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An investigation into modelling approaches for industrial symbiosis: A literature review and research agenda

Melissa Demartini [a,*], Flavio Tonelli [b], Kannan Govindan [a]

[a] SDU–Centre for Sustainable Supply Chain Engineering, Department of Technology and Innovation, University of Southern Denmark, Campusvej 55, Odense, Denmark
[b] Department of Mechanical, Energy, Management and Transportation Engineering, University of Genoa, Via all'Opera Pia, Genova, Italy

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ABSTRACT

Industrial symbiosis is a promising business model that pushes companies to move from linear production to a circular path. However, this transformation is complex because it requires companies to rethink and redesign their supply chains by considering the involvement of new stakeholders, the introduction of waste and their impact on product development, economic investments, and technological resources. As a result, companies need innovative modelling tools able to capture, investigate, and quantify the results of these changes and to work on the strategic planning, design, implementation, and management of their industrial symbiosis networks. This paper presents a systematic literature review to investigate the most used modelling approaches to analyse industrial symbiosis, and to research their characteristics in terms of simulation methods, interaction mechanisms, and simulations software. Findings from our research suggest that an Agent-Based System Dynamics hybrid approach is an appropriate method for industrial symbiosis design and analysis. The paper also presents a theoretical framework that aims at supporting researchers and practitioners approaching industrial symbiosis and, in conclusion, a research agenda is suggested for scholars.

1. Introduction

In the last few years, companies have worked towards the redesign of their business models to reduce costs and, at the same time, improve the sustainability of their activities (Elia et al., 2017; Beske and Seuring, 2014; Tonelli et al., 2013). This shift requires awareness and a total overhaul to reduce resource consumption and emissions and to move towards a circular economy paradigm (Govindan and Hasanagic, 2018). Academics have studied how traditional ways of doing business are affected by circular economy (Salvador et al., 2021) and by sustainability (Formentini and Taticchi, 2016). The resulting challenges involve building organisations with a sense of purpose, sustaining creation of shared value, co-creating practices with stakeholders, and integrating environmental, social, governance (ESG) factors in decision-making to get a competitive positioning and profitability (Taticchi and Demartini, 2021). A promising business model is represented by Industrial Symbiosis (IS), where two or more companies cooperate by making sustainable business decisions and sharing their common resources (Chertow, 2000). All types of material, energy, waste, labour, knowledge, logistics, and expertise can be efficiently shared within the network. Particularly, IS focuses on the concept of sharing and getting value from waste; indeed, what is considered waste for one company can be used as an input for another one. The literature distinguishes between two different kinds of IS: i) *bottom-up, the self-organizing IS* (i.e., Kalundborg, Denmark; Guayama, Puerto Rico; Campbell Industrial Park, Hawaii; or Shenzhen Huaqiang Holdings, China) and ii) *top–down, Planned Eco Industrial Park* (i.e., Synergy Park, Australia; Verdal, Norway; Devens Planned Community, United States; Nanning Sugar Co. Ltd., China). This distinction is founded on the formation mechanism which determines the creation of the synergies. In the first type, bottom-up, the synergy arises spontaneously through companies' self-organisation supported by the government; whilst the latter, top–down approach, revolves around central authority planning (Chertow, 1998). The complex links among IS, industry, resource, and policy require the maximization of synergies within the economy from both industrial and policy perspectives. IS exhibits both detailed and dynamic complexity due to the degree of circularity and uncertainty on forward-reverse logistics modelling and optimisation levels. It is a form of a Complex Adaptive System (CAS) which involves multiple domains and agents and displays non-linear and non-rational interacting behaviours (Demartini et al., 2018). Furthermore, the system mutates and transforms over time by

* Corresponding author.
E-mail address: med@iti.sdu.dk (M. Demartini).

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self-organising and adjusting its format to increase well-being; its adaptivity is influenced only by the interaction among agents (Albino et al., 2016; Chertow and Ehrenfeld, 2012). New paradigms, which can capture the complexity of such a system and focus their efforts on modelling and designing IS processes, are necessary, indeed, traditional approaches such as material flow analysis or input/output analysis are not able to capture these dynamic behaviours (Demartini et al., 2019). Therefore, this research can contribute by providing a set of the most used modelling approaches for IS to support researchers and practitioners approaching the study and modelling of IS. For this purpose, a content analysis is performed to capture qualitative evidence from literature and rigorous facts. The next section presents a review of the literature available in the domain of IS. Section 3 provides the methodology adopted to review the literature, and Section 4 identifies the most relevant modelling approaches for IS in which an in-depth analysis is provided. Section 5 follows with a discussion of the key findings, the theoretical framework and research agenda proposed by this research, and, finally, Section 6 presents conclusions.

2. Review of literature reviews

In this section, the existing literature reviews on IS have been analysed to understand areas that have not been given proper attention. Boix et al. (2015) reviewed optimisation methods for IS networks. Their findings suggested the importance of optimisation to improve the design of IS networks. However, they pointed out the presence of different research gaps: i) a lack of multi-objective optimisation studies (particularly, the social dimension is the least analysed one), ii) a lack of taking into account uncertainties related to energy supplies, and iii) a lack in considering the surrounding environment of IS (i.e., social and economic situations of the region). Jiao and Boons (2014) developed a literature review and research agenda to define mechanisms of policy intervention and facilitation of IS. They reviewed implications on the role of policy and, in particular, they suggested further analysis of the link between policy- making and practice of IS and between IS and circular economy. Zhang et al. (2015a,b) provided a literature review on theory, methodological studies, and formation mechanism for IS. They identified material flow analysis, substance flow analysis, social network analysis, and ecological network analysis as the main methods for examining IS complexes. In the suggestion for future research, they underlined the importance to adopt a more flexible method able to "analyse the relationships and interactions among all companies in a complex for multiple resources, thereby providing a more holistic description of the internal processes, metabolism, and exchanges of all resources involved in the complex." Neves et al. (2020) identified the main lines for research in IS and published case studies. They emphasized that life cycle assessment is the most used method to analyse the environmental impacts of IS; therefore, they suggested the development of methods able to quantify all the triple bottom dimensions related to IS. Turken and Geda (2020) analysed the intersection between IS and supply chain management underlying the immaturity of the field which is characterized by a few studies. They provided a review on the symbiotic supply chain introducing definitions and taxonomy. Finally, they proposed different research lines to be explored in the future such as facilitating mechanism, policies, public and private actions, geographical and spatial constraints, and trust among companies. Table 1 presents a summary of the relevant existing literatures related to IS. It highlights the need for an integrated approach able to capture and analyse the complex interactions among IS (policy and supply chain), by looking at all TBL dimensions. Although existing reviews on IS have covered various aspects including policy, optimisation methods, supply chain implica-

Table 1
Summary of the existing literature review related to IS.

Title	Authors	Summary
A review of the industrial symbiosis network	Zhao et al., 2016	Reviewed IS network from five different areas: definition, structure, function and assessment, evolution, and management
A comprehensive review of industrial symbiosis	Neves et al., 2020	Reviewed the main lines for research in IS, as case studies with emphasis on the location, type of industry, and employed methodologies
Critical factors for industrial symbiosis emergence process	Mortensen and Kørnøv, 2019	Reviewed 1) awareness and interest in IS, 2) reaching out and exploration of connections, and 3) organising
Toward a research agenda for policy intervention and facilitation to enhance industrial symbiosis	Jiao and Boons, 2014	Reviewed governmental policy actions on IS
Enhancing policies for deployment of industrial symbiosis – What are the obstacles, drivers and future way forward?	Lybaek et al., 2020	Reviewed IS policies
Waste valorisation through additive manufacturing in an industrial symbiosis setting	Ferreira et al., 2021	Reviewed input wastes for additive manufacturing processes and exchanges in IS
A review of industrial symbiosis research: theory and methodology	Zhang et al., 2015c	Reviewed theoretical and methodological bases, as well as trends in IS
Regional industrial symbiosis: A review based on social network analysis	Vahidzadeh et al., 2020	Reviewed the main topics and trends in IS
Unveiling the conceptual development of industrial symbiosis: Bibliometric analysis	Mallawaarachchi et al., 2020	Reviewed the evolution of IS concept
Supply chain implications of industrial symbiosis: A review and avenues for future research	Turken and Geda, 2020	Reviewed IS from a supply chain perspective
Industrial symbiosis tools—A review	Lawal et al., 2020	Reviewed IS tools
Reuse and recycling of by-products in the steel sector: Recent achievements paving the way to circular economy and industrial symbiosis in Europe	Branca et al., 2020	Reviewed by-products for the steelmaking IS
Life cycle environmental and economic assessment of industrial symbiosis networks: a review of the past decade of models and computational methods through a multi-level analysis lens	Kerdlap et al., 2020	Reviewed LCA and LCC studies of IS network
Current options for the valorisation of food manufacturing waste: A review	Mirabella et al., 2014	Reviewed feasibility and constraints of IS in food processing
Energy management on industrial parks in Flanders	Maes et al., 2011	Reviewed energy strategy for IS and eco-industrial parks
Optimisation methods applied to the design of eco-industrial parks: A literature review	Boix et al., 2015	Reviewed optimisation methods for IS
"Uncovering" industrial symbiosis	Chertow, 2008	Reviewed motivations and means for pursuing IS

tions, theory and challenges, there is a lack in terms of reviewing modelling approaches able to capture the dynamic behaviours and complexity of IS. Therefore, this gap is the starting point of this work.

3. Research methodology

A systematic literature review methodology has been chosen to cover the above mentioned research gap. Two datasets have been created with different scopes. The first dataset (now called the "comprehensive dataset") was constructed from Scopus as it is one of the most consistent repositories of business and management papers (Liao et al., 2017). The comprehensive dataset has been populated by identifying scientific articles containing the words "industrial symbiosis" AND "simulation" AND "modelling" in the title, abstract, or keywords of articles. An initial selection was performed by using the following criteria:

- Journal or review articles published in English

An initial interrogation resulted in a set of 114 papers that were downloaded. At this point, the abstracts of all articles were carefully read, and an additional filter was applied to improve the quality and significance of the dataset:

- A number of articles were removed because the focus was not relevant for the objective of this research (e.g., absence of modelling approaches).

The final dataset included 71 papers. In accordance with best practices for bibliometric analysis, two authors independently reviewed the dataset with the goal of verifying the accuracy of records and fixing eventual errors. Following this high-level analysis, we decided to study in greater depth the papers focusing on hybrid modelling and simulation approaches which are considered relevant to model and to understand IS problems (Demartini et al., 2018; Demartini et al., 2019). This second dataset (now termed the "relevant dataset") was constructed again from Scopus by identifying scientific articles containing the words "hybrid simulation" and "sustainability" in the title, abstract, or keywords of articles available. At this point it is important to underline that "sustainability" was used as the second keyword instead of "industrial symbiosis" to capture as many papers as possible on this topic. An initial selection was performed by using the following criteria:

- Journal or review articles published in English

This initial interrogation resulted in a set of 99 papers that were downloaded. After reading all the abstracts, an additional filter was introduced to improve the quality and significance of the dataset:

- A number of articles were removed as they were written in Chinese (even if English was selected as filter) or because the focus was not relevant for the objective of this research (i.e., papers focus on only one approach).

The final "relevant dataset" included 39 papers that did not present any overlapping with the previous dataset. The systematic literature review was performed using classic descriptive and content analysis. The descriptive analysis consists of three related investigations: i) number of publications, ii) time distribution of publications, and iii) most popular journals for publications. For the content analysis, a framework was developed to perform a characterisation of the approaches in use (Table 2).

Therefore, the purpose of this paper is to review the existing literature to answer to the following research questions:

Table 2
Framework used to characterise modelling approaches in use.

Grouping	Dimensions	Rationale
1. Analysis of approaches in use to model IS (comprehensive dataset)	Most frequently used modelling approaches Time distribution of most frequently used modelling approaches Most frequently used modelling approaches in the most popular journals	Relevant modelling approaches Trends in the use of modelling approaches Relevant modelling approaches in relevant journals
2. Analysis of the most relevant modelling approaches (hybrid approaches) (relevant dataset)	Interaction mechanism and type of hybrid modelling In conjunction with which software is the hybrid approach used?	How the modelling simulation approaches interact with each other Most popular software

- *RQ1:* What are the relevant approaches to model industrial symbiosis?
- *RQ2:* Which hybrid approach is a suitable method to model industrial symbiosis?

4. Content analysis

Results of the literature review are organised using the structure of the two different datasets (Comprehensive and Relevant datasets).

4.1. Comprehensive dataset

Fig. 1 depicts the most used approaches to model IS. The list is led by Agent Based (AB) with 15 publications, followed by Input – Output model (IOM) with 6 publications, Lifecycle Assessment (LCA), Material Flow Analysis (MFA), Network Analysis (NA), Mixed Integer Linear Programming (MILP) with 4 publications respectively, and DEMATEL, Ecological network analysis (ENA), and System Dynamics (SD) with 2 publications respectively.

The following is an overview of each modelling approach presented from the most frequently used to the least frequently used by describing the most relevant and cited papers.

4.1.1. Agent based

AB modelling has increased in popularity throughout different disciplines over the last few years. It describes behaviours of complex systems through the interaction of agents. Agents are independent and heterogeneous, and they can communicate and cooperate with each other (Castro et al., 2020). The main advantages of adopting AB in a IS network lies at the core of understanding learning processes and complex macrostructures by studying the interactions among individual agents. However, it is important to underline that AB is a highly path dependence model; it requires large set of parameters and data to describe agents' behaviours, and validation methods are often challenging due to the complexity of combining simulations with real data (Pasqualino and Jones, 2021). Mantese and Amaral (2018) developed an AB model to evaluate IS feasibility under different scenarios; they compared indicators such as Symbiotic Utilization, Eco-Efficiency, Resource Productivity, and Environmental Impact. The AB model consisted of different agents representing companies' behaviours within the Eco Industrial Park. Each company transformed input into output, and the model took into consideration energy and raw material consumptions, emissions, and final products for each agent. Two scenarios were studied to evaluate different conditions: i) Scenario I - stable conditions within the Eco Industrial Park and ii) Scenario II - unstable conditions, no fixed rules in the park with companies entering and leaving constantly. The goal was to analyse how specific indicators behave in

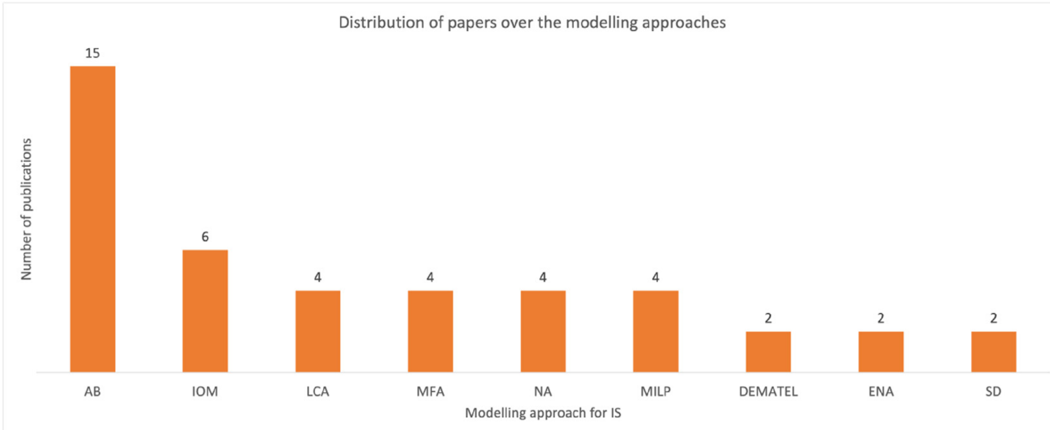

Fig. 1. Distribution of most used modelling approaches for industrial symbiosis.

environments where there are drastic changes in the number of companies. In Fraccascia et al. (2020), AB was adopted to study the impact of the redundancy strategy on companies participating in IS from both an economic and environmental points of view. A specific example of self-organised IS was modelled. AB has been chosen as a modelling approach for its ability to capture heterogeneity and was used in combination with Enterprise Input-Output and Path dependence theory which were used to model the specific companies. They also stated that AB is a suitable method to model IS as it can capture the complex system behaviours through the agent's interactions instead of being set by the modeler.

4.1.2. Input – Output model

The IOM is a top-down approach able to track "transactions between activities measured in monetary units and extend them at the environmental level in terms of greenhouse gas (GHG) emissions (environmental extended input–output analysis)" (Yazan et al., 2016). It is frequently used to analyse carbon footprint by considering both direct and indirect flows. Also, it is often combined with other modelling methodologies to address dynamic problems (Pollitt et al., 2015). A common combination is the one between IOM and LCA, which is used to evaluate IS by considering different levels of analysis, a focus on micro entities through LCA and a focus on macro entities through IOM (Fang et al., 2017). Generally, IOM assumes (i) linearity between input and output, (ii) continuity of system behaviour towards the future, and (iii) instantaneous adjustment of productive factors to obtain production (Pasqualino and Jones, 2020). Therefore, its application is limited to short-term evaluations. The main weakness of IOM is the need for vast amounts of data necessary to create the input–output table; inaccuracy could occur if this data is not precise or if it presents different grades of aggregation (Mattila et al., 2010). Zhang et al. (2018) adopted an IOM to analyse usage patterns of material resources and carbon footprint emissions by considering symbiotic cooperation under different product demands. IOM was adopted to evaluate the economic input–output table as well as the environmental input–output table to measure material consumptions and GHG emissions between the different companies within the IS network. This analysis was then used as an input to define economic and environmental constraints within the network through an optimisation model developed with a fuzzy programming approach. The model aimed to reduce emissions. Fraccascia et al. (2017a,b) proposed an IOM to assess the amount of waste generated and exchanged in an IS network under different scenarios. First, IOM was used to define the amount of waste production for each company within the network (single company perspective). Then it was used to evaluate the waste exchange between the symbiotic companies (network perspective). Finally, the results of these analyses have been used to measure the technical efficiency of firms. Particularly, different scenarios of IS patterns have been considered according to supply and demand level of waste. For all scenarios, usage and disposed waste rates were measured.

4.1.3. Life cycle assessment

LCA is a tool to measure amounts of resources, material and energy, and the environmental impacts produced during a product's life cycle from raw material extraction up to a product's end of life (Finnveden et al., 2009). LCA is often used in combination with different approaches such as Discrete Event Simulation (DES), SD and IOM (Löfgren and Tillman, 2011; Fang et al., 2017; Mattila et al., 2010) to measure both micro entities (LCA) impact as well as macro entities impact (DES, SD, IOM). Mohammed et al. (2016) dealt with the problem of emissions in nitric acid plants; that paper analysed the resulting environmental effects generated by using by-products of chemical absorption to produce potassium nitrate fertilizer. LCA was adopted to quantify environmental impacts of this symbiotic pattern in terms of GHG emissions, solid waste volume, acidification level, and water contamination. LCA allowed the identification of the best industrial symbiotic relationship for setting an optimum and environmentally friendly pathway for IS. Dong et al. (2017) adopted a hybrid approach composed of LCA and IOM to evaluate the benefits of an urban IS in China. LCA provided information about material consumptions and emissions while IOM has been developed to analyse upstream and downstream flows of information.

4.1.4. Material flow analysis

MFA is an analytical method to quantify stocks and flow of materials and energy and to assess environmental sustainability through the usage of environmental indicators (Sendra et al., 2007). It is based on the concept of "mass conservation," and it uses input/output flows, including both material and economic data. It is often used to assess the environmental impact of countries and regions, while it is less applied to evaluate micro entities such as products and processes (in this case, LCA is preferred). The main weaknesses of MFA are a lack in life cycle views and in reflecting the impacts on the ecosystem (Sun et al., 2017). Regarding the application of MFA to IS, Sendra et al. (2007) stated that there are some specific aspects that need to be considered: i) need to integrate MFA with an energy and water flow analysis, ii) companies' indirect flows, and iii) need to evaluate both subsystems (single company) and the whole network (IS). Li et al. (2015) adopted an MFA to evaluate the environmental benefits of a regional IS located in China to face the goal of creating a "resource dependent city." In combination with urban statistics, MFA was used to analyse the impact of IS on cities. Specifically, urban waste can be used as input to local industries, and, in return, heat is guaranteed to citizens. The study underlined the importance of connecting cities and industries in facing the problem of resource consumption and pollution. Dong et al. (2013) implemented an MFA to evaluate the environmental and economic benefits of an IS based on steel and iron industries. It considered material flows in terms of virgin materials, energy, by-product, and waste in scenarios with and without IS.

4.1.5. Network analysis

NA is a method for evaluating the structural and functional characteristics of a system. NA is based on collecting data and information on the stock and flow of resources among companies revealing the network pattern (Szyrmer and Ulanowicz, 1987). NA can be used to analyse IS by using metrics such as density, centrality, or connectivity to comprehend the network structure and understand the degree of complexity of the relationships between companies (Zhang et al., 2015a,b; Chopra and Khanna, 2014). Also, NA is a useful tool to identify the functional properties of the network as well as to visually depict the relationship within the network (social network), quantify economic and environmental relationship, and define the boundary of the system (Zhang et al., 2015a,b). Fraccascia et al. (2017a,b) focused on the resiliency dimension of IS, which was conceptualized using NA and network diversity concepts. The IS has been represented through a network where nodes are factories, and links between nodes represented exchanges of resources. Two different resilience outcomes have been identified: i) disruptive events that have an impact on the whole network and ii) core industries whose unavailability, caused by these disruptive events, create major impact and risks on the network. Zhang et al. (2015a,b) implemented a NA to evaluate inorganic and salt chemical industries in a Chinese eco-industrial park and to study the sulphur flows through the park. NA consisted of a structural and functional analysis of the Eco Industrial Park and the main nodes and links are identified. The results of the analysis have been used to determine and stabilize the weaknesses of the park.

4.1.6. Mixed Integer linear programming

MILP involves problems in which only some of the variables are constrained to be integers, while other variables are allowed to be non-integers. Usually, it is extensively applied in industrial problems such as production planning and scheduling. MILP can be adopted to study IS networks to compare different design schemes and processes, as well as to find potential improvements in the structure (Wolf and Karlsson, 2008). Karlsson and Wolf (2008) adopted a MILP to evaluate IS in a forest industry by analysing resource flows – materials and energy – on both the supply and the demand sides. The study underlined that MILP is a particularly useful tool in evaluating IS by searching the optimum operational strategy and by comparing the results with different systems. In this specific case, MILP was used to support companies in the decision-making process and in the IS planning. The model demonstrated that there are economic and operational benefits related to IS implementation. Afshari et al. (2020) proposed a MILP to manage energy demand fluctuations and promote energy symbiosis. The model optimised total cost, environmental impact, and social value.

4.1.7. Decision making trial and evaluation laboratory

DEMATEL is considered as an effective method for the identification of cause-effect chain components of a complex system. It deals with evaluating interdependent relationships among factors and finding the critical ones through a visual structural model. Concerning IS, DEMATEL allows the generation of a cause-and-effect map which depicts the effects of each company or factors to another (Lin, 2013). Therefore, these results can be used to assess the primary causal factors that mainly impact the network. Bacudio et al. (2016) used a DEMATEL model to identify the main barriers in IS implementation. A specific eco-industrial park in Laguna Philippines was considered. According to the DEMATEL model, the main barriers in IS implementation were: “Lack of awareness of industrial symbiosis,” “Lack of willingness to collaborate,” “Lack of an institutional support for integration, coordination and communication,” “Lack of top management support,” and “Lack of funding to promote industrial symbiosis.”

4.1.8. Ecological network analysis

ENA tracks the flow of energy and material from input to output over a network and analyses the structure and function of a system. The application of ENA to IS allows capturing indirect interactions to get more concise insights in evaluating functional and structural properties of the system through ecological flows (Wu et al., 2019). Wu and Jin (2020) adopted an ENA to evaluate the IS between iron and carbon industries. It allowed evaluating both structural and functional considerations within the network and studied the interrelationships between actors. It described the characteristics of the direct and indirect pairwise relationship and highlighted the nodes connected by indirect flow.

4.1.9. System dynamics

SD is an approach to understand the nonlinear behaviour of complex systems over time using stocks, flows, and feedback loops. Forrester (1970) described the most important SD characteristics: i) system boundaries, ii) reinforcing and balancing feedback loops, iii) stocks, the accumulation within the feedbacks, and iv) flows, the velocity variables. SD aims at understanding how and why the dynamic changes are generated and look for relevant strategies and policies to advance the system performance (Cui et al., 2018). SD enables tracing the patterns of system behaviours through feedback structures at an aggregate level over time (Scholl, 2001). It is a suitable method for IS as it captures the causality processes and feedback loops (Morales and Diemer, 2019). Norbert et al. (2020) adopted SD to assess both the economic and environmental impacts arisen over time from an IS between iron and steel plants. SD mapped the system structure, from which the behaviour of the system arises. Morales and Diemer (2019) developed a SD model to evaluate the IS in Dunkirk by considering several dimensions: i) economic and political, ii) behavioural patterns of stakeholders, and iii) conflicts of interests, values, and motivations. The study demonstrated that geographical proximity is a relevant factor for all the mentioned dimensions. Particularly, it should be carefully managed by considering location, landscape, territory, scaling, spatial differentiation and uneven development, and spatial embeddedness and path dependency.

Table 3 is the first output of our research; it provides an answer to the first research question (RQ1). Indeed, it highlights the most used modelling approaches for IS by highlighting their advantages and limitations.

Fig. 2 shows the time evolution of the modelling approaches from 2008 up to 2020. It is interesting to note that from 2015 there is an important growth in the adoption of modelling approaches; indeed, 90% of these approaches are applied starting from 2015 and before 2015 only MILP, AB, and MFA had been implemented to analyse IS.

4.2. Relevant dataset

The review of particularly relevant literature leads to several insights. Fig. 3 depicts the most used hybrid approaches: DES-SD, AB-SD, AB-DES, and AB-DES-SD. The following is an overview of hybrid modelling approaches presented from most frequently used to least frequently used by describing the most relevant and cited papers.

4.2.1. DES-SD

This hybrid approach is most commonly used to study sustainability problems. None of the papers tackles IS issues. DES and SD have been extensively used to analyse sustainability issues in the healthcare sector (Mielczarek, 2019; Mielczarek and Zabawa, 2016; Landa et al., 2018; Zulkepli and Eldabi, 2016; Bell et al., 2016; Ahmad et al., 2015; Zulkepli et al., 2012; Ahmad et al., 2014). They represent 47% of the publications, while 30% of publications adopt a DES-SD hybrid model to deal with specific supply and industrial sustainability issues

Table 3
Summary of the approaches used to model IS and their main characteristics.

Modelling approach	Advantages	Limitations
AB	It allows understanding learning processes and complex macrostructures by studying the interactions among individual agents (heterogeneity and behavioural interactions, modularity, flexibility, and expressiveness features).	Path dependence model, high demand of parameters and data to develop agents' behaviours and complexity in validation methods.
IOM	Mainly used to measure the emissions of macro entities such as nations and industries.	Its application is limited to short-term evaluations due to linearity and continuity assumptions. Risks of inaccuracy of data due to the high level of data aggregation.
LCA	Detailed results, focus on micro entities such as products and processes.	Uncertainty and risks of data unavailability due to the vast amount and heterogeneity of data requested. It doesn't consider the indirect effects due to the system-wide interactions between the network components.
MFA	Basic approach to identify and quantify material/energy flows in a network. It is mainly used to evaluate macro entities such as nations and regions.	It lacks life cycle view and doesn't reflect the impacts on the ecosystem. Water and air are generally considered as independent flows; therefore, they need to be evaluated with other approaches.
NA	It focuses on network metrics such as density, network degree centralization, centrality, or connectivity to comprehend the network structure and understand the degree of complexity of the relationships between companies.	If IS exchanges are not organised with a network governance (i.e., one-off exchanges), the approach can't be used. Also, it doesn't capture dynamic behaviours and heterogeneity among nodes.
MILP	It is a multi-objective approach providing an exact resolution that allows studying different resources flows simultaneously. It defines improvements in the structure of the network to find the optimal path, and to evaluate and compare different systems.	It doesn't investigate the nature of the relationships between nodes. Also, it doesn't capture dynamic behaviours and heterogeneity among companies.
DEMATEL	It allows the generation of a cause-and-effect map which depicts the effects of each company or factors to another. Therefore, these results can be used to assess the primary causal factors that mainly impact the network.	It primarily focuses on identifying the main factors that influence performance and fetching the connections and dependencies between elements.
ENA	It focuses on the analysis of ecological relationships among the system's members. It evaluates the system path and flows within the network.	It doesn't investigate the nature of the relationships between nodes. Also, it doesn't capture dynamic behaviours and heterogeneity among companies.
SD	It reveals the trends and system level behaviour easily and intuitively. It does not require vast data.	The key structure of the model is deterministic and does not capture individual variability. It lacks flexibility.

(Doluweera et al., 2020; Oleghe, 2019; Fakhimi et al., 2015; Rabelo et al., 2015; Abduaziz et al., 2015; Sigurðardóttir et al., 2014). Doluweera et al. (2020) focused on the topic of electric vehicles; they considered the impact of electric vehicle energy and greenhouse emissions by developing a hybrid model which allows the management of the electric fleets. In the model: i) SD took into account demand and power flows and ii) DES modelled specific events to analyse control decisions in specific discrete points. The model was applied in a Canadian context to gain insights into the impacts of transitioning from gasoline-fuelled conventional vehicles to battery electric vehicles. The hybrid model by Oleghe (2019) was developed with the aim of testing different strategies in an aquaculture company which wanted to expand its production capacity without reducing performance of its value chain. The SD model represented the supply chain of the aquaculture company highlighting materials and cash flows. To test different capacity scenarios and understand how throughput rate varies with respect to capacity, a DES sub-model was linked to the main SD model. The choice of DES was justified due to the discrete nature of starting and completion rates of fish shops. The two models (DES and SD) interacted and shared data through the usage of shadow variables. Two main facts related to hybrid approaches were considered: i) how a multi-method simulation modelling software facilitates the integration between different simulation methods and ii) the importance of the implementation of a hybrid approach able to capture time-related dynamics without which these finds could not be exposed.

4.2.2. AB-SD

This hybrid approach is the second most often used. All the examined papers in this category focus on sustainability issues and one paper proposes AB-SD as a suitable method for IS. Pros and cons of AB and SD are evaluated by Romero and Ruiz (2014) who concluded that the two "differ strongly on the modelling approaches, units of analysis or formal expression, amongst other features. Nonetheless, both are feasible paradigms for eco industrial park modelling. As a conclusion from the contribution analysis, the selection of the modelling method should be in line with the specific purpose of the study and the most relevant characteristics of the modelled system". Two different applications of the AB-SD model can be found in Sitepu et al. (2016) and Golroudbary et al. (2019). The prior applied the framework to a natural rubber industry for the allocation of rubber replanting in different districts in a province in Indonesia. The model was applied for decision making purposes with the aim of reducing the environmental, social, and economic impacts of the industrial activities. The SD model captured high level industrial sector dynamics, and the relationships between different stakeholders within the sector (i.e., rubber smallholder, private plantation, state-owned plantation, land area, latex, stepper, village collector, district supplier, and trader.) The purpose of the AB model was to analyse individual behaviours, locations, and decision making performed by heterogeneous agents. Regarding the integration of the two models, emphasis was placed on the importance of sharing data; specifically, the AB model required data related to material stocks which were modelled in the SD. Beyond this no additional information is provided for the interaction mechanisms adopted. In Golroudbary et al. (2019) the AB-SD model was applied to logistics issues to reduce congestion, air pollution and noise, which affect traffic safety and quality of life. AB and SD were used to understand: i) deliverers' behaviour in handling proper delivery and their environmental consciousness, ii) customers' accessibility to relevant information and service regarding social consciousness, and iii) the effect of policy decision making. More specifically, the influence of intelligent factors on system behaviour was addressed by SD, while deliverer's behaviours were analysed by AB. Finally, both examined customer service rate and customer satisfaction.

4.2.3. AB – DES

This hybrid approach is mainly used for analysing sustainable supply chain problems (Farsi et al., 2019; Mittal and Krejci, 2019; Rondini et al., 2017; Mittal and Krejci, 2015). A hybrid AB-DES model was applied by Farsi et al. (2019) to a complex manufacturing system based on parallel multi agent discrete events. In the AB–DES frameworks, AB was employed to model the manufacturing system and components, macro and micro level respectively. However, manufacturing

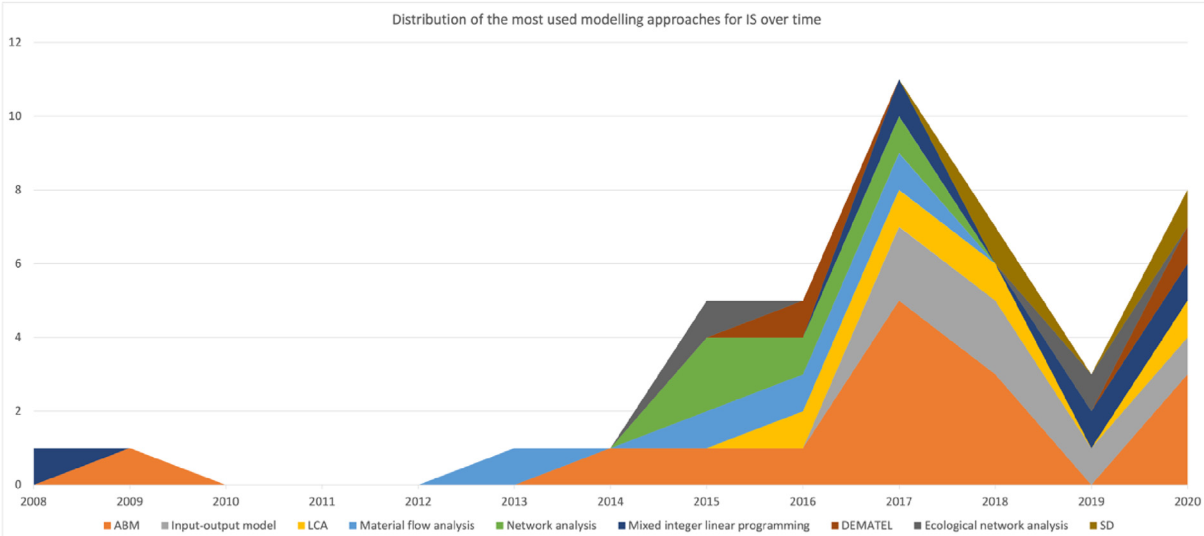

Fig. 2. Time distribution of most frequently used modelling approaches for IS.

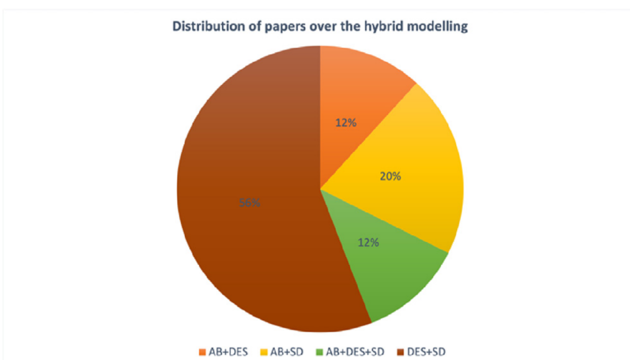

Fig. 3. Distribution of publications over the most used hybrid modelling.

systems can also be divided into multiple sub-systems, which can interact with each other in a parallel manner. Each sub-system had an individual dynamical DES structure composed of multiple repeating modules. Finally, the framework was corroborated by using data of a specific company from the cell and gene therapy industry. Mittal and Krejci (2015) applied a hybrid AB-DES model in a food hub scenario to determine the effects of the incorporation of various efficiency enhancing practices. They employed AB to capture producers' delivery scheduling decisions and behaviours and DES to represent the food hub's receiving process. "In the DES model, each producer entity receives service from the food hub personnel, and its queue time is written to an output file. These queue times become inputs to the ABM that will inform the producer agents' scheduling decisions."

4.2.4. AB - DES - SD

Finally, a few papers use all three simulation methods (AB, DES, and SD) (Gu and Kunc, 2019; Elia et al., 2016; Wang et al., 2014). Wang et al. (2014) improved a traditional LCA by developing a hybrid approach. The framework, which was tested in the beverage sector, consisted of different parts: i) the beverage supply chain was modelled with SD with specific emphasis placed on bottled water production and distribution bringing attention to energy and material flows; ii) customer and market preferences were designed by AB and DES, particularly DES "was embedded in the state chart of agent behaviours, where the state of agent will change to another state when time elapses or by certain rates depending on various variables." The purpose of the hybrid approach developed by Gu and Kunc (2019) was to compare different strategies and test the model on a supermarket which aims to increase market share and sales. The SD sub-model simulated financial operations and research and development; the operational process and supply chain system were represented by the DES model, while the market sector and individual customer behaviours were represented by the AB model.

Table 4 presents the summary of the hybrid approaches found in the literature and it highlights their main characteristics. It is impor-

Table 4
Hybrid approaches main characteristics.

Hybrid approach	Characteristics
DES-SD	DES aims at modelling specific entities by employing state variables that evolve at discrete time intervals. It represents stochastic aspects such as uncertainty and unplanned perturbations and it can monitor the entities' evolution. It is a top-down approach. SD provides a feedback perspective; it allows viewing the impact of DES entities on the entire system. It captures links and time delays between DES entities by using the feedback loops. Also, it detects causes and effects among entities by investigating dynamic and evolutionary behaviours of the system. It is a top-down approach.
AB-SD	SD assumes homogeneity and it is based on the concept of aggregation. Stock and flows are aligned with agents to store information which are essential for their learning capabilities. Stock and flows can also be used to comprehend the agent's states. AB can capture heterogeneity of individuals in an interconnected network by using data stored in SD. It can also use the dynamics of feedback loops to manage agents' behaviour when advancing from short to long term.
AB-DES	AB presents high level of flexibility and autonomy encapsulation. It can model and capture autonomous behaviours of DES entities. Also, events modelled with DES makes AB to be able to provide a high-level flexibility in modelling various agent behaviours, cognition, and decisions. DES presents larger runtime performances with respect to AB, and it can monitor agents' performances and create specific entities and events impacting on agents.
AB-DES-SD	AB understands complex adaptive systems by using self-organising properties. It models emergent and learning behaviours. DES models distinct agents' behaviours by using a sequence of events occurring at specific points of time by considering resources, capacities, and interaction rules. SD examines the behavioural patterns and interactions within the network. It uses aggregate variables.

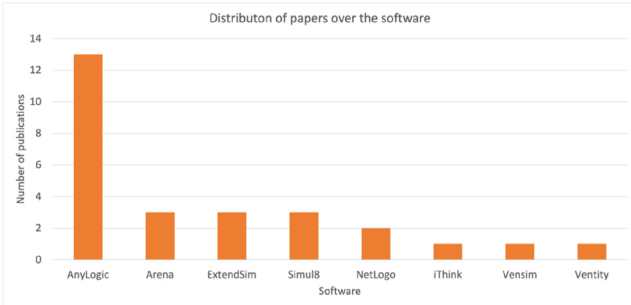

Fig. 4. Distribution of publications over the most used software.

tant to highlight that among these papers only one relies on IS, and it suggested an AB-SD hybrid approach. Therefore, we can conclude that Table 4 provides an answer to our second research question (RQ2).

Fig. 4 depicts the most used simulation software for hybrid approaches. The most adopted is Anylogic which is used in 49% of the publications, the second most used options are Arena, ExtendSim, and Simul8 which represent 12% of papers respectively. Anylogic is largely used with hybrid approaches as it is a multimethod simulation modelling tool supporting AB, DES, and SD simulation methodologies. Therefore, a hybrid model can be developed using only one tool.

5. Discussions of findings

This paper employed a systematic process to review the existing modelling approaches for IS. The comprehensive dataset allows answering to the RQ1; indeed, the most used modelling approaches for IS are AB, IOM, LCA, MFA, NA, MILP, DEMATEL, ENA, and SD (Fig. 1). Starting from this result, an investigation on the potentialities to adopt hybrid approaches to model IS has been proposed. Results from this latter analysis revealed that different combinations of the three main simulations methods (AB, DES, and SD) can be used for sustainability purposes; however, only one paper relies on the modelling of IS and it suggests an AB-SD hybridization (RQ2).

Therefore, in this section, an in-depth analysis of AB-SD hybrid approach for IS is provided and a theoretical framework based on the results of this study is presented. As is known, the key reason for the emergence of integrated modelling and simulation approaches considers both the advantages and limitations of individual methods. Hybrid approaches take advantage of the strengths of both models, while reducing their drawbacks. Different studies have analysed the advantages and limitations of AB and SD and they have demonstrated that they are somewhat complimentary (Abdelghany and Eltawil, 2017; Van Baal, 2020; Muravev et al., 2021; Golroudbary et al., 2019; Aly and Managi, 2018; Zhao et al., 2011). AB is a bottom-up approach, which primarily focuses on interactions between agents, whilst SD is a top-down approach which is not able to capture individual behaviour and is mainly deterministic. AB requires a lot of data and knowledge for its development whereas SD does not.

IS displays detail and dynamic complexity, so AB is an effective tool to analyse both micro and macro dynamic behaviours by capturing heterogeneous details. However, the increased detail comes at the cost of introducing large numbers of parameters. Due to the prohibitive nature of the computing resources required to carry out sensitivity tests, it can be difficult to analyse the behaviour of an AB model (Rahmandad and Sterman, 2008). Consequently, the individuality of AB should be used for those variables that need it because of limited resources.

Therefore, we propose to adopt AB to describe the emerging, complex, and dynamic behaviours that characterize IS. SD can model supply chains, production, and waste flows, because it is largely diffused in modelling supply chains and factories (Venkateswaran and Son, 2005; Venkateswaran et al., 2006; Rabelo et al., 2015). Particularly, we suggest using AB to model the learning and complex behaviours of companies within the IS network, and the interactions between companies, their supply chains, and policy makers. Also, AB allows to scale up the model to study the system with an increased number of companies and parameters affecting the IS network. SD models the internal structure of each agent; specifically, stocks and flows are used to depict the production flows of each company within the network. This structure simulates the change of stock depending on changes in the reserves of the stocks of all interrelated agents. The SD approach is used to investigate the change of the main parameter of the IS (i.e., the willingness to do IS), depending on the change of other parameters (such as costs and production capacities). The goal is to simplify the AB structure adopting the aggregation capability of SD as an internal structure of agents. The combination of SD, with a high level of aggregation, and AB, which captures heterogeneities, enables understanding the complex dynamics of IS. To model this dynamic environment, we propose the following modelling suggestions:

- *AB:* it should be used to capture heterogeneity and complexity of interactions; it can be used to model various stakeholders such as companies involved in the IS, suppliers, governments, policy makers, and consumers. The main source of companies' heterogeneity could be geographic location and production and waste capacities and learning and adaptive processes.
- *SD:* it should be used to model production and management dynamics of the firms; it provides information about production and waste rate, costs, taxes, revenue, and amount of symbiotic exchanges.
- *AB-SD interactions:* the internal structure of agents is modelled with a SD structure; therefore, agents' behaviours (learning and adaptive processes) are influenced by data stored in the SD model and feedback loops in the long period.

Finally, as suggested by the results of our review, we propose the adoption of the integrated tool Anylogic, which provides the environment to model both AB and SD. Otherwise, researchers need to develop specific interfaces to make AB and SD able to share data.

Fig. 5 depicts the theoretical framework which summarises the main results of our study. It can be used by researchers and practitioners approaching IS. The framework highlights traditional approaches that can be adopted to model IS (Table 3), and it guides researchers and practitioners who want to explore the advantages of an AB-SD hybrid approach for IS. Further, it provides key insight on i) design of hybridization – we suggest using SD to model the internal structure of agents, ii) key characteristics of the hybridization (aggregation vs heterogeneity), and iii) an integrated tool that can be used to develop the AB-SD model (Anylogic).

5.1. Research agenda

Building on the findings of this study, we propose the following avenues for future research:

Study IS from a modelling point of view: we invite scholars to continue to analyse and investigate IS. Indeed, the field is immature as the total amount of literature is limited. More research is necessary to demonstrate the economic, environmental, and social benefits and to get practical design insights related to IS. Therefore, we invite scholars to adopt different modelling approaches (Fig. 5) according to their investigation purposes. Table 3 provides an overview of advantages and limitations of traditional modelling approaches.

Adopt AB-SD hybrid approach to model IS: we have found that the number of AB-SD models applied to IS is limited (only one paper); therefore, we invite scholars to adopt an AB-SD hybrid approach to

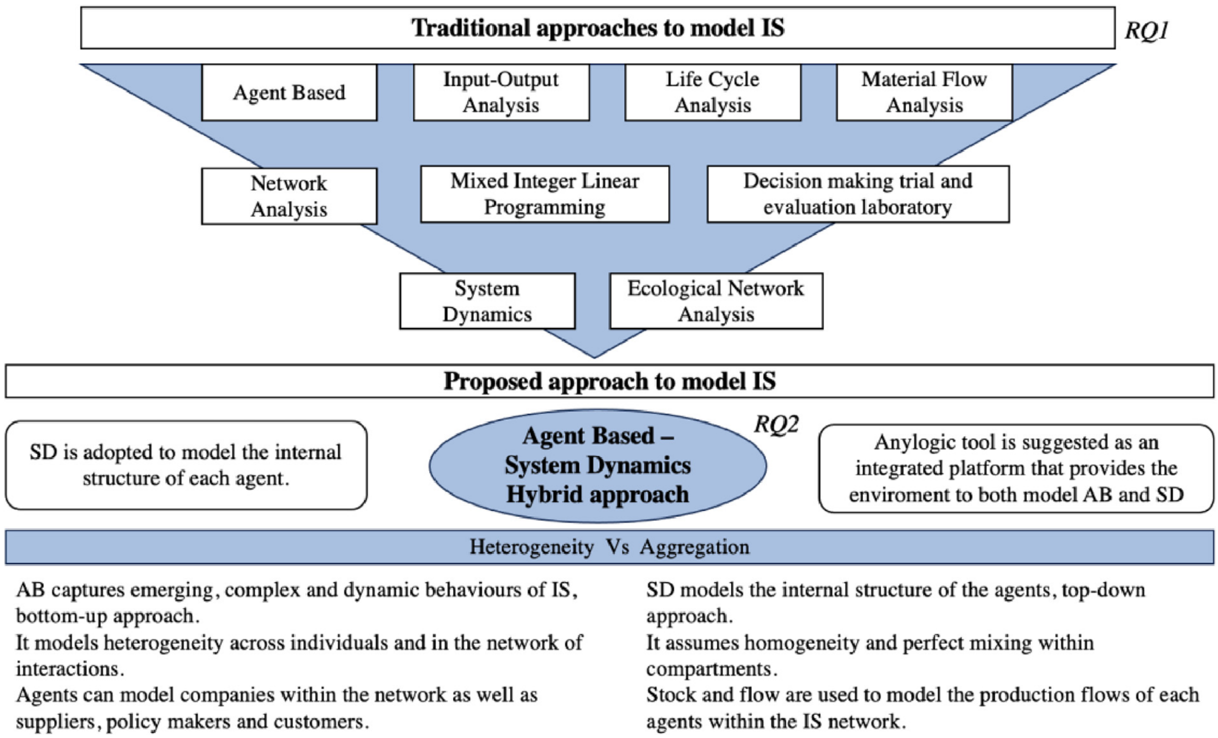

Fig. 5. Theoretical framework to approach and model industrial symbiosis.

approach and model several IS issues. Also, Table 4 provides an overview of the different hybrid approaches and their main characteristics.

Hybridization design: we recommend researchers develop AB-SD models by using SD to model the internal structure of agents. We suggest adopting SD to model internal structures of companies and AB to describe dynamic interactions emerging between companies, consumers, suppliers, and policy makers. We also invite scholars to investigate new potential formats for the integration of AB and SD.

Use of multilevel perspectives: by adopting the AB-SD approach, scholars can investigate different perspectives: i) intra-firm level by using SD, ii) firm-level and network level by using AB. Therefore, we invite scholars to use this modelling approach to gain insights related to individual, supply, and network perspectives.

TBL dimensions: we invite scholars to develop AB-SD models to investigate IS from all the TBL dimensions. Indeed, the hybrid approach can study and provide implications related to economic, environmental, and social for both micro and macro entities such as economic feasibility at company and national levels.

Tool: Linking AB and SD models together is quite arduous, particularly when models have been developed with different tools. However, thanks to the advances in computer hardware and software, the adoption of different modelling and simulation approaches is facilitated. We invite scholars to use Anylogic because it is an integrated tool which combines both AB and SD environments. It does not require the development of specific functions or interfaces to make the approaches capable of interacting with each other.

5.2. Practical implications

Our work presents some practical contributions:

- *For practitioners:* they can use the AB-SD hybrid approach to get insights related to strategic planning, design, implementation, and management of IS such as direction on location, symbiotic relationships and waste demand, role of suppliers, trust mechanisms, dynamics of change (technological and organisational), and impact on products, services, and customers. Indeed, IS requires a rethink and redesign of company's internal and external processes. One of the main problems related to the reliability of IS is the availability of a continuous flow of waste, since this implies a higher level of dependence with companies involved.
- *For policy makers:* they can use the AB-SD hybrid approach to investigate and get insights about policy implications, incentives, and tax reduction to push companies to invest in IS. Also, the model can support governments to develop strategies that should be pursued by companies to implement a top-down development process. Governments and policy makers should promote IS by supporting companies from the economic point of view. The tool can allow them to understand the impact of taxes and incentives on a vast scale by considering specific behaviours of different industrial sectors and regional areas.

6. Conclusions

This paper proposes a literature review to identify the most used modelling approaches for IS. Findings highlighted traditional modelling approaches for IS (Table 3), and an in-depth analysis of hybrid approaches (Table 4). The application of an AB-SD hybrid approach to focus efforts towards the modelling of IS processes and effects on the transition towards a zero- waste economy has been highlighted. We stated that the interaction between AB and SD is a suitable method to understand emerging, dynamic, and complex behaviours which characterize IS. There is a clear need for further research regarding the modelling of IS, so we have provided a theoretical framework (Fig. 5) and a research agenda for future avenues (Section 5.1).

6.1. Limitations and future directions

This literature review has some limitations. We have only reviewed publications in English. There might be an important loss of knowledge by not including publications in other languages. Potentially relevant publications in the forms of conference papers, industry reports, books, and book chapters were not included in the structured literature review; instead, the review methodology deliberately focused on peer-reviewed academic journal articles to ensure the quality of the publications reviewed.

As a future work, we plan to develop a hybrid AB-SD to model an IS network and to evaluate its feasibility from different perspectives (i.e., economic, environmental, and social). The model will test different assumptions in the industrial system while generating a top-down perspective to take effective policies towards a circular economy.

Declaration of Competing Interest

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

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