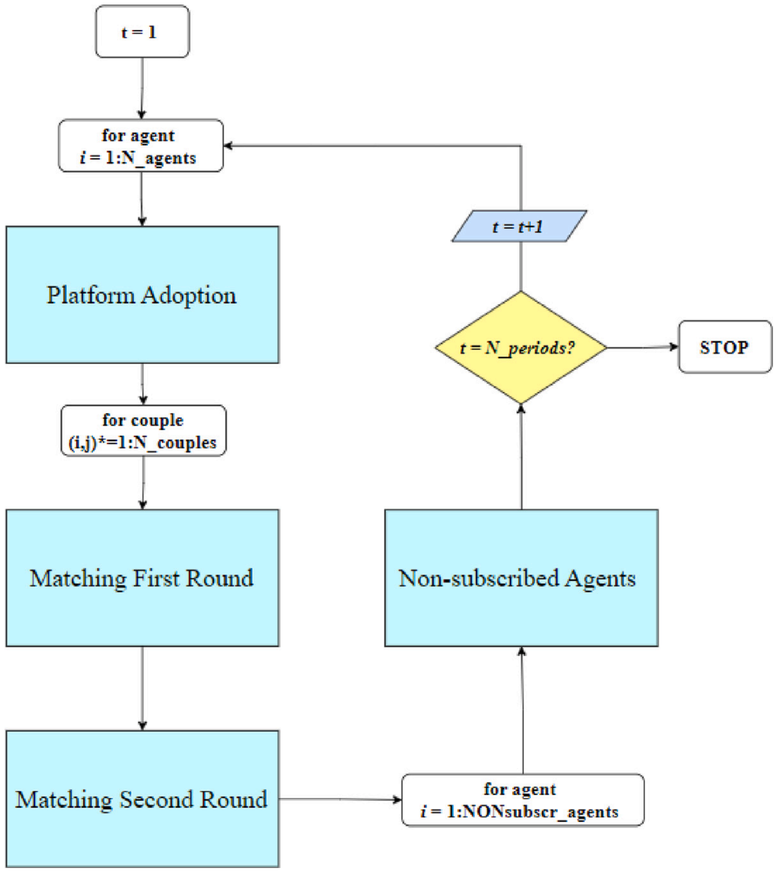


Fig. 1. Simulation flowchart: macroview.

Table 1
Simulation setting.

Variable	Value
udc	30 $\frac{\text{eur}}{\text{t alcohol slops}}$
upc	70 $\frac{\text{eur}}{\text{t alcohol slops}}$
$utrec$	–
$utrac$	5 $\frac{\text{eur}}{\text{km t alcohol slops}}$
R_B	0.4 $\frac{\text{t alcohol slops}}{\text{t fertilizer}}$
W_A	0.8 $\frac{\text{t alcohol slops}}{\text{t alcohol}}$
$\overline{d_A}$	10000 t/year
$\overline{d_B}$	20000 t/year

Table 2
Levels for the investigated factors.

Factor	Levels
Market dynamicity (CV)	0.1; 0.3; 0.5
Subscription fee (F)	0; $0.5 \cdot \overline{TC}$[a]; $1 \cdot \overline{TC}$; $1.5 \cdot \overline{TC}$
Average trust level in the OP ($\overline{\psi}$)	$-0.2 \cdot N_T$[b]; $+0.2 \cdot N_T$

[a] $\overline{TC}$ is the average total transaction cost.
[b] N_T is the total number of agents of the other side of the platform with respect to $T \in \{A, B\}$.

The analysis has been conducted subjected to variation of three factors: (1) the market dynamicity, which determines the variability of both waste supply and demand – measured in terms of demand coefficient of variation, (2) the subscription fee – whose extent is defined relative to the total transaction costs, and (3) the average trust level in the OP, which regards the beliefs of agents towards other agents OP adoption decisions — measured in terms of expected number of new subscribers (or unsubscribers) per period. Different levels has been assigned to each factor, as reported in Table 2. Hence, a total amount of 24 scenarios has been defined and 100 replications for each scenario have been performed.

4.2. Metrics

In this subsection, the metrics adopted to derive insights from the simulations will be provided. First, the metrics related to the number of subscriptions will be presented, and then the metrics related to the evaluation of the economic and environmental benefits.

To answer the first research question (RQ1), the average number of agents subscribed to the OP over time – both of type A and B, denoted as $\overline{N}^A_{subs}$ and $\overline{N}^B_{subs}$, respectively – has been analyzed. The metrics employed for this purpose have been computed as follows:

$$\overline{N}^A_{subs} = \frac{\sum_{t=1}^{T} \sum_{i=1}^{n} s_i(t)}{T} \; ; \quad \overline{N}^B_{subs} = \frac{\sum_{t=1}^{T} \sum_{j=1}^{m} s_j(t)}{T} \tag{16}$$

where $s_i = 1$ ($s_j = 1$) if agent i of type A (j of type B) is subscribed to the OP at time t, and 0 otherwise. The arithmetic mean of these metrics, denoted as $\overline{N}^{TOT}_{subs}$ (%), provides an aggregate measure representative for the average percentage of agents subscribed to the OP:

$$\overline{N}^{TOT}_{subs} (\%) = \frac{\overline{N}^A_{subs} + \overline{N}^B_{subs}}{n + m} \tag{17}$$

During the simulations, additional data on the number of subscribers has been stored to allow deeper investigations of the results.

In particular, the initial and final percentages of agents subscribed to the OP:

$$IS^A(\%) = \frac{\sum_{i=1}^{n} s_i(1)}{n} \; ; \quad FS^A(\%) = \frac{\sum_{i=1}^{n} s_i(T)}{n}$$
$$IS^B(\%) = \frac{\sum_{j=1}^{m} s_j(1)}{m} \; ; \quad FS^B(\%) = \frac{\sum_{j=1}^{m} s_j(T)}{m} \tag{18}$$

Furthermore, the coefficient of variation of the number of subscribers over the simulation time:

$$CVS^A = \frac{std(N^A_{subs})}{\overline{N}^A_{subs}} \; ; \quad CVS^B = \frac{std(N^B_{subs})}{\overline{N}^B_{subs}} \; ;$$
$$CVS^{TOT} = \frac{std(\overline{N}^A_{subs} + \overline{N}^B_{subs})}{\overline{N}^A_{subs} + \overline{N}^B_{subs}} \tag{19}$$

These metrics were aimed at understanding whether agents were leaving and entering the platform continuously or whether the number of subscribers was nearly constant over time.

To answer the second research question (RQ2), the total percentage of economic benefit obtained by the agents and the total percentage of waste diverted from the landfill during the overall period of simulation have been analyzed.

In particular, from the economic perspective, the benefits have been defined and computed as follows:

1. Total percentage of economic benefit directly obtained through the OP, i.e., from an ISR suggested by the OP at time t and established:

$$ECOB^{OP}_{direct}(\%) = \frac{\sum_{t=1}^{T}\sum_{k=1}^{n+m} DOP\_NEB^{IS}_k(t)}{\sum_{t=1}^{T}\sum_{i=1}^{n} W_A \cdot udc \cdot d_i(t) + \sum_{t=1}^{T}\sum_{j=1}^{m} R_B \cdot upc \cdot d_j(t)} \tag{20}$$

2. Total percentage of economic benefit indirectly obtained through the OP, i.e., from an ISR suggested by the OP before time t and still established at time t but no more suggested:

$$ECOB^{OP}_{indirect}(\%) = \frac{\sum_{t=1}^{T}\sum_{k=1}^{n+m} IOP\_NEB^{IS}_k(t)}{\sum_{t=1}^{T}\sum_{i=1}^{n} W_A \cdot udc \cdot d_i(t) + \sum_{t=1}^{T}\sum_{j=1}^{m} R_B \cdot upc \cdot d_j(t)} \tag{21}$$

3. Total percentage of economic benefit obtained without the OP, i.e., from an ISR established outside the OP:

$$ECOB^{NOOP}(\%) = \frac{\sum_{t=1}^{T}\sum_{k=1}^{n+m} NOOP\_NEB^{IS}_k(t)}{\sum_{t=1}^{T}\sum_{i=1}^{n} W_A \cdot udc \cdot d_i(t) + \sum_{t=1}^{T}\sum_{j=1}^{m} R_B \cdot upc \cdot d_j(t)} \tag{22}$$

All in all, the total percentage of economic benefit has been computed as:

$$TOT\_ECOB(\%) = ECOB^{OP}_{direct}(\%) + ECOB^{OP}_{indirect}(\%) + ECOB^{NOOP}(\%) \tag{23}$$

From the environmental perspective, the benefits have been defined and computed as follows:

1. Total percentage of waste directly diverted from the landfill through the OP:

$$WD^{OP}_{direct}(\%) = \frac{\sum_{t=1}^{T}\sum_{i=1}^{n} e^{DOP}_{i\to J}}{\sum_{t=1}^{T}\sum_{i=1}^{n} W_A \cdot d_i(t)} \tag{24}$$

2. Total percentage of waste indirectly diverted from the landfill through the OP:

$$WD^{OP}_{indirect}(\%) = \frac{\sum_{t=1}^{T}\sum_{i=1}^{n} e^{IOP}_{i\to J}}{\sum_{t=1}^{T}\sum_{i=1}^{n} W_A \cdot d_i(t)} \tag{25}$$

3. Total percentage of waste diverted from the landfill without the OP:

$$WD^{NOOP}(\%) = \frac{\sum_{t=1}^{T}\sum_{i=1}^{n} e^{NOOP}_{i\to J}}{\sum_{t=1}^{T}\sum_{i=1}^{n} W_A \cdot d_i(t)} \tag{26}$$

Hence, the total percentage of waste diverted from the landfill has be computed as:

$$TOT\_WD(\%) = WD^{OP}_{direct}(\%) + WD^{OP}_{indirect}(\%) + WD^{NOOP}(\%) \tag{27}$$

5. Results

In this section, the results of the AB simulations will be provided. In particular, variations in the metrics presented in Section 4.2 will be analyzed according to the different levels of the investigated factors (i.e., market dynamicity, subscription fee, and average trust level in the OP).

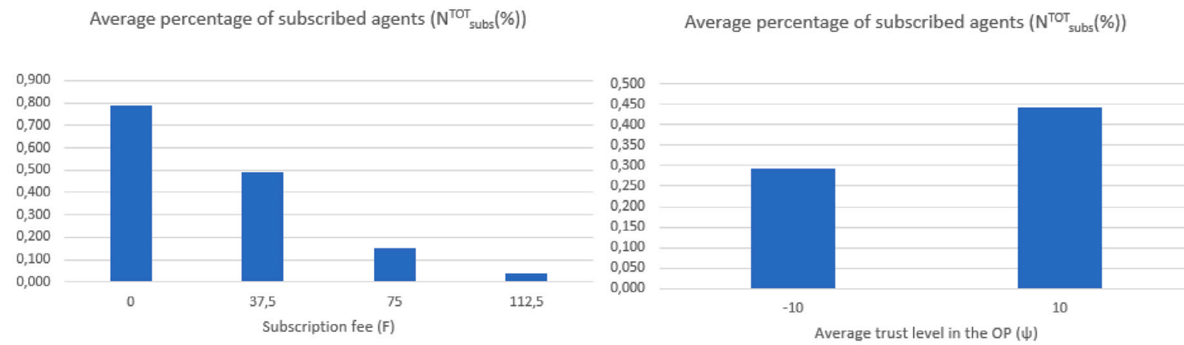
5.1. Analysis of the single effects: model validation

The single effects of the investigated factors have been analyzed to ensure the consistency of the results with the theoretical model developed in Section 3.2.

To prove the soundness of the agents subscription decisions, the average percentage of subscribers ($\overline{N}^{TOT}_{subs}(\%)$) has been analyzed subjected to the variation of the subscription fee (F) and of the average trust level in the OP ($\overline{\psi}$), respectively, as shown in Fig. 2. In particular, the higher the subscription fee, the lower the number of subscribers should be, *ceteris paribus*: this behavior was confirmed by the simulation, as the metric $\overline{N}^{TOT}_{subs}(\%)$ decreased monotonously from 79% to 3.6% when the fee progressively moved from 0 to 112.5 eur/period. Conversely, a higher average trust level in the OP exerted a positive effect on the total number of subscribers, *ceteris paribus* - again, in line with the expectations. Indeed, it raised the average number of subscribers from 29.2% to 44.2% when moving from −10 to +10.

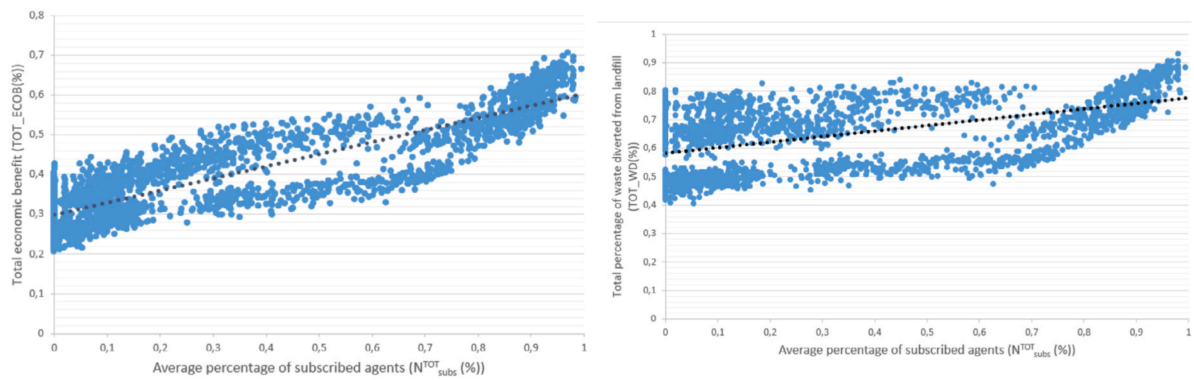
Moreover, according to the literature (Fraccascia and Yazan, 2018; Fraccascia, 2020), a positive influence of the total percentage of subscribers both on the economic and environmental benefits achieved by the system have been detected (Fig. 3). It is worth noting that the effect of the number of subscribers on the economic benefit is stronger than the effect on the environmental benefit, as a result of the specific aim of the designed platform, i.e., maximizing the economic benefit, instead of the amount of waste exchanged. In particular, the linear regression between the metrics $TOT\_ECOB(\%)$ and $\overline{N}^{TOT}_{subs}(\%)$, not only revealed a positive and significant relationship between these two variables (slope coefficient equal to 0.306 and p-value lower than 0.01), but also highlighted that up to 76.4% of the variance in the total percentage of economic benefit obtain during the simulations can be attributed to the average percentage of subscribers. On the other hand, the linear regression between $TOT\_WD(\%)$ and $\overline{N}^{TOT}_{subs}(\%)$ still returned a positive and significant slope coefficient equal to 0.193 but with an R^2 of only 0.293.

Finally, still in accordance with the literature (Fraccascia and Yazan, 2018), market dynamicity (CV) was proved to exert a negative effect both on the economic and environmental benefits obtained by the system (Fig. 4), as a result in the increased mismatch between supply and demand of waste (Fichtner et al., 2005; Fraccascia and Yazan, 2018; Eilering and Vermeulen, 2004). Indeed, the total percentage of waste diverted form the landfill moved from 78.1% to 50.6% and the percentage of economic benefit fell from 49.9% to 30.4%, as the demand coefficient of variation raised from 0.1 to 0.5.



(a) *a* (b) *b*

Fig. 2. Comparison in the average percentage of subscribers depending on the subscription fee and the trust level in the OP.



(a) *a* (b) *b*

Fig. 3. Behavior of the total percentage of economic and environmental benefit depending on the average percentage of subscribers.

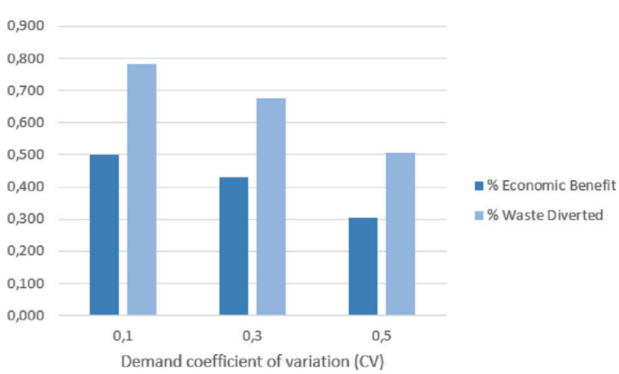


Fig. 4. Total economic and environmental benefit (%) depending on the market dynamicity.

5.2. Analysis of the combined effects: model insights

5.2.1. Average percentage of subscribed agents

This subsection underscores how the combination of market dynamicity, fee level, and trust level in the OP future widespread affect the company's choice to subscribe to the OP: hence it contributes to answer the first research question (RQ1).

Fig. 5 shows the mean and the standard deviation of the average percentage of subscribed agents for each possible scenario, i.e., for each possible combination of the investigated factors. According to the simulation results, the optimal scenario in terms of the average number of subscribers is the one with low levels of both subscription fee and market dynamicity, while the average trust level in the OP is high. The major effect on the number of subscribers is exerted by the fee level: companies are mostly guided by savings in transaction costs when facing subscription decisions. Indeed, they give more importance to sure benefits or losses rather than to potential – hence uncertain – future ones, since they act as rational economic agents. While this result might have been expected, the most interesting insights from the model lie in the combination of the investigated factors. Specifically, the analysis highlighted that the positive effect of the average trust level in the OP is stronger when the subscription fee is higher than zero. For instance, in the case of low market dynamicity, a higher trust level increased the average number of subscribers only by 1% when the fee was equal to zero, while in the case of a fee equal to half of the transaction costs, the average number of subscribers raised by 66%, and with the highest fee level increasing trust made the average number of subscribers 34 times higher. The same patterns can be found in the scenarios with higher levels of market dynamicity. This result suggests that making companies' expecting a widespread usage of the OP among other companies might drive them to subscribe even when there is a higher subscription fee to pay, *ceteris paribus*. Acknowledging this phenomenon could be helpful for platform providers to design and exploit proper tools to drive companies' subscription, still gaining some revenues from fees.

Nonetheless, another interesting insight can be provided analyzing the combined effects of the investigated factors: the average number of subscribers decreases when the market dynamicity increases, but the negative effect of market dynamicity can be smoothed by the trust level in the OP. For instance, while in the case of low trust – even in the absence of the fee – an increase in the demand coefficient of variation from 0.1 to 0.5 reduced the average percentage of subscribers by 46.3%, in the case of high trust level, the reduction is lowered to 26.4%, *ceteris paribus*. This latter result suggests that companies'

		Demand coefficient of variation (CV)											
		0.1				0.3				0.5			
		Subscription fee (F)				Subscription fee (F)				Subscription fee (F)			
		0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC
Trust level in the OP (ψ)	LOW	0,914	0,536	0,132	0,003	0,852	0,305	0,088	0,002	0,490	0,141	0,044	0,001
		0,039	*0,077*	*0,040*	*0,008*	*0,043*	*0,051*	*0,029*	*0,006*	*0,071*	*0,026*	*0,018*	*0,003*
	HIGH	0,924	0,890	0,348	0,106	0,884	0,754	0,198	0,070	0,680	0,320	0,099	0,036
		0,040	*0,044*	*0,069*	*0,036*	*0,043*	*0,063*	*0,041*	*0,030*	*0,053*	*0,040*	*0,026*	*0,016*

Fig. 5. Average percentage of subscribers depending on the combined effect of the investigated factors.

trust in the future usage widespread of the OP has an additional role, i.e., hedging from market dynamicity. Indeed, in highly dynamic markets, it is more challenging for firms to gain benefits from symbiotic relationships because of the higher mismatch between demand and supply of waste resulting from of market demand fluctuations over time (Golev et al., 2015; Neves et al., 2019), *ceteris paribus*. In this regard, companies can recognize the OP as a useful tool to ensure a proper allocation of waste. Specifically, this effect is stronger if the number of potential symbiotic partners (i.e., subscribed agents) increases, because companies will have higher chances of finding a good partner with whom to match their waste demand (or supply). Moreover, a deeper investigation into this result allows to notice that market dynamicity strongly affects both the final number of subscribers and the fluctuations in such number over time. Indeed, the coefficient of variation of the number of subscribers CVS^{TOT} raised from 0.44 to 0.56 until 1.19 as market dynamicity progressively increased. This means that, if the benefits ensured by the adoption of the platform are not constant over time (due, for instance, to a higher mismatch between demand and supply of waste in a given time period), companies will be more willing to abandon the OP. In this regard, a higher level of trust in the future usage widespread of the OP can also hold back companies from leaving the platform, as they will expect higher benefits in the future, when more potential partners will be subscribed to the OP.

5.2.2. Total percentage of economic benefit and waste diverted from the landfill

This subsection highlights how the strategic choice of subscribing to the OP impacts the environmental and economic benefit derived from IS (RQ2).

The total percentage of economic benefit obtained by the agents and the total percentage of waste diverted from the landfill depending on the different levels of the investigated factors are shown in Figs. 6 and 7, respectively. The minimum percentage of economic benefit (24.9%) has been obtained in the scenario with the highest levels of fee and market dynamicity but low average trust level in the OP, which corresponds to the scenario with minimum percentage of waste exchanged (47.6%) and minimum average number of subscribers (see Section 5.2.1). Conversely, the best scenarios from the economic and environmental perspectives (63% is the maximum percentage of the economic benefit obtained, corresponding to 83% of waste diverted from the landfill at best) were those with no subscription fee and low market dynamicity. In this case, the average trust level in the OP played a minor role: the statistical difference in the means was found to be not significant (p-values equal to 0.308 and 0.915 for the economic and environmental benefit, respectively).[9]

[9] A t-test has been performed to compare the means of the total percentage of economic benefit and waste diverted from the landfill when the demand coefficient of variation is 0.1 and the subscription fee is equal to zero.

Despite the corresponding economic and environmental performances in the best and worst scenarios, looking at Figs. 6 and 7, it is possible to notice how the worsening of the environmental performance (from the bottom left to the upper right) does not perfectly match the pattern displayed for the economic one. This result suggests that, when the percentage of subscribers decreases, companies are still able to implement ISRs outside the platform but the exchange of waste happens less profitably than it could have been if supported by the OP. This mechanism is even clearer when looking at Fig. 8, where it is possible to observe the mean of both the total percentage of economic benefit and waste diverted from the landfill under the different levels of market dynamicity and subscription fee. It is possible to highlight that, while the decline of the environmental benefit follows a linear trend with CV and F, the economic benefit declines much more sharply when keeping fixed the market dynamicity and follows a periodic trend mostly guided by the fee level: this reveals how the waste diverted from the landfill is exchanged in a sub-optimal way from the economic perspective. Indeed, from the scenarios when the average percentage of subscribers is maximum (i.e., in the absence of the fee) to the scenarios when the average percentage of subscribers is minimum (i.e., fee equal to $1.5 \cdot \overline{TC}$), the percentage of waste diverted from the landfill was reduced by 11%, while the economic benefit by 37.8%.

Finally, Fig. 9 shows how the percentage of economic and environmental benefits are distributed among those (1) directly, (2) indirectly, and (3) not attributable to the OP (see metrics in Section 4.2) depending on the subscription fee level. In line with the previous discussion, the percentage of economic benefit attributable to the platform (i.e., directly and indirectly) when the number of subscribers was maximum (i.e., when the fee was equal to zero) largely surpassed the percentage of economic benefit not attributable to the platform when the average percentage of subscribers was minimum (+69.29%). Conversely, the percentage of waste diverted from the landfill was exceeded less substantially (by 14.64%), *ceteris paribus*.

6. Discussion

Results from the simulations allow us to answer research questions RQ1 and RQ2.

Concerning RQ1, we can assess that all the investigated factors (i.e., subscription fee, average trust level in the OP, and market dynamicity) have a role in driving the subscription decisions of companies – assuming they act as rational economic agents –, with the subscription fee level being the leading driver.

About the subscription fee, the negative effect exerted by this factor is not surprising: for instance, Grimmel et al. (2024, p. 396) already noticed that *"accessing IS applications is hindered by paywalls and mandatory registration requirements"*. According to our simulations' results, the platform is able to attract almost the overall number of companies in

		Demand coefficient of variation (CV)											
		0.1				0.3				0.5			
		Subscription fee (F)				Subscription fee (F)				Subscription fee (F)			
		0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC
Trust level in the OP (ψ)	LOW	0,629	0,513	0,386	0,361	0,533	0,435	0,343	0,327	0,358	0,299	0,257	0,249
		0,032	*0,029*	*0,027*	*0,025*	*0,030*	*0,024*	*0,025*	*0,023*	*0,025*	*0,018*	*0,014*	*0,016*
	HIGH	0,624	0,619	0,478	0,381	0,539	0,509	0,415	0,340	0,393	0,334	0,288	0,255
		0,033	*0,033*	*0,029*	*0,027*	*0,033*	*0,032*	*0,026*	*0,026*	*0,026*	*0,020*	*0,018*	*0,018*

Fig. 6. Total percentage of economic benefit depending on the combined effect of the investigated factors.

		Demand coefficient of variation (CV)											
		0.1				0.3				0.5			
		Subscription fee (F)				Subscription fee (F)				Subscription fee (F)			
		0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC
Trust level in the OP (ψ)	LOW	0,832	0,766	0,745	0,739	0,709	0,670	0,651	0,643	0,538	0,498	0,480	0,476
		0,037	*0,030*	*0,031*	*0,032*	*0,036*	*0,027*	*0,025*	*0,027*	*0,026*	*0,022*	*0,022*	*0,023*
	HIGH	0,832	0,823	0,766	0,743	0,717	0,688	0,674	0,646	0,558	0,526	0,496	0,479
		0,040	*0,039*	*0,033*	*0,028*	*0,042*	*0,037*	*0,026*	*0,027*	*0,029*	*0,022*	*0,021*	*0,024*

Fig. 7. Total percentage of waste diverted from the landfill depending on the combined effect of the investigated factors.

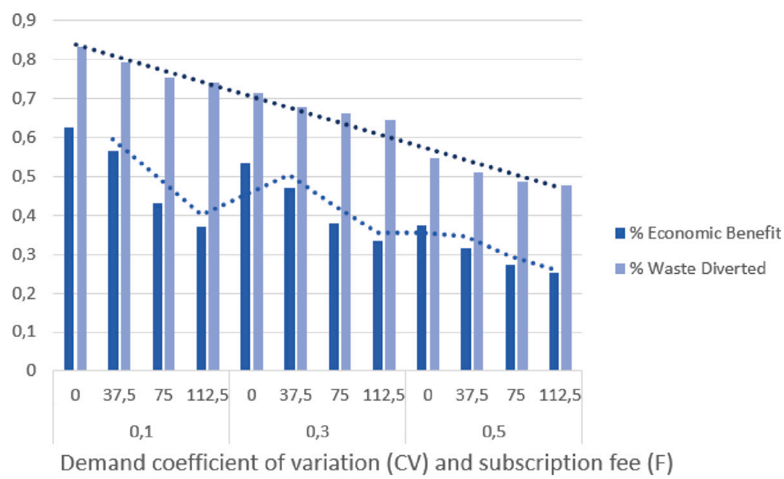
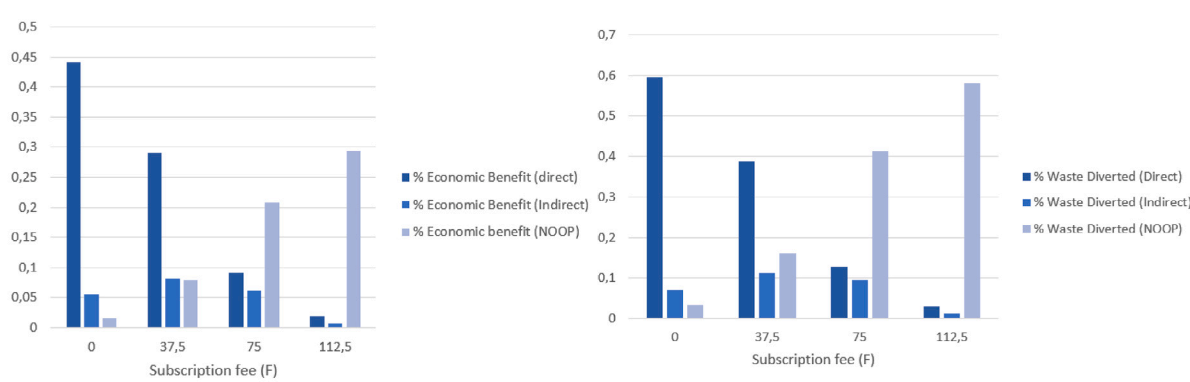


Fig. 8. TOT_ECOB (%), and TOT_WD (%) under the effect of the market dynamicity and subscription fee.



(a) *a* (b) *b*

Fig. 9. Percentage of economic and environmental benefit directly, indirectly and not attributable to the OP depending on the fee level.

the system only if it is free of charge, which is in line with several policy recommendations. Indeed, among the recommended steps to accelerate the transition, the sixth report on Circular Economy in Italy[10] recommends the promotion of free of charge platforms to support IS for SMEs. The *"subscription free of charge"*- policy seems to be already pursued by many operating platforms, in which companies are offered to use the platform without costs, at least for a limited period of time (e.g. one year) (Krom et al., 2022). However, releasing the platform free of charges can hinder the economic sustainability of the platform itself (Chaudhuri et al., 2021). In this regard, on the one hand, governments might play a key role by providing subsidies for IS platforms' providers (Krom et al., 2022). On the other hand, for platforms to be self-sustaining and survive in the long-run, sources of revenue have to be sought by the platform itself, and different strategies might be adopted to this aim. Indeed, several pricing strategies for two-sided digital platforms are available in the literature. Specifically, two main revenue streams can be exploited: the first is related to subscriptions, the second comes from selling advertising slots or sharing user's information with advertisers (Gopal et al., 2018). While this latter strategy seems to be currently unexploited by IS platforms, the need for ensuring the confidentiality of the data shared with the IS platforms is a critical issue (Patricio et al., 2022; Benedict et al., 2018). Indeed, the literature on IS platforms already argued that companies should place trust in the fact that the platform 's owner would not disclose their sensitive information to other companies for them to be willing to subscribe (Fraccascia, 2020). Accordingly, several studies have highlighted the pivotal role played by data governance issues as determinants for platforms' adoption, not only in the case of IS, but in the wider environment of B2B digital platforms. As argued by Anderson et al. (2022, p. 4512) this *"will create an advantage for those platforms that are sponsored by a consortium of industry members"*, since they might benefit of higher levels of trust compared to private platforms. Given that the revenue stream obtainable from selling information should be excluded in the case of IS platforms, we can argue that their sustainability depends on the proposed subscription pricing strategy. Winning strategies might include free trials, differential pricing, dynamic pricing, and segmentation (Yelkur and DaCosta, 2001; Zhao et al., 2022; Duan et al., 2022; Kumar and Sethi, 2009).

With regard to trust, while the importance of companies trusting the platform in the sense of non-disclosure of sensible information has been already extensively discussed, our results suggest its prominent role in terms of companies' belief in a sufficiently high platform's usage rate. Indeed, this kind of trust in the OP makes companies more willing to subscribe even if they have to pay a *"moderate"* fee, i.e., as long as the fee does not exceed transaction costs. This interesting insight suggests that it is important to promote and increase awareness about the platform, thus convincing companies to subscribe even if they have to pay for the service. To boost companies' beliefs about other companies adopting a given platform, the literature suggests several strategies, e.g., making publicly available the number of users on either the supply or the demand side. As argued by Haurand and Stummer (2023), determining the right time for letting companies have this information is key to ensure a positive network effect. Indeed, if the actual number of users is lower than companies' initial beliefs, they might be retained from subscribing to the platform. Another proper strategy is to rely not only on the cross-side value of the platform, but to increase its stand-alone technological value, which might contrast companies initial poor trust in the platform's usage widespread (Anderson et al., 2022).

Finally, about market dynamicity, the developed AB simulations showed that it exerts a negative effect on subscription decisions. However, another interesting insight from the model suggests that a higher trust level in the OP's usage rate can smooth this effect. The negative effect of market dynamicity is related to the less stable benefits achievable through the ISRs suggested by the platform over time. Indeed, companies might think that the benefits from adopting the platform are not sufficiently high. However, if more companies are believed to subscribe to the platform in the future, the expected benefit from future ISRs will increase, *ceteris paribus*. Accordingly, increasing the trust level in the OP's usage widespread is key, which strengthens the suggestion made by Fraccascia and Yazan (2018) that companies should place trust in the facilitator owning the platform.

Regarding the second research question (RQ2), results allow to conclude that a higher number of platform adopters positively impact both the economic and environmental benefits achievable through the platform. Hence, the developed AB model confirmed the result discussed by Fraccascia (2020), showing that both the economic and the environmental benefits obtained by the system are higher if the number of agents subscribed to the OP is higher, *ceteris paribus*. The simulations' results showed that, without the aid of the platform, waste is still exchanged but in suboptimal ways, while the extensive use of the OP leads to the achievement of optimal solutions. Moreover, the analysis highlighted a major impact of the number of subscriptions on the economic benefits, rather than on the environmental ones: this is due to the specific maximization problem solved by the OP. Indeed, in this paper, the economic objective is pursued. This modeling choice is due to the fact that the mathematical formulation of this problem (i.e., the maximization of the overall economic benefit) is the easiest and the most frequently employed in the literature (Boix et al., 2015). Nonetheless, it can be argued that different objectives might be pursued by IS platforms, e.g., environmental or social benefit maximization. Indeed, the optimization of an ISN should strive to satisfy all the three pillars of Sustainable Development, i.e., economy, environment, and society.

7. Conclusions

This paper proposes a novel theoretical framework to model companies' subscription decisions toward an OP supporting the creation of ISRs through ABM. The model aimed to define what drives companies – acting as rational economic agents – to subscribe to such an OP (RQ1), and how this strategic choice impacts the environmental and economic benefits achievable through IS by the overall system (RQ2).

The performances of the platform in terms of average number of subscriptions and the effectiveness from the economic and environmental perspectives have been analyzed subjected to the variation of (1) market dynamicity, (2) subscription fee, and (3) average trust level in the OP's usage widespread.

Results of the simulations are in line with the expected behavior of agents and consistent with the literature in terms of economic and environmental effectiveness. Specifically, the model highlighted a negative effect exerted by the subscription fee and by the market dynamicity and a positive effect exerted by the trust level on the total number of subscriptions. The most interesting insights from the model concern the role of companies' trust in the future widespread of the OP in enabling a higher tolerance for higher levels of subscription fee and its hedging role in relation to market dynamicity. Moreover, the positive effect of the number of subscribers on both the economic and environmental performances of the system has been confirmed, with a higher impact exerted on the economic benefit rather than on the environmental one.

The present study allows to derive relevant implications from the theoretical, managerial, and policy perspectives.

From the theoretical point of view, the developed model represents a novel contribution in the literature of ICT tools for IS as it is the first to consider the companies' decision-making perspective concerning the issue of subscription. Moreover, while the methodological framework adopted in this study, i.e., ABM, is commonly used to investigate the dynamics underlying the development of IS, it is the first to introduce a

[10] https://circulareconomynetwork.it/rapporto-sulleconomia-circolare-in-italia-2024/.

Table 3
Parameters' changes in the input dataset.

Variable	BASE	LOWER	HIGHER
udc $[\frac{eur}{t\ alcohol\ slops}]$	30	25	35
upc $[\frac{eur}{t\ alcohol\ slops}]$	70	60	80
$utrac$ $[\frac{eur}{km\ t\ alcohol\ slops}]$	5	4.5	5.5

double decision-stage that influences the setting environment in which agents are called to take the cooperation decision.

From the managerial and policy perspectives, the analysis allows to derive several practical implications and recommendations for both platform providers and policymakers.

According to our results, releasing a platform free of charge is the preferable option to boost subscriptions. Therefore, on the one hand, platform providers are encouraged to offer their services free of charge, and policymakers are called to subsidize their efforts — at least in the launching stage of the platform. On the other hand, platform providers are recommended to define proper pricing strategies to ensure the self-sustainability of the platform in the long run. Additionally, we have shown that it is possible to attract a higher number of subscribers by increasing trust in the future usage widespread of the platform, *ceteris paribus*. Therefore, we suggest platform providers to design proper marketing strategies, too, e.g., sharing information about the number of subscribers or emphasizing the high technological stand-alone value of the platform. To this aim, they are called to investigate properly companies' preferences and willingness to pay for the service, and propose the best strategic solution for their specific context, both in terms of pricing and marketing strategies. Concerning the role of trust, we have found out that its enhancement results in hedging the platform from market dynamicity, too. Indeed, demand fluctuations might hamper the economic benefit achievable through the OP over time and, therefore, companies' subscription renewal. In this regard, we can argue that employing IS platforms in the context of facilitated IS programs can be a winning strategy, as companies might be more confident in the involvement of a large number of potential partners and – accordingly – in the advantages deriving from subscription. Therefore, governments should promote facilitated IS programs – where platforms might have higher chances of succeeding – and encourage companies to join them. Finally, our results confirmed that the number of subscriptions to the platform exerts a positive impact on both the economic and environmental performances of the system. However, the impact of the number of subscribers on the economic benefit is higher than the impact on the environmental one, and this result is due to the specific maximization problem that the investigated platform is called to solve (i.e., maximizing the economic benefit). Nonetheless, we suggest that different optimization models can be solved by different platforms (or within a single platform), to provide increased benefits to all three pillars of Sustainable Development. Indeed, platform providers should tailor the objective of the platform to the specific industrial context in which they will be operating.

Certainly, this study is not without limitations. Firstly, it is not tested on a real case study on an existing platform. However, as already argued in the literature (Grant et al., 2010), it is very difficult to assess the contribution of IS platforms, since it is not possible to determine whether a certain relationship created through the platform would have been created even without its support. From the modeling perspective, agents are considered as rational economic agents: they are only guided by economic reasoning and, therefore, the model neglects the psychological perspective. On the one hand, since agents are representatives of companies, this assumption is reasonable. On the other hand, managers who are in charge of taking decisions for companies, might also be guided by other motivations, e.g., opportunistic behaviors, word of mouth, etc. Moreover, only one-to-one ISRs are allowed in each time period and agents are not allowed to exchange more than one type of waste within the platform. They cannot leave or enter the network, nor store exceeding waste to exchange it in later periods. In a real context, all these factors might impact the success of the platform. In particular, a single platform should be able to consider several potential matches between wastes and input materials. This might affect markedly both the subscription choices and the cooperation decisions of companies. Additionally, the trust level in the OP's usage widespread has been modeled as static, but it might be defined as a dynamic variable in future extensions of the model. Considering the platform design, as already noticed, the investigated platform maximizes the economic benefit, but different objectives might be pursued, too, e.g., environmental or social benefit maximization.

The above-mentioned limitations can all be matters for future studies. Moreover, starting from the insights provided in the paper, further questions can be posed as future avenues for research: for instance, what would happen in case of different pricing and/or marketing strategies adopted by the OP provider? What would happen whether economic incentives are provided by policymakers? Researchers are called to improve the model starting from the above-mentioned limitations. Indeed, this paper is only the first step toward a possible deeper investigation of agents' behavior toward OP for IS.

CRediT authorship contribution statement

Melissa Mollica: Writing – original draft, Visualization, Validation, Software, Investigation, Formal analysis, Data curation. **Luca Fraccascia:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Data curation, Conceptualization. **Alberto Nastasi:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

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

Acknowledgments

This paper has been written in the context of the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3 - Call for tender No. 341 of 15/03/2022 of Italian Ministry of University and Research funded by the European Union–NextGenerationEU. Award Number: PE00000004, Concession Decree No. 1551 of 11/10/2022 adopted by the Italian Ministry of University and Research, CUP B53C22004130001, MICS (Made in Italy - Circular and Sustainable).

Appendix. Model validation

In the following, the model will be validated through (1) micro-face validation, (2) macro-face validation, (3) input validation, and (4) output validation (Bianchi et al., 2008; Manson, 2003; Giannoccaro and Carbone, 2017).

The criteria of the micro-face validation are satisfied as the decision-making processes of the agents and the mechanisms of the model described in Section 3.2 (i.e., the subscription decision depends on three components including (1) savings in transaction costs, (2) indirect network effect, and (3) path dependence, while the willingness to cooperate in an ISR depends on the economic benefits stemming from cooperation and the path dependence) are consistent with the literature.

The criteria of the macro-face validation are satisfied because the dynamics of the model presented in Section 3.4 are in line with real-world dynamics: agents subscribe to the platform only if their utility is higher than their threshold, while they accept to cooperate in an

Average percentage of subscribers

		Demand coefficient of variation (CV)											
		0.1				0.3				0.5			
		Subscription fee (F)				Subscription fee (F)				Subscription fee (F)			
		0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC
Trust level in the OP (ψ)	LOW	0,907	0,537	0,128	0,004	0,836	0,316	0,088	0,002	0,485	0,140	0,044	0,001
		0,043	0,080	0,039	0,008	0,052	0,065	0,034	0,006	0,069	0,023	0,018	0,003
	HIGH	0,908	0,884	0,344	0,099	0,872	0,733	0,200	0,075	0,666	0,315	0,103	0,038
		0,040	0,044	0,057	0,038	0,049	0,068	0,039	0,027	0,048	0,044	0,023	0,017

Total percentage of economic benefit

		Demand coefficient of variation (CV)											
		0.1				0.3				0.5			
		Subscription fee (F)				Subscription fee (F)				Subscription fee (F)			
		0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC
Trust level in the OP (ψ)	LOW	0,616	0,504	0,371	0,347	0,521	0,431	0,332	0,318	0,347	0,291	0,248	0,242
		0,033	0,030	0,026	0,026	0,031	0,025	0,024	0,027	0,024	0,017	0,019	0,017
	HIGH	0,610	0,616	0,469	0,366	0,524	0,496	0,408	0,333	0,380	0,328	0,284	0,245
		0,034	0,027	0,031	0,032	0,032	0,031	0,023	0,029	0,019	0,023	0,021	0,018

Total percentage of waste diverted from the landfill

		Demand coefficient of variation (CV)											
		0.1				0.3				0.5			
		Subscription fee (F)				Subscription fee (F)				Subscription fee (F)			
		0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC
Trust level in the OP (ψ)	LOW	0,823	0,758	0,734	0,724	0,696	0,664	0,640	0,633	0,523	0,491	0,470	0,466
		0,044	0,028	0,031	0,027	0,039	0,026	0,035	0,031	0,024	0,020	0,024	0,023
	HIGH	0,816	0,822	0,757	0,727	0,702	0,677	0,665	0,644	0,544	0,516	0,490	0,469
		0,042	0,037	0,034	0,036	0,041	0,033	0,031	0,032	0,025	0,027	0,025	0,021

Fig. 10. Sensitivity analysis: LOW udc.

ISR only if the benefits they would achieve are higher than a certain minimum expected benefit.

Regarding the input validation, we have performed a sensitivity analysis on the input dataset reported in Table 1 to ensure the independence of the results obtained during the simulations from the specific numeric inputs chosen. Specifically, the economic parameters udc, upc, and $utrac$ have been modified one at the time, *ceteris paribus*, as shown in Table 3. 100 replications of the model have been run for each parameter variation and the results of the simulations with the twelve new settings analyzed are reported below (Figs. 10, 11, 12, 13, 14, 15). As we can notice, results are consistent with those provided in the main of the manuscript. In particular, the identified patterns – from which the implication of the study have been derived – have remained unchanged. As a further criterion for the input validation, it is worth mentioning that the same input dataset has been already used in other AB models in the literature of IS (e.g., Fraccascia (2020)).

Finally, the criteria of the output validation are satisfied as results from the simulation are in line with the expected behavior of agents and with the literature. For instance, a higher number of agents subscribes to the platform when the subscription fee is low and when the trust level is high, *ceteris paribus*, which is the desired outcome. Moreover, the higher the number of agents subscribed to the platform, the higher the overall economic and environmental benefit obtained by the system, as argued by Fraccascia (2020).

Data availability

Data will be made available on request.

Average percentage of subscribers

		Demand coefficient of variation (CV)											
		0.1				0.3				0.5			
		Subscription fee (F)				Subscription fee (F)				Subscription fee (F)			
		0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC
Trust level in the OP (ψ)	LOW	0,909	0,536	0,129	0,003	0,856	0,294	0,087	0,002	0,499	0,134	0,042	0,001
		0,048	0,085	0,038	0,006	0,047	0,053	0,031	0,006	0,072	0,024	0,016	0,003
	HIGH	0,931	0,892	0,333	0,095	0,889	0,759	0,188	0,072	0,686	0,325	0,093	0,034
		0,040	0,040	0,062	0,035	0,043	0,062	0,038	0,025	0,050	0,044	0,022	0,015

Total percentage of economic benefit

		Demand coefficient of variation (CV)											
		0.1				0.3				0.5			
		Subscription fee (F)				Subscription fee (F)				Subscription fee (F)			
		0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC
Trust level in the OP (ψ)	LOW	0,635	0,519	0,399	0,367	0,541	0,438	0,357	0,333	0,367	0,305	0,267	0,254
		0,037	0,038	0,029	0,024	0,029	0,022	0,025	0,026	0,026	0,018	0,018	0,017
	HIGH	0,641	0,632	0,483	0,378	0,549	0,518	0,419	0,348	0,404	0,342	0,293	0,263
		0,033	0,032	0,030	0,031	0,032	0,031	0,026	0,029	0,023	0,019	0,017	0,017

Total percentage of waste diverted from the landfill

		Demand coefficient of variation (CV)											
		0.1				0.3				0.5			
		Subscription fee (F)				Subscription fee (F)				Subscription fee (F)			
		0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC
Trust level in the OP (ψ)	LOW	0,829	0,773	0,758	0,747	0,716	0,673	0,661	0,651	0,545	0,506	0,490	0,479
		0,047	0,034	0,027	0,033	0,032	0,025	0,026	0,031	0,028	0,023	0,022	0,023
	HIGH	0,838	0,828	0,768	0,747	0,723	0,699	0,677	0,655	0,571	0,534	0,502	0,488
		0,044	0,038	0,031	0,030	0,041	0,035	0,034	0,029	0,028	0,021	0,018	0,022

Fig. 11. Sensitivity analysis: HIGH udc.

Average percentage of subscribers

		Demand coefficient of variation (CV)											
		0.1				0.3				0.5			
		Subscription fee (F)				Subscription fee (F)				Subscription fee (F)			
		0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC
Trust level in the OP (ψ)	LOW	0,902	0,544	0,124	0,002	0,828	0,327	0,096	0,002	0,452	0,145	0,044	0,001
		0,037	0,065	0,037	0,006	0,047	0,055	0,032	0,008	0,074	0,027	0,019	0,003
	HIGH	0,905	0,869	0,354	0,100	0,863	0,725	0,214	0,081	0,647	0,302	0,102	0,037
		0,040	0,049	0,054	0,036	0,040	0,076	0,039	0,029	0,055	0,047	0,021	0,019

Total percentage of economic benefit

		Demand coefficient of variation (CV)											
		0.1				0.3				0.5			
		Subscription fee (F)				Subscription fee (F)				Subscription fee (F)			
		0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC
Trust level in the OP (ψ)	LOW	0,607	0,498	0,367	0,346	0,502	0,421	0,334	0,319	0,333	0,283	0,243	0,237
		0,032	0,033	0,027	0,029	0,030	0,024	0,024	0,024	0,024	0,018	0,015	0,015
	HIGH	0,603	0,595	0,460	0,363	0,508	0,480	0,396	0,333	0,362	0,318	0,274	0,240
		0,037	0,034	0,029	0,032	0,030	0,034	0,026	0,026	0,028	0,022	0,018	0,017

Total percentage of waste diverted from the landfill

		Demand coefficient of variation (CV)											
		0.1				0.3				0.5			
		Subscription fee (F)				Subscription fee (F)				Subscription fee (F)			
		0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC
Trust level in the OP (ψ)	LOW	0,816	0,748	0,721	0,709	0,679	0,653	0,630	0,621	0,508	0,477	0,454	0,454
		0,040	0,036	0,035	0,034	0,034	0,026	0,031	0,029	0,029	0,022	0,019	0,019
	HIGH	0,815	0,805	0,750	0,719	0,686	0,661	0,650	0,630	0,527	0,503	0,474	0,454
		0,044	0,042	0,034	0,033	0,035	0,041	0,030	0,029	0,032	0,025	0,024	0,024

Fig. 12. Sensitivity analysis: LOW *upc*.

Average percentage of subscribers

		Demand coefficient of variation (CV)											
		0.1				0.3				0.5			
		Subscription fee (F)				Subscription fee (F)				Subscription fee (F)			
		0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC
Trust level in the OP (ψ)	LOW	0,916	0,535	0,133	0,003	0,868	0,288	0,091	0,002	0,519	0,130	0,040	0,002
		0,036	0,083	0,041	0,007	0,045	0,056	0,033	0,006	0,066	0,027	0,016	0,005
	HIGH	0,929	0,898	0,312	0,100	0,901	0,773	0,175	0,071	0,693	0,327	0,087	0,033
		0,040	0,042	0,062	0,032	0,040	0,063	0,035	0,028	0,053	0,051	0,020	0,018

Total percentage of economic benefit

		Demand coefficient of variation (CV)											
		0.1				0.3				0.5			
		Subscription fee (F)				Subscription fee (F)				Subscription fee (F)			
		0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC
Trust level in the OP (ψ)	LOW	0,647	0,533	0,394	0,373	0,558	0,448	0,360	0,343	0,379	0,314	0,271	0,262
		0,033	0,030	0,030	0,027	0,032	0,023	0,022	0,023	0,027	0,020	0,016	0,017
	HIGH	0,644	0,637	0,493	0,386	0,571	0,536	0,427	0,354	0,421	0,350	0,300	0,268
		0,034	0,031	0,032	0,027	0,033	0,029	0,025	0,025	0,028	0,022	0,020	0,017

Total percentage of waste diverted from the landfill

		Demand coefficient of variation (CV)											
		0.1				0.3				0.5			
		Subscription fee (F)				Subscription fee (F)				Subscription fee (F)			
		0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC
Trust level in the OP (ψ)	LOW	0,835	0,782	0,758	0,759	0,732	0,683	0,668	0,667	0,561	0,523	0,503	0,495
		0,038	0,027	0,030	0,032	0,039	0,025	0,028	0,029	0,027	0,024	0,021	0,023
	HIGH	0,838	0,832	0,780	0,759	0,745	0,713	0,684	0,671	0,588	0,546	0,513	0,502
		0,042	0,038	0,034	0,033	0,038	0,034	0,028	0,026	0,030	0,024	0,021	0,020

Fig. 13. Sensitivity analysis: HIGH *upc*.

Average percentage of subscribers

		Demand coefficient of variation (CV)											
		0.1				0.3				0.5			
		Subscription fee (F)				Subscription fee (F)				Subscription fee (F)			
		0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC
Trust level in the OP (ψ)	LOW	0,931	0,560	0,138	0,003	0,861	0,281	0,083	0,002	0,527	0,136	0,039	0,002
		0,040	0,085	0,044	0,006	0,046	0,059	0,029	0,006	0,066	0,025	0,013	0,005
	HIGH	0,931	0,895	0,330	0,108	0,903	0,779	0,179	0,078	0,703	0,337	0,098	0,033
		0,036	0,042	0,055	0,029	0,042	0,064	0,037	0,024	0,044	0,048	0,022	0,018

Total percentage of economic benefit

		Demand coefficient of variation (CV)											
		0.1				0.3				0.5			
		Subscription fee (F)				Subscription fee (F)				Subscription fee (F)			
		0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC
Trust level in the OP (ψ)	LOW	0,660	0,539	0,397	0,375	0,556	0,442	0,363	0,345	0,381	0,316	0,271	0,267
		0,031	0,035	0,027	0,029	0,030	0,027	0,024	0,023	0,025	0,019	0,015	0,015
	HIGH	0,652	0,646	0,499	0,395	0,569	0,538	0,435	0,356	0,420	0,360	0,301	0,263
		0,032	0,030	0,028	0,031	0,033	0,034	0,027	0,020	0,027	0,021	0,020	0,018

Total percentage of waste diverted from the landfill

		Demand coefficient of variation (CV)											
		0.1				0.3				0.5			
		Subscription fee (F)				Subscription fee (F)				Subscription fee (F)			
		0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC
Trust level in the OP (ψ)	LOW	0,851	0,786	0,766	0,760	0,725	0,679	0,675	0,666	0,562	0,523	0,501	0,497
		0,037	0,030	0,031	0,030	0,035	0,026	0,029	0,028	0,027	0,020	0,019	0,023
	HIGH	0,846	0,832	0,783	0,770	0,746	0,719	0,689	0,672	0,586	0,554	0,516	0,496
		0,038	0,037	0,029	0,028	0,040	0,037	0,023	0,021	0,030	0,021	0,021	0,021

Fig. 14. Sensitivity analysis: LOW *utrac*.

Average percentage of subscribers

Trust level in the OP (ψ)		Demand coefficient of variation (CV)											
		0.1				0.3				0.5			
		Subscription fee (F)				Subscription fee (F)				Subscription fee (F)			
		0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC
	LOW	0,899	0,546	0,130	0,002	0,838	0,304	0,086	0,002	0,467	0,144	0,043	0,001
		0,044	0,068	0,042	0,006	0,046	0,061	0,032	0,005	0,069	0,025	0,018	0,002
	HIGH	0,905	0,875	0,355	0,103	0,878	0,733	0,207	0,074	0,652	0,313	0,104	0,036
		0,046	0,046	0,057	0,030	0,042	0,073	0,039	0,027	0,048	0,045	0,024	0,017

Total percentage of economic benefit

Trust level in the OP (ψ)		Demand coefficient of variation (CV)											
		0.1				0.3				0.5			
		Subscription fee (F)				Subscription fee (F)				Subscription fee (F)			
		0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC
	LOW	0,604	0,497	0,367	0,340	0,513	0,417	0,335	0,315	0,334	0,289	0,242	0,237
		0,033	0,031	0,032	0,025	0,029	0,028	0,025	0,025	0,025	0,019	0,018	0,015
	HIGH	0,607	0,603	0,457	0,363	0,518	0,489	0,398	0,330	0,364	0,320	0,276	0,244
		0,035	0,034	0,029	0,025	0,032	0,036	0,027	0,024	0,024	0,021	0,017	0,017

Total percentage of waste diverted from the landfill

Trust level in the OP (ψ)		Demand coefficient of variation (CV)											
		0.1				0.3				0.5			
		Subscription fee (F)				Subscription fee (F)				Subscription fee (F)			
		0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC	0	0.5 TC	TC	1.5 TC
	LOW	0,815	0,751	0,723	0,708	0,693	0,654	0,633	0,622	0,510	0,486	0,456	0,454
		0,044	0,033	0,034	0,034	0,034	0,027	0,029	0,028	0,026	0,025	0,023	0,023
	HIGH	0,814	0,809	0,747	0,725	0,701	0,672	0,653	0,627	0,527	0,505	0,480	0,459
		0,043	0,044	0,036	0,027	0,037	0,040	0,035	0,026	0,028	0,030	0,024	0,024

Fig. 15. Sensitivity analysis: HIGH *utrac*.

References

Aid, G., Brandt, N., Lysenkova, M., Smedberg, N., 2015. Looplocal–a heuristic visualization tool to support the strategic facilitation of industrial symbiosis. J. Clean. Prod. 98, 328–335. http://dx.doi.org/10.1016/j.jclepro.2014.08.012.

Akrivou, C., Lekawska-Andrinopoulou, L., Tsimiklis, G., Amditis, A., 2021. Industrial symbiosis platforms for synergy identification and their most important data points: a systematic review. Open Res. Eur. 1, 101. http://dx.doi.org/10.12688/openreseurope.13893.1.

Albino, V., Fraccascia, L., Giannoccaro, I., 2016. Exploring the role of contracts to support the emergence of self-organized industrial symbiosis networks: an agent-based simulation study. J. Clean. Prod. 112, 4353–4366. http://dx.doi.org/10.1016/j.jclepro.2015.06.070.

Anderson, E.G., Lopez, J., Parker, G.G., 2022. Leveraging value creation to drive the growth of B2B platforms. Prod. Oper. Manage. 31 (12), 4501–4514. http://dx.doi.org/10.2139/ssrn.3975711.

Arthur, W.B., 1994. Increasing Returns and Path Dependence in the Economy. University of michigan Press.

Asratian, A.S., Denley, T.M., Häggkvist, R., 1998. Bipartite Graphs and their Applications, vol. 131, Cambridge University Press.

Batten, D.F., 2009. Fostering industrial symbiosis with agent-based simulation and participatory modeling. J. Ind. Ecol. 13 (2), 197–213. http://dx.doi.org/10.1111/j.1530-9290.2009.00115.x.

Benedict, M., Kosmol, L., Esswein, W., 2018. Designing industrial symbiosis platforms - from platform ecosystems to industrial ecosystems. In: Pacific Asia Conference on Information Systems. https://api.semanticscholar.org/CorpusID:53226379.

Bianchi, C., Cirillo, P., Gallegati, M., Vagliasindi, P.A., 2008. Validation in agent-based models: An investigation on the CATS model. J. Econ. Behav. Organ. 67 (3–4), 947–964. http://dx.doi.org/10.1016/j.jebo.2007.08.008.

Bichraoui, N., Guillaume, B., Halog, A., 2013. Agent-based modelling simulation for the development of an industrial symbiosis-preliminary results. Procedia Environ. Sci. 17, 195–204. http://dx.doi.org/10.1016/J.PROENV.2013.02.029.

Boix, M., Montastruc, L., Azzaro-Pantel, C., Domenech, S., 2015. Optimization methods applied to the design of eco-industrial parks: a literature review. J. Clean. Prod. 87, 303–317. http://dx.doi.org/10.1016/j.jclepro.2014.09.032.

Boons, F., Howard-Grenville, J.A., 2009. The Social Embeddedness of Industrial Ecology. Edward Elgar Publishing.

Boyle, C., Baetz, B., 1998. A prototype knowledge-based decision support system for industrial waste management: Part II. Application to a Trinidadian industrial estate case study. Waste Manage. 17 (7), 411–428. http://dx.doi.org/10.1016/S0956-053X(97)10025-3.

Brown, J., 2002. The MatchMaker ! System : Creating virtual eco-industrial parks 1997. https://api.semanticscholar.org/CorpusID:32126382.

Cao, K., Feng, X., Wan, H., 2009. Applying agent-based modeling to the evolution of eco-industrial systems. Ecol. Econom. 68 (11), 2868–2876. http://dx.doi.org/10.1016/J.ECOLECON.2009.06.009.

van Capelleveen, G., Amrit, C., Yazan, D.M., 2018. A literature survey of information systems facilitating the identification of industrial symbiosis. From science to society: New trends in environmental informatics 155–169. http://dx.doi.org/10.1007/978-3-319-65687-8_14.

Casey, T.R., Töyli, J., 2012. Dynamics of two-sided platform success and failure: An analysis of public wireless local area access. Technovation 32 (12), 703–716. http://dx.doi.org/10.1016/j.technovation.2012.08.003.

Chaudhuri, A., Datta, P.P., Fernandes, K.J., Xiong, Y., 2021. Optimal pricing strategies for manufacturing-as-a service platforms to ensure business sustainability. Int. J. Prod. Econ. 234, 108065. http://dx.doi.org/10.1016/j.ijpe.2021.108065.

Chen, Z., Li, H., Kong, S.C., Hong, J., Xu, Q., 2006. E-commerce system simulation for construction and demolition waste exchange. Autom. Constr. 15 (6), 706–718. http://dx.doi.org/10.1016/j.autcon.2005.09.003.

Chen, P.-C., Ma, H.-w., 2015. Using an industrial waste account to facilitate national level industrial symbioses by uncovering the waste exchange potential. J. Ind. Ecol. 19 (6), 950–962. http://dx.doi.org/10.1111/jiec.12236.

Chertow, M., 2000. Industrial symbiosis: literature and taxonomy. Annu. Rev. Energy Environ. 25 (1), 313–337. http://dx.doi.org/10.1146/annurev.energy.25.1.313.

Chertow, M., 2007. "Uncovering" industrial symbiosis. Journal of industrial Ecology 11 (1), 11–30. http://dx.doi.org/10.1162/jiec.2007.1110.

Chertow, M., Ehrenfeld, J., 2012. Organizing self-organizing systems: Toward a theory of industrial symbiosis. J. Ind. Ecol. 16 (1), 13–27. http://dx.doi.org/10.1111/j.1530-9290.2011.00450.x.

Clayton, A., Muirhead, J., Reichgelt, H., 2002. Enabling industrial symbiosis through a web-based waste exchange. Greener Manage. Int. (40), 93–106. http://dx.doi.org/10.9774/GLEAF.3062.2002.wi.00008.

Cote, R., Hall, J., 1995. Industrial parks as ecosystems. J. Clean. Prod. 3 (1–2), 41–46. http://dx.doi.org/10.1016/0959-6526(95)00041-C.

Cutaia, L., Morabito, R., Barberio, G., Mancuso, E., Brunori, C., Spezzano, P., Mione, A., Mungiguerra, C., Li Rosi, O., Cappello, F., 2014. The project for the implementation of the industrial symbiosis platform in sicily: the progress after the first year of operation. Pathways Environ. Sustain.: Methodol. Exp. 205–214. http://dx.doi.org/10.1007/978-3-319-03826-1_20.

D'Amato, D., Korhonen, J., Toppinen, A., 2019. Circular, green, and bio economy: how do companies in land-use intensive sectors align with sustainability concepts? Ecol. Econ. 158, 116–133. http://dx.doi.org/10.1016/j.ecolecon.2018.12.026.

David, P.A., 1994. Why are institutions the 'carriers of history'?: Path dependence and the evolution of conventions, organizations and institutions. Struct. change Econ. Dyn. 5 (2), 205–220. http://dx.doi.org/10.1016/0954-349X(94)90002-7.

De Reuver, M., Sørensen, C., Basole, R.C., 2018. The digital platform: a research agenda. J. Inf. Technol. 33 (2), 124–135. http://dx.doi.org/10.1057/s41265-016-0033-3.

Demartini, M., Tonelli, F., Govindan, K., 2022. An investigation into modelling approaches for industrial symbiosis: A literature review and research agenda. Clean. Logist. Supply Chain 3, 100020. http://dx.doi.org/10.1016/j.clscn.2021.100020.

Dhanorkar, S., Donohue, K., Linderman, K., 2015. Repurposing materials and waste through online exchanges: overcoming the last hurdle. Prod. Oper. Manage. 24 (9), 1473–1493. http://dx.doi.org/10.1111/poms.12345.

Dietrich, J., Becker, F., Nittka, T., Wabbels, M., Modoran, D., Aionesei, C., Kast, G., Williams, I.D., Curran, T., den Boer, E., et al., 2014. Extending product lifetimes: A reuse network for ICT hardware. In: Proceedings of the Institution of Civil Engineers-Waste and Resource Management. Vol. 167, Thomas Telford Ltd, pp. 123–135. http://dx.doi.org/10.1680/warm.13.00024.

Domenech, T., Bahn-Walkowiak, B., 2019. Transition towards a resource efficient circular economy in Europe: policy lessons from the EU and the member states. Ecol. Econom. 155, 7–19. http://dx.doi.org/10.1016/j.ecolecon.2017.11.001.

Dooley, K.J., 1997. A complex adaptive systems model of organization change. Nonlinear Dyn. Psychol. Life Sci. 1, 69–97. http://dx.doi.org/10.1023/A:1022375910940.

Duan, Y., Liu, P., Feng, Y., 2022. Pricing strategies of two-sided platforms considering privacy concerns. J. Retail. Consum. Serv. 64, 102781. http://dx.doi.org/10.1016/j.jretconser.2021.102781.

Dubester, L., 2000. Materials Flow through the Community: creating New Resource Opportunities. RBED Report August 2000.

Eilering, J.A., Vermeulen, W.J., 2004. Eco-industrial parks: toward industrial symbiosis and utility sharing in practice. Prog. Ind. Ecol. Int. J. 1 (1–3), 245–270. http://dx.doi.org/10.1504/PIE.2004.004681.

Fichtner, W., Tietze-Stöckinger, I., Frank, M., Rentz, O., 2005. Barriers of interorganisational environmental management: Two case studies on industrial symbiosis. Prog. Ind. Ecol. Int. J. 2 (1), 73–88. http://dx.doi.org/10.1504/PIE.2005.006778.

Fortuna, L.M., Diyamandoglu, V., 2015. NYC WasteMatch–An online facilitated materials exchange as a tool for pollution prevention. Resour. Conserv. Recycl. 101, 122–131. http://dx.doi.org/10.1016/j.resconrec.2015.05.010.

Fraccascia, L., 2019. The impact of technical and economic disruptions in industrial symbiosis relationships: An enterprise input-output approach. Int. J. Prod. Econ. 213, 161–174. http://dx.doi.org/10.1016/j.ijpe.2019.03.020.

Fraccascia, L., 2020. Quantifying the direct network effect for online platforms supporting industrial symbiosis: an agent-based simulation study. Ecol. Econ. 170, 106587. http://dx.doi.org/10.1016/j.ecolecon.2019.106587.

Fraccascia, L., Albino, V., Garavelli, C.A., 2017. Technical efficiency measures of industrial symbiosis networks using enterprise input-output analysis. Int. J. Prod. Econ. 183, 273–286. http://dx.doi.org/10.1016/j.ijpe.2016.11.003.

Fraccascia, L., Yazan, D.M., 2018. The role of online information-sharing platforms on the performance of industrial symbiosis networks. Resour. Conserv. Recycl. 136, 473–485. http://dx.doi.org/10.1016/j.resconrec.2018.03.009.

Fraccascia, L., Yazan, D.M., Albino, V., Zijm, H., 2020. The role of redundancy in industrial symbiotic business development: A theoretical framework explored by agent-based simulation. Int. J. Prod. Econ. 221, 107471. http://dx.doi.org/10.1016/j.ijpe.2019.08.006.

Fraccascia, L., Yazdanpanah, V., Van Capelleveen, G., Yazan, D.M., 2019. A framework for industrial symbiosis systems for agent-based simulation. In: 2019 IEEE 21st Conference on Business Informatics. CBI, Vol. 1, IEEE, pp. 419–428. http://dx.doi.org/10.1109/CBI.2019.00055.

Ghali, M.R., Frayret, J.-M., Ahabchane, C., 2017. Agent-based model of self-organized industrial symbiosis. J. Clean. Prod. 161, 452–465. http://dx.doi.org/10.1016/j.jclepro.2017.05.128.

Ghali, M.R., Frayret, J.-M., Robert, J.-M., 2016. Green social networking: concept and potential applications to initiate industrial synergies. J. Clean. Prod. 115, 23–35. http://dx.doi.org/10.1016/j.jclepro.2015.12.028.

Giannoccaro, I., Carbone, G., 2017. An ising-based dynamic model to study the effect of social interactions on firm absorptive capacity. Int. J. Prod. Econ. 194, 214–227. http://dx.doi.org/10.1016/j.ijpe.2017.05.003.

Giannoccaro, I., Pontrandolfo, P., 2009. Negotiation of the revenue sharing contract: An agent-based systems approach. Int. J. Prod. Econ. 122 (2), 558–566. http://dx.doi.org/10.1016/j.ijpe.2009.02.014.

Golev, A., Corder, G.D., Giurco, D.P., 2015. Barriers to industrial symbiosis: Insights from the use of a maturity grid. J. Ind. Ecol. 19 (1), 141–153. http://dx.doi.org/10.1111/jiec.12159.

Gopal, R.D., Hidaji, H., Patterson, R.A., Rolland, E., Zhdanov, D., 2018. How much to share with third parties? User privacy concerns and website dilemmas. Mis Q. 42 (1), 143–A25. http://dx.doi.org/10.25300/MISQ/2018/13839.

Grant, G.B., Seager, T.P., Massard, G., Nies, L., 2010. Information and communication technology for industrial symbiosis. J. Ind. Ecol. 14 (5), 740–753. http://dx.doi.org/10.1111/j.1530-9290.2010.00273.x.

Grimmel, P., Tan, C.F., Niemeyer, J.F., Yeo, Z., Mennenga, M., Hermsen, M., Yajuan, S., Yang, Z., Herrmann, C., 2024. Collaboration platform for enabling industrial symbiosis: Integrated knowledge graph database. Procedia CIRP 122, 395–400. http://dx.doi.org/10.1016/j.procir.2024.01.057.

Haurand, M.D., Stummer, C., 2018. The early-stage development of two-sided digital platforms: a simulation approach. In: European Conference on Information Systems. https://api.semanticscholar.org/CorpusID:56149759.

Haurand, M.D., Stummer, C., 2023. Determining the right time to advertise adopter numbers for a two-sided digital platform: An agent-based simulation optimization approach. EURO J. Decis. Process. 11, 100032. http://dx.doi.org/10.1016/j.ejdp.2023.100032.

Hein, A., Weking, J., Schreieck, M., Wiesche, M., Böhm, M., Krcmar, H., 2019. Value co-creation practices in business-to-business platform ecosystems. Electron. Mark. 29, 503–518. http://dx.doi.org/10.1007/s12525-019-00337-y.

Hobbs, J.E., 1996. A transaction cost approach to supply chain management. Supply Chain Manage.: Int. J. 1 (2), 15–27. http://dx.doi.org/10.1108/13598549610155260.

Holland, J.H., 2002. Complex adaptive systems and spontaneous emergence. In: Complexity and Industrial Clusters: Dynamics and Models in Theory and Practice. Springer, pp. 25–34. http://dx.doi.org/10.1007/978-3-642-50007-7_3.

Hsien, C., Foo, C.K., Low, J.S.C., Tan, D.Z.L., 2020. A collaboration platform for enabling industrial symbiosis: Application of the database engine for eco-efficient waste-to-resource conversions. Procedia CIRP 90, 115–120. http://dx.doi.org/10.1016/j.procir.2020.02.059.

Hsien, C., Low, J.S.C., Chung, S.Y., Tan, D.Z.L., 2019. Quality-based water and wastewater classification for waste-to-resource matching. Resour. Conserv. Recycl. 151, 104477. http://dx.doi.org/10.1016/j.resconrec.2019.104477.

Jacobsen, N.B., 2006. Industrial symbiosis in Kalundborg, Denmark: a quantitative assessment of economic and environmental aspects. J. Ind. Ecol. 10 (1–2), 239–255. http://dx.doi.org/10.1162/108819806775545411.

Johnson, M.A., Johnson, D.M., 2005. Integrated strategy of industrial product suppliers: Working with B2B intermediaries. Internet Res. 15 (4), 471–492. http://dx.doi.org/10.1108/10662240510615209.

Jovanovic, M., Sjödin, D., Parida, V., 2022. Co-evolution of platform architecture, platform services, and platform governance: Expanding the platform value of industrial digital platforms. Technovation 118, 102218. http://dx.doi.org/10.1016/j.technovation.2020.102218.

Kerdlap, P., Low, J.S.C., Steidle, R., Tan, D.Z.L., Herrmann, C., Ramakrishna, S., 2019. Collaboration platform for enabling industrial symbiosis: Application of the industrial-symbiosis life cycle analysis engine. Procedia CIRP 80, 655–660. http://dx.doi.org/10.1016/j.procir.2019.01.081.

King, S., Lusher, D., Hopkins, J., Simpson, G.W., 2020. Industrial symbiosis in Australia: The social relations of making contact in a matchmaking marketplace for SMEs. J. Clean. Prod. 270, 122146. http://dx.doi.org/10.1016/j.jclepro.2020.122146.

Krom, P., Piscicelli, L., Frenken, K., 2022. Digital platforms for industrial symbiosis. J. Innov. Econ. Manage. I124–XXVI. http://dx.doi.org/10.3917/jie.pr1.0124.

Kumar, S., Sethi, S.P., 2009. Dynamic pricing and advertising for web content providers. European J. Oper. Res. 197 (3), 924–944. http://dx.doi.org/10.1016/j.ejor.2007.12.038.

Lombardi, D.R., Laybourn, P., 2012. Redefining industrial symbiosis: Crossing academic–practitioner boundaries. J. Ind. Ecol. 16 (1), 28–37. http://dx.doi.org/10.1111/j.1530-9290.2011.00444.x.

Lütje, A., Willenbacher, M., Möller, A., Wohlgemuth, V., 2019. Enabling the identification of industrial symbiosis through ict. http://hdl.handle.net/10125/59511.

Madanaguli, A., Parida, V., Sjödin, D., Oghazi, P., 2023. Literature review on industrial digital platforms: A business model perspective and suggestions for future research. Technol. Forecast. Soc. Change 194, 122606. http://dx.doi.org/10.1016/j.techfore.2023.122606.

Manson, S., 2003. Validation and verification of multi-agent models for ecosystem management. Complex. Ecosyst. Manage.: Theory Pract. Multi-Agent Appr. 63–74.

Maqbool, A.S., Mendez Alva, F., Van Eetvelde, G., 2018. An assessment of European information technology tools to support industrial symbiosis. Sustainability 11 (1), 131. http://dx.doi.org/10.3390/books978-3-03928-253-1.

Mirata, M., 2004. Experiences from early stages of a national industrial symbiosis programme in the UK: determinants and coordination challenges. J. Clean. Prod. 12 (8–10), 967–983. http://dx.doi.org/10.1016/j.jclepro.2004.002.031.

Neves, A., Godina, R., Azevedo, S.G., Matias, J.C., 2020. A comprehensive review of industrial symbiosis. J. Clean. Prod. (ISSN: 0959-6526) 247, 119113. http://dx.doi.org/10.1016/j.jclepro.2019.119113.

Neves, A., Godina, R., G. Azevedo, S., Pimentel, C., C.O. Matias, J., 2019. The potential of industrial symbiosis: Case analysis and main drivers and barriers to its implementation. Sustainability (ISSN: 2071-1050) 11 (24), http://dx.doi.org/10.3390/su11247095.

Patricio, J., Kalmykova, Y., Rosado, L., Cohen, J., Westin, A., Gil, J., 2022. Method for identifying industrial symbiosis opportunities. Resour. Conserv. Recycl. 185, 106437. http://dx.doi.org/10.1016/j.resconrec.2022.106437.

Rammel, C., Stagl, S., Wilfing, H., 2007. Managing complex adaptive systems—a co-evolutionary perspective on natural resource management. Ecol. Econ. 63 (1), 9–21. http://dx.doi.org/10.1016/j.ecolecon.2006.12.014.

Rindfleisch, A., Heide, J.B., 1997. Transaction cost analysis: Past, present, and future applications. J. Mark. 61 (4), 30–54. http://dx.doi.org/10.2307/1252085.

Rochet, J.-C., Tirole, J., 2004. Two-Sided Markets: An Overview. Institut d'Economie Industrielle working paper, pp. 1–44.

Ruutu, S., Casey, T., Kotovirta, V., 2017. Development and competition of digital service platforms: A system dynamics approach. Technol. Forecast. Soc. Change 117, 119–130. http://dx.doi.org/10.1016/j.techfore.2016.12.011.

Rysman, M., 2009. The economics of two-sided markets. J. Econ. Perspect. 23 (3), 125–143. http://dx.doi.org/10.1257/jep.23.3.125.

Saghafi, Z., Roshandel, R., 2024. Agent-based simulation for technology implementation in an energy-based industrial symbiosis network. Resour. Conserv. Recycl. Adv. 21, 200201. http://dx.doi.org/10.1016/j.rcradv.2023.200201.

Schirrmacher, N.-B., Ondrus, J., Kude, T., 2017. Launch strategies of digital platforms: platforms with switching and non-switching users. In: European Conference on Information Systems. https://api.semanticscholar.org/CorpusID:37464359.

Shree, D., Singh, R.K., Paul, J., Hao, A., Xu, S., 2021. Digital platforms for business-to-business markets: A systematic review and future research agenda. J. Bus. Res. 137, 354–365. http://dx.doi.org/10.1016/j.jbusres.2021.08.031.

Silva, M.G., de Carvalho, T.S., Castagna, A.G., do Rocio Strauhs, F., Piekarski, C.M., 2022. The role of online platforms to enable the process of industrial symbiosis: An analysis of tools available in the market. Clean. Prod. Lett. (ISSN: 2666-7916) 3, 100021. http://dx.doi.org/10.1016/j.clpl.2022.100021.

Stummer, C., Kundisch, D., Decker, R., 2018. Platform launch strategies. Bus. Inf. Syst. Eng. 60, 167–173. http://dx.doi.org/10.1007/s12599-018-0520-x.

Taddeo, R., Simboli, A., Morgante, A., Erkman, S., 2017. The development of industrial symbiosis in existing contexts. experiences from three Italian clusters. Ecol. Econom. 139, 55–67. http://dx.doi.org/10.1016/j.ecolecon.2017.04.006.

Tudor, T., Adam, E., Bates, M., 2007. Drivers and limitations for the successful development and functioning of EIPs (eco-industrial parks): A literature review. Ecol. Econom. 61 (2–3), 199–207. http://dx.doi.org/10.1016/j.ecolecon.2006.10.010.

Williamson, O.E., 1981. The economics of organization: The transaction cost approach. Am. J. Sociol. 87 (3), 548–577. http://dx.doi.org/10.1086/227496.

Yang, S., Feng, N., 2008. A case study of industrial symbiosis: Nanning Sugar Co., Ltd. in China. Resour. Conserv. Recycl. (ISSN: 0921-3449) 52 (5), 813–820. http://dx.doi.org/10.1016/j.resconrec.2007.11.008.

Yazan, D.M., Yazdanpanah, V., Fraccascia, L., 2020. Learning strategic cooperative behavior in industrial symbiosis: A game-theoretic approach integrated with agent-based simulation. Bus. Strategy Environ. (ISSN: 1099-0836) 29 (5), 2078–2091. http://dx.doi.org/10.1002/bse.2488.

Yelkur, R., DaCosta, M.M.N., 2001. Differential pricing and segmentation on the internet: the case of hotels. Manage. Decis. 39 (4), 252–262. http://dx.doi.org/10.1108/00251740110391411.

Yeo, Z., Low, J.S.C., Tan, D.Z.L., Chung, S.Y., Tjandra, T.B., Ignatius, J., 2019a. A collaboration platform for enabling industrial symbiosis: Towards creating a self-learning waste-to-resource database for recommending industrial symbiosis transactions using text analytics. Procedia CIRP 80, 643–648. http://dx.doi.org/10.1016/j.procir.2019.01.015.

Yeo, Z., Masi, D., Low, J.S.C., Ng, Y.T., Tan, P.S., Barnes, S., 2019b. Tools for promoting industrial symbiosis: A systematic review. J. Ind. Ecol. 23 (5), 1087–1108. http://dx.doi.org/10.1111/jiec.12846.

Yoon, Y.L., Yoon, Y., Nam, H., Choi, J., 2021. Buyer-supplier matching in online B2B marketplace: An empirical study of small-and medium-sized enterprises (SMEs). Ind. Mark. Manage. 93, 90–100. http://dx.doi.org/10.1016/j.indmarman.2020.12.010.

Young, R., 1999. By-product synergy: A demonstration project Tampico, Mexico. Bus. Counc. Sustain. Dev.-Gulf Mex. http://dx.doi.org/10.1016/j.resconrec.2018.09.026.

Zhao, D., Yuan, Z., Chen, M., Yang, S., 2022. Differential pricing strategies of ride-sharing platforms: choosing customers or drivers? Int. Trans. Oper. Res. 29 (2), 1089–1131. http://dx.doi.org/10.1111/itor.13045.

Zheng, K., Jia, S., 2017. Promoting the opportunity identification of industrial symbiosis: Agent-based modeling inspired by innovation diffusion theory. Sustainability 9 (5), 765. http://dx.doi.org/10.3390/su9050765.

Zhu, F., Iansiti, M., 2012. Entry into platform-based markets. Strateg. Manag. J. 33 (1), 88–106. http://dx.doi.org/10.1002/smj.941.

Zhu, Q., Lowe, E.A., Wei, Y.-a., Barnes, D., 2007. Industrial symbiosis in China: a case study of the Guitang Group. J. Ind. Ecol. 11 (1), 31–42. http://dx.doi.org/10.1162/jiec.2007.929.