A Framework of Industrial Symbiosis Systems for Agent-based Simulation

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***Abstract*—The industrial symbiosis (IS) practice refers to replacing production inputs with wastes generated by other production processes, thus helping to close the loop of manufacturing processes. Companies adopting IS can reduce the amounts of wastes disposed of in landfills and primary inputs used in production processes, enhancing their production efficiency and reducing their production cost. The Agent-based modeling (ABM) approach has been recently adopted to advance the knowledge in the IS field, in particular to explore the extent to which the establishment of IS relationships can be affected by policy measures, benefit-sharing contracts, information-sharing tools, or social factors. However, the agent-based models proposed in the literature are highly different in terms of agents considered, their attributes, possible actions, and decisional rules. In particular, these models might result far from the real world, in terms of how the agents are modeled, as well as on the actions that they can undertake. The aim of this paper is to provide a general framework on how to model IS systems with ABM in a comprehensive way. The paper provides a literature review on IS aimed at identifying the potential agents in IS, their attributes, and their potential actions, shaped by technical, economic, and regulatory issues affecting the behavior of agents in terms of strategic management. Based on the results of the literature review, a general framework is proposed and discussed. This paper is expected to advance the knowledge on ABM for IS by providing useful suggestions to modelers and academicians.**

Keywords—*Industrial Symbiosis, Agent-Based Modeling, Circular Economy, Multiagent Technology, Decision support*

I. Introduction

One of the key strategies that companies can adopt to support the transition towards the circular economy is the Industrial Symbiosis (IS) practice [1]. IS is a subfield of industrial ecology that engages different companies in physical exchanges of materials, energy, and services. The IS practice refers to replacing production inputs with wastes generated by other production processes [2], thus helping to close the loop of manufacturing processes. Companies adopting IS can reduce the amounts of wastes disposed of in landfills and primary inputs used in production processes [3], thus enhancing production efficiency [4] and reducing production costs [5]. Gaining economic benefits is the main driver pushing companies towards implementing IS synergies [5]–[7].

The Agent-Based Modeling (ABM) approach has been recently adopted to advance the knowledge in the IS field, in particular to explore the extent to which the establishment of IS synergies among different companies can be affected by policy measures [8], benefit-sharing contracts [9], information-sharing tools [10], as well as social factors concerning the relationships among companies [11]. In fact, ABM is a suitable methodology to study complex systems consisting of autonomous decision-making entities, aimed at building new theories, concepts, and knowledge about some fundamental processes of these systems [12]. Each entity is modeled as an independent agent, which is provided with: 1) a set of goals it has to accomplish through the interaction with other agents and the environment; and 2) a set of rules of social engagement, driving such interactions [13]. The modeler does not define the system behavior, which spontaneously emerges from the interactions among the agents and between agents and the environment [14]. Therefore, the ABM approach allows researchers to investigate the system dynamics in a way that analytical models fail to capture [15]. In this sense, one of the main advantages of ABM is the possibility to simulate the same system under different scenarios, defined by the combination of different values of selected variables, in order to highlight if and how one or more specific variables can affect one of more outputs of the system.

However, the agent-based models proposed in the literature that simulate IS systems are highly different in terms of agents considered, their attributes, possible actions, and decisional rules. In fact, characteristics and behavior of agents are designed taking into account the specific issues that the model investigates and, therefore, they do not consider all of the aspects related to IS in a comprehensive way. For example, agent-based models aimed at investigating the impact of benefit-sharing contracts do not consider social factors when modeling the possible actions undertaken by companies.

978-1-7281-0650-2/19/$31.00 ©2019 IEEE
DOI 10.1109/CBI.2019.00055

Therefore, these models might result far from the real world, in terms of how the agents are modeled, as well as on the actions that they can undertake. However, so that agent-based models can be effective, decision rules must be as realistic as possible, otherwise simulations may lead to misconceived results [16]. Therefore, it is critical to design agent-based models as accurately as possible.

The aim of this paper is to design a framework on how to model IS systems via ABM. The structure of the framework, which is adapted from previous works by Barbati et al. [17] and Romero and Ruiz [18], is developed in three blocks: 1) description of the phenomenon to study, by identifying the different categories of IS synergies; 2) characterization of the agents' population and, for each agent, drivers and actions that they can undertake; and 3) surrounding and factors of external changes, which can impact on the interaction paradigm among agents.

The framework is built based on the results of a literature review on IS that identifies the potential agents in IS, their attributes, and their potential actions, shaped by technical, economic, and regulatory issues which in turn affect the behavior of agents in terms of strategic management. This paper is expected to advance the knowledge on ABM for IS by providing useful suggestions to modelers and academicians. Our work can be used as input by IS network analysts to develop realistic agent-based models, in which the set of agents correspond to the context of application, and accordingly to formulate behavioral rules based on real-life IS practices. In this regard, our results contribute to the contextualization of ABM for IS. See similar approaches, focused on context-aware methods, in Jie et al. [19] on inter-organizational trade and in Edmonds [20] on the use of qualitative measures for informing ABM.

II. Methodology for the Literature Review

The study is based on a bibliographic research started on 30th January 2018. The first step was to collect papers presenting and discussing cases of IS. The data were retrieved from Scopus, an academic citation indexing and search service of Elsevier. The following research keywords have been applied to title, abstract, and keywords of papers to cover the largest possible selection:

(*Case study* OR *case studies* OR *case* OR *cases*) AND (*Industrial Symbiosis* OR *Industrial Ecology* OR *Circular Economy* OR *Industrial park** OR *Eco-industrial park** OR *Closed-loop supply chain**).

Research keywords were selected to encompass the concept of IS including "industrial ecology", "circular economy", and "closed-loop supply chain" concepts. Such an approach was adopted because, according to the authors' experience, some papers might discuss cases of IS without explicitly defining them as IS but contextualizing them within the above-mentioned fields. As a result of the research, 1100 papers were collected, 1041 of them (94.64%) in English. We further limited the analysis by considering only papers published in international scientific journals [21], [22]. The first database was composed of 682 papers (65.80% of the original sample). A selection process was carried out through analyzing these papers, aimed at excluding papers discussing cases not relevant for the aim of this research. Furthermore, some papers were excluded from the analysis because the full text was not available. The final database is composed of 159 papers. The overall process is graphically displayed in Figure 1.

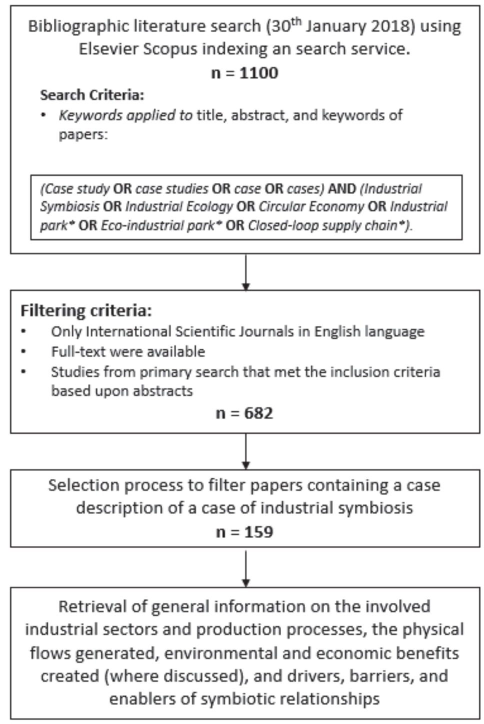

Fig. 1. The methodology followed for the literature review.

III. Theoretical Framework

In this Section, the theoretical framework designed in this paper, which is shown graphically in Figure 2, is described.

The phenomenon to study concerns the exchange of waste between separate companies. Here, "waste" is intended as something not useful for the company that has its ownership but that can be exploited by a different company. According to this definition, four categories of IS synergies can be distinguished: 1) material-based synergies; 2) energy-based synergies; 3) water-based synergies; and 4) service-based synergies. These categories are described in Section IV.

Concerning the agents' population, three different agents can be modeled: *companies* exchanging wastes, *policymakers*, and IS *facilitators*. The characteristics of these agents, together with the actions driving the interaction among them, are described in Section V.

Finally, several factors of external change are observed. These factors might directly impact on the waste exchange by reducing or enhancing the willingness of companies to operate IS. Four factors can be highlighted, two concerning technical issues – i.e., the match between demand and potential supply of waste and the quality of waste – and two concerning economic issues – i.e., the economic viability of the IS synergy and the contractual clauses related to the waste exchange. These factors are described in Section VI.

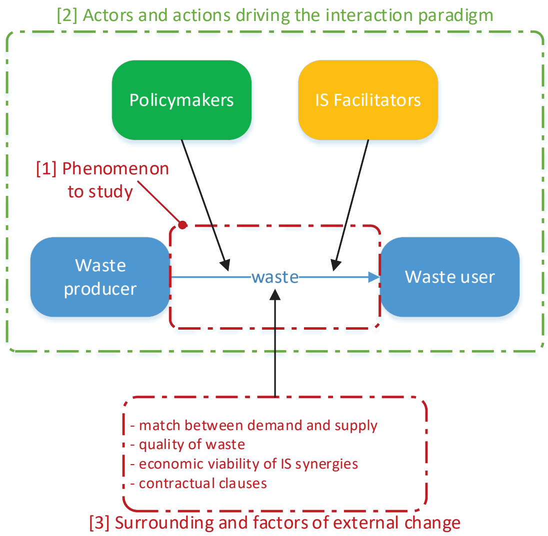

Fig. 2. The theoretical framework on ABM for IS.

IV. Phenomenon Description: Categories of IS Synergies

In the following subsections, the categories of IS synergies are described: *material-based, energy-based, water-based, and service-based* synergies are respectively presented in Sections A, B, C, and D.

A. *Material-based synergies*

Material-based synergies are the most diffused and implemented IS synergies. They involve recovering wastes produced in industrial, urban, and rural areas instead of disposing them of in the landfill. According to the use of wastes, two categories of material-based IS synergies can be distinguished: 1) *input replacement*; and 2) *co-product generation* [23]. In *input-replacement* strategies, wastes produced by one production process are used by other processes to replace inputs. In such a case, the waste user company gains economic benefits from reducing input purchasing costs. In *co-product generation* strategies, wastes are exploited to produce new products, which are sold in the market. In this case, the waste user company gains economic benefits in the form of additional gains from selling an additional product. Since wastes are usually transported by trucks, i.e., no physical infrastructures are required for exchanging wastes, material-based IS synergies can be implemented even among companies not in close geographic proximity [24].

B. *Energy-based synergies*

Energy-based IS synergies are mainly aimed at reducing the amount of energy produced by traditional fuels. Three categories of energy-based IS can be recognized: 1) *energy cascade*; 2) *fuel replacement*; and 3) *bioenergy production*. In particular, an *energy cascade* between two companies occurs when the waste energy (e.g., heat or steam) produced by one company is used by the other company [25]–[27]. Waste energy is produced by power plants or industrial facilities and it is sent to other industrial facilities or to townspeople through pipelines. Characteristics of the energy-based synergy, such as the type of energy and the amount of energy produced, also define the infrastructural requirements, e.g., the need for conversion technology and reliance on new or existing transportation networks, e.g., pipelines. Hence, the involved companies are often expected to be in close geographic proximity so that energy transportation is both technically and economically feasible. From the structural perspective, energy cascade among different companies can be implemented according to two different models: 1) the producer directly supplies user(s) with energy; 2) the producer sends energy to a heat recovery system facility, which supplies energy to other companies located close to the plant and townspeople. A *fuel replacement* IS synergy occurs when waste materials are used to replace traditional fuels in existing fuel-based energy production processes (e.g., coal-based energy production) [28], [29]. Finally, *bioenergy production* IS synergies exploit organic wastes to produce bioenergy [30], [31]. In the case of fuel replacement and bioenergy production, solid wastes can be produced in industrial, urban, and rural areas [28], [30], [32]. In addition to reducing the amount of energy produced by traditional fuels, these IS synergies may induce environmental benefits in the form of lower amounts of waste disposed of in the landfill and GHG emitted to the atmosphere. In both cases, since wastes are usually transported by trucks, geographic proximity is not a fundamental requisite for the effectiveness of these strategies. However, for degradable types of wastes (such as food- or beverage-processing wastes), distance matters.

C. *Water-based synergies*

Water-based IS synergies are mainly aimed at reducing the water consumption of industrial complexes. They involve recovering wastewater produced by industrial processes or residential areas [33], [34]. In particular, the water can be reused as industrial water by industrial processes, as cooling water by companies and houses, or in agriculture. The water can be contaminated by organic components, thus requiring to be treated before being used in other processes as pure water or grey water. From the structural perspective, two models can be recognized: 1) water exchanges directly implemented among companies; 2) water exchanges supported by a centralized water recycling system. In the former case, the wastewater is directly exchanged among companies, while in the latter the water is sent to a water recycling and collection facility and then sent to other processes. Since the water is usually transported by pipelines, water-based IS synergies are implemented among facilities (both companies and houses) in close geographic proximity, in order to minimize infrastructural costs [33], [34].

D. *Service-based synergies*

Unlike the above-mentioned IS-based categories, service-based IS synergies do not concern physical exchanges of wastes among companies. Companies are involved in sharing the production facility resources such as the machinery, the capacity of a production location or any services related to the support activities of an organization, e.g., waste recycling facilities, waste-to-energy production plants, wastewater treatment facilities, etc. Usually, companies share facilities in eco-industrial parks.

V. Agents and Actions Driving the Interaction Paradigm

In this section, the main agents involved in IS relationships are discussed: companies exchanging wastes are presented in subsection A, policymakers in subsection B, and IS facilitators in subsection C. For each agent, first the characteristics and drivers behind their involvement in the IS practice are discussed. Then, the possible actions that agents might implement are presented.

A. Companies exchanging wastes

Characteristics and drivers. Four kinds of companies can be involved in the IS-synergies: 1) *waste producers*; 2) *waste users*; 3) *waste treatment companies*; and 4) *waste transportation companies*.

Waste producers might decide to adopt the IS practice instead of disposing of wastes conventionally. *Waste users* might adopt the IS practice aimed at replacing production inputs with wastes or at producing new products for the market. *Waste treatment* companies are in charge of making wastes available as substitutes of inputs. The involvement of these companies is not mandatory for all IS relationships. In fact, it should be noted that: 1) some wastes can be directly used to replace inputs without any treatment process; 2) the waste treatment process might be operated directly by waste producer and waste user companies involved, without involving a third-party in the IS synergy. Furthermore, waste treatment companies can arise as joint ventures of waste producer and waste user companies or be independent third companies [35], [36]. Independent waste recycling companies can decide to be located close to the existing companies (or in the eco-industrial park area) attracted by the availability of wastes produced in that area, hence pushing companies located in that area to adopt the IS practice [27], [37]. Finally, *waste transportation* companies are in charge of the transportation of wastes among the involved companies. For these companies, being involved in IS exchanges is not different from traditional business.

Companies can decide to implement the IS practice because they are motivated by various drivers. The main driver highlighted by the literature is gaining economic benefits, aimed at achieving competitive advantage compared to other companies not adopting IS [5]–[7]. In particular, waste producers are pushed by the willingness to reduce their waste disposal costs while waste users are prompted by the willingness to reduce their input purchase costs. Furthermore, all these companies might be also driven by the willingness to exploit economic incentives that the government may provide for the implementation of IS synergies (see subsection B). Companies can also achieve competitive advantage thanks to the better market image and business reputation [38]–[40]. Besides profit, a further driver for companies to engage in IS is the compliance with environmental regulations imposed by the government (see subsection B) [41].

In some cases, the adoption of IS might require companies to renovate their business model. Hence, the propensity to innovation, which is an idiosyncratic property of firms, can influence the implementation of IS [42]. An imitation effect can be recognized, which leads to a diffusion mechanism: accordingly, companies can adopt the IS practice because their competitors already adopted such a practice [43], [44].

Several studies highlight the role of trust among companies as an enabler for IS, since it affects the willingness to cooperate of companies. Here, trust is intended as the expectation that the business partner will not adopt opportunistic behavior when carrying out the symbiotic relationship. In fact, companies might be willing to establish IS synergies with other companies they know, e.g., because of personal relationships among managers [45].

Companies can be characterized by different propensity to share information with their symbiotic partners. The literature highlights the benefits of information sharing, such as better match between demand and supply of wastes and better planning of IS synergies [10], [27], [46], [47]. Information sharing among companies may be a *conditio sine qua non* for IS relationships requiring companies to share investments or manage shared infrastructures [48]. However, if companies are not willing to share information, a strong barrier may arise.

Actions. Companies can be involved in several actions:

- <u>*Finding inputs that can be replaced by wastes and vice versa*</u>. Waste producers might be not aware of inputs that can be replaced by wastes they produce. Similarly, waste users might not be aware of wastes able to replace the inputs they require [46]. In this case, companies need to identify possible symbiotic opportunities and explore them from technical and legal perspective. More than one opportunity might exist for a given waste. For instance, end-of-life tires can replace coal in cement production or resilient granules in synthetic grass production [4]. Furthermore, the quality of waste may influence the feasibility of IS opportunities (see Section V, subsection B).
- <u>*Finding potential symbiotic partners*</u>. Spatial and social issues can affect this process. From the spatial perspective, companies may decide to cooperate with other firms in close geographic proximity, aimed at minimizing waste transportation costs. From the social perspective, companies may decide to cooperate with a company they know or might prefer to cooperate with a company because of its good reputation [45].
- <u>*Assessing the feasibility of the IS relationship*</u>. In order to assess the feasibility of IS relationships, companies need to carry out several actions: 1) designing the IS relationship from the operational perspective; 2) negotiating contractual clauses related to the IS relationship; and 3) computing the net economic benefits stemming from the IS relationship.
  The simplicity, the time, the cost of implementation, the return on investment, and the payback period are amongst the elements that companies consider for deciding which solution to implement [49], [50].
- <u>*Exploring new solutions to exploit wastes*</u>. Apart from the waste exchange, companies can interact amongst each other aimed at exploring new ways to reuse wastes. In such a way, eco-innovations can be promoted, in terms of new products, new waste treatment processes, or new ways to exploit a given waste [36], [51]. However, this practice requires that companies cooperate in implementing new processes

and sustain additional investments. Nevertheless, companies would prefer the traditional way (although ensuring lower profits) because in this way they keep low dependence on the partner (strategic reasons) or because they are not willing to invest (economic reasons).

B. Policymakers

Characteristics and drivers. Policymakers may decide to encourage companies to implement IS practices because of the environmental benefits that can be created, in favor of the overall collectivity. Both national and local governments can be involved in such a process.

Actions. Policymakers may adopt different policy instruments to push the adoption of the IS approach:

- Creating environmental regulations. Some examples of regulations are the following:
  - Regulatory restrictions on how certain waste materials may be processed. For instance, the government can impose the diversion of a given waste from the landfill, can promote/prohibit the use of a given waste to replace a given input [27], [47], [52]–[56], or define a mandatory percentage of waste usage [57]. In this regard, some regulations might exist limiting the symbiotic use of wastes with a high percentage of heavy metals [58]. Similarly, regulations were found limiting the amount of organic and inorganic pollutant in treated wastewater used in agriculture or in industrial applications [40], [59]. While in some cases these regulations might limit the feasibility of IS projects (e.g., the process to reduce the amount of pollutant in wastewater is not economically feasible), the lack of regulations on waste quality may hamper companies to establish IS relationships [60];
  - Regulations imposing companies to reduce the amount of waste disposed of in landfills [55] or even ban the use of certain materials [52];
  - Regulations on the waste disposal price. Such a price affects the economic benefits that can be created by the IS approach: hence, the higher the waste disposal price, the higher the willingness of companies to adopt IS will be, *ceteris paribus* [8]. In fact, if the waste disposal price is too low, companies might be not interested in implementing IS because of the scant economic benefits they can potentially gain [61], [62];
  - Taxes on carbon emissions generated by companies [61]. In this regard, several studies demonstrate that the IS practice may be able to reduce the CO_2 emitted by companies [63], [64];
  - Other *ad hoc* regulations. For instance, in Puerto Rico, a US regulation specifying that energy providers must also produce output other than electricity initiated steam production at the power plant, serving as a basis for the Guayama IS [65].
- Providing companies with economic incentives. Economic incentives may be useful for creating economic convenience or reducing the payback period of IS projects. Some examples of incentives are the following:
  - *Ad hoc* incentives for attracting companies in a given area, e.g.: provision of land, preferential policies on land lease, and tax reduction [61], [66], [67]. Such types of incentives can be useful when governments are willing to create an eco-industrial park where companies can exploit the geographic proximity to exchange wastes;
  - Financing partially or totally the physical infrastructures (e.g., pipelines) required to operate energy-based and/or water-based IS exchanges [35];
  - Subsidies on the use or implementation of cleaner production and waste treatment technologies [68];
  - Subsidies for producing renewable energy from wastes which cannot be recycled, e.g., organic wastes [30], [31];
  - Capital support, e.g., pre-financing (loans) [55];
  - Voluntary resource efficiency programs and cleaner technologies programs [69];
- *Creating public institutions aimed at supporting companies in adopting IS.* This action is discussed in subsection C.

C. IS Facilitators

Characteristics and drivers. Facilitators can play an anchoring role by creating social and institutional conditions that favor the emergence of IS relationships. Such actors can be public institutions or private consultancy companies [53]. Whilst public institutions are financed by governments and may support companies free of charge, private companies create value and make money through supporting companies in adopting the IS practice. In the literature, facilitators have been referred via several terms, such as "institutional anchors" [53], "organizing teams" [70], "coordinating bodies" [71], "champions" [72], and "network orchestrators" [73].

Actions. Facilitators can support the IS practice by providing companies with the knowledge that is relevant to IS, e.g.:

- Sharing knowledge about IS practices and processes, for instance by spreading success stories [51] or providing information on chemical properties, quality and related impacts of waste and their potential IS synergies [60];
- Providing safety information on how to process wastes, for example by sharing know-how methods that assure the transition to waste usage and giving measures on their substitutability with traditionally utilized inputs [60];
- Facilitating the development of social infrastructures, for example by setting up forums, organizing events where actors can meet, or by stimulating actors to participate in joint programs [53], [69];
- Providing companies with guidance, e.g., how to guarantee the proper pretreatment to waste flows for more efficient recycling or the possible symbiotic use of a given waste [53], [61]. These guidelines can be provided through *ad hoc* designed platforms for education;
- Creating inventories and databases of inputs required and wastes produced in a given area and making them

available for companies, aimed at favoring the match between waste demand and supply [44], [53];

- *Identifying possible symbiotic opportunities and synergies for companies*, for instance by organizing workshops among the group of potential partners and by fostering the contracting procedure [27];
- *Exploring technical and economic feasibility of IS projects* by providing detailed assessment of technical feasibility, environmental impacts and benefits, projected savings, capital costs, pros/cons of implementation and recommendations for action [27];
- *Facilitating the negotiation or mediation process among actors,* based on their experience on similar collaborations or by applying their knowledge about the socio-economic context of the relation [7], [69];
- *Operating the monitoring function of a shared facility*, such as the distribution platform of waste heat in a waste heat utilization network [74];
- *Assisting in political support*, e.g., how to obtain permits, change regulations, obtain subsidies, or in general facilitate governmental mediation [56].

VI. AGENTS' ENVIRONMENT AND FACTORS OF EXTERNAL CHANGE

In the following subsections, the surrounding and the factors of external changes are presented: the match between demand and potential supply of waste, the quality of waste, the economic profitability of IS, and the contractual clauses related to the waste exchange are presented in Sections A, B, C, and D, respectively.

A. Match between demand and potential supply of waste

A critical issue influencing the viability of the IS practice is that the required amount of waste should be delivered to the right waste user at the right time [75]. However, the mismatch between demand and supply of waste can influence IS synergies. Such a mismatch can exist because of several reasons:

- The lack of firms producing (requiring) a given waste for which demand (supply) exists [76]–[79];
- The lack of information, i.e., demand (supply) for a given waste exists but firms producing (requiring) that waste are not aware of such a demand (supply) [80]–[85];
- The lack of awareness on possible solutions for exploiting a given waste or wastes that can replace a given input [46], [75];
- Seasonality of main products demand (which drives the production of wastes and demand for inputs) [49]. Seasonality may depend on the specific industry but can also change across companies belonging to the same industry;
- Unreliable production processes leading to the production volumes which cannot be matched to a stable demand [86], or unreliable markets not able to produce enough demand [87], or suddenly disappear at all [88]. In cases where waste is utilized for energy production, often a backup generator is part of the solution to conserving the stability of electricity production [89]. In some cases, stocking may also provide a solution to such problems [42].

The mismatch between demand and supply of waste reduces the environmental benefits created by the IS synergy, thereby eroding the expected economic benefits for companies. Moreover, if the demand (supply) is much higher than supply (demand), the waste user (producer) will gain a scant advantage on its input purchase (waste disposal) costs, not enough for motivating it to start (or keep) the IS synergy.

The mismatch between demand and supply can occur over time, because of changes in the amount of main product generated or in production technologies. The uncertainty associated to the amount of waste available as well as the amount of waste required in the long period is perceived as a discouraging factor for companies when deciding to establish new IS relationships [49].

B. Quality of waste

Waste quality is another critical issue affecting the feasibility of IS synergies. For instance, the use of ashes deriving from energy generation in agricultural activities calls for strict quality control and safety protocols to avoid introduction or accumulation of potentially toxic chemicals in soil and subsequent transfer to (arable) crops and/or surface waters [90]. Environmental regulations in this sense may exist. Similarly, in case of water-based IS synergies, the waste user might have quality requirements (e.g., limited presence of contaminants, temperature of water, etc.) [33], [34], [40], [91]. Concerning energy-based IS synergies, in case of heat exchange a match must exist between the pressure of steam available and the pressure of steam needed [79], [92]. Also, for waste heat utilization the temperature or the pressure can be of a decisive importance as the recoverable energy potential from waste heat must be high enough to make the practice economically viable [79], [93].

The quality of waste can be affected by several factors, such as the inputs of production process generating that waste, the technology of the production process, and the production volume. For instance, the chemical composition of fly ash can vary depending on the raw biomass used as fuel and combustion technology employed in the production [90], [94], [95]. In the chemical sector, the continuity of production has relevant impacts on the quality of the flows detected [49].

Finally, the quality of waste can affect the amount or the quality of the main product produced by the process using the waste as input [96]. For example, when wastes are used to produce energy, the chemical composition of the waste can influence the amount of energy produced [30].

One important issue to be highlighted is the uncertainty over time on the quality of produced wastes. This uncertainty is perceived as a discouraging factor by the waste user [49].

C. Economic viability of IS synergies

The economic profitability of IS relationships depends on several factors: the waste disposal costs, the price of inputs replaced by wastes, and the operational costs of the synergy (i.e., waste transportation and waste treatment costs [86], [91]). The higher these costs, the higher the economic benefits created by the synergy will be, *ceteris paribus*. Furthermore, the investments required to build new infrastructures (e.g., pipelines to operate the waste exchange) or to adapt production structure to waste use should be taken into account when assessing the profitability of IS relationships.

The uncertainty in the above-mentioned costs is perceived as a discouraging factor for companies when deciding whether to implement IS practices. Furthermore, these prices can fluctuate over time, according to specific market dynamics. Hence, the economic profitability of IS synergies could change over time, according to fluctuations in these costs.

D. *Contractual clauses related to waste exchange*

IS synergies are usually ruled by contracts agreed between the companies exchanging wastes. These contracts are useful so that the overall economic benefits are shared between companies [9], [10]. Two kinds of contractual clauses can be implemented: 1) clauses related to the waste exchange price; and 2) clauses related to the additional costs to operate IS (e.g., waste treatment costs and waste transportation costs). Concerning the waste exchange price, three clauses can be adopted: 1) the waste producer pays the waste user an economic compensation because it does not have to dispose the waste; 2) the waste user pays the waste producer to use its waste; and 3) the waste exchange is operated free of charge. Three clauses can be implemented to share the additional costs arising from treating and transporting wastes: 1) all costs are paid by the waste producer; 2) all costs are paid by the waste user; and 3) costs are shared. All of these cases can also include the intervention of governments in terms of encouraging subsidies or binding regulations.

Actually, contractual clauses are a matter of negotiation between companies. In this regard, even in cases where a high economic benefit is created by IS, it could happen that one firm gains the greatest part of these benefits while the other receives a scant advantage, not high enough to motivate the company towards the symbiotic cooperation [9]. In this case, the IS relationship is hampered by an incentive misalignment among companies.

VII. Discussion and Conclusions

This paper proposes a framework on how to model IS systems via ABM. This framework is built on a detailed literature review on the practical cases of IS, which sheds light on the important aspects and parameters influencing the success of IS-based businesses. The framework categorizes the typologies of IS from the structural perspective and defines all of the (potential) actors involved in IS identification, assessment, and implementation as well as their potential actions within IS. As the paper aims to draw an agent-based modeling framework, it also addresses the external factors impacting on the implementation of IS, i.e. the impact of the surrounding.

It is observable that IS is capable of inducing economic savings while the challenge of dealing with additional costs raises the barriers against IS. This confirms the statement of Yazdanpanah and Yazan [97], who define IS as a *coopetition* model in which companies are willing to cooperate to create added value while they compete to share the additional costs of running IS. Additionally, these costs are shaped by the external factors discussed in Section VI. Therefore, the company behavior plays a critical role in the business strategy development, which is a confirmation for the suitability of agent-based modeling to analyze IS relationships.

The extensive field of IS lists numerous characteristics of agents motivated to get involved in IS businesses. Such motivations are mainly driven by economic gains; however, other drivers such as regulations, sustainable company image, enhancement of technological know-how, or capturing environmental and social benefits play a significant role on the adoption of IS. This paper captures the essential elements; however, further empirical research is required to understand which factors play a stronger or weaker role in the decision-making process of companies. Considering the structural diversity and (sometimes) conflicting interests within IS businesses, agent-based models for IS should be specific for different categories proposed in this paper so to address as much as factors shaping such businesses in detail. This is critical to capture the adaptability characteristics of agents and IS networks. For example, while the investment costs of water-based and energy-based IS cases might push the involved companies to look for governmental support together, in material-based IS the challenge of sharing treatment and transportation costs could be more dominant pushing companies to behave rather individually to maximize their own benefits. Therefore, one agent-based modeling framework is not sufficient to draw a generic conclusion based on identified actions in the literature.

Modeling-wise, as mentioned by Ghali et al. [11], because the values of the dependent variables of an agent-based model emerge from its components' behaviors and interactions, its accuracy must be tested against actual data and empirical observations. This requires a dedicated collection of data to configure the model's parameters and to measure its accuracy. For instance, besides data that could be used to assess the model's social parameters, historical data concerning plant/process establishment or closure, as well as social structure and dynamics between plants are necessary to validate such a model. However, this will only be possible when models are both capable of modeling actual IS dynamics and validated with actual data. Consequently, agent-based models for IS analysis must be developed further. One procedure for validating the results of ABM for IS would be to distribute the results among heterogeneous groups of stakeholders and refine the models based on their input.

To ensure participatory ABM, one approach could be to use the perception of stakeholders as a method for co-production of the ABM with companies' management and policy-making representatives. Using the accumulated data from the community, one can implement well-justified behavioral rules in the ABM model. Such an approach would facilitate the systematic analysis of regulations with respect to their effectiveness and community acceptance.

Our general ABM framework can be used to generate case-specific instances for modeling the long-term behavior of industrial symbiosis networks, with respect to their efficiency and resilience. To that end, a standard approach would be to compare the case of presence of symbiotic relations – in different scenarios – and the traditional case. Then the dynamics of sustainability indicators can be measured to analyze how the establishment of IS influences the transition from linear economy models to circular models.

Finally, a potential line of future work would be to capture the ability of agents to communicate in the ABM of IS. For such a purpose, one may define communication protocols through which the IS network members can communicate, opt to leave the network, or collectively decide on accepting new members. As argued in Folke et al. [98] and Ostrom [99], capturing the openness aspect of virtual organizations would be a key factor in the design and development of sustainable business models.

The ABM framework for IS would also enhance the proper and efficient design of eco-industrial parks which are different than self-emerging IS networks. Self-emerging IS networks provide precious information about (potential) flows, sharing of facilities, and the adaptation process of companies to IS networks, which indicates future study fields in the IS domain.

ACKNOWLEDGEMENT

The project leading to this work has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 680843.

VIII. References

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