An investigation into modelling approaches for industrial symbiosis: a literature review

Demartini, Melissa and Bertani, Filippo and Tonelli, Flavio and Raberto, Marco and Cincotti, Silvano

University of Southern Denmark, University of Genoa

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AN INVESTIGATION INTO MODELLING APPROACHES FOR INDUSTRIAL SYMBIOSIS: A LITERATURE REVIEW

Melissa Demartini*[1], Filippo Bertani[2], Flavio Tonelli[2], Marco Raberto[2], Silvano Cincotti[2]

[1] *Centre for Sustainable Supply Chain Engineering, Department of Technology and Innovation, Danish Institute for Advanced Study, University of Southern Denmark, Odense, Denmark*

[2] *Department of Mechanical, Energy, Management and Transportation Engineering, University of Genoa, Via all'Opera Pia, Genova, Italy*

**Corresponding Author:* Centre for Sustainable Supply Chain Engineering, Department of Technology and Innovation, Danish Institute for Advanced Study, University of Southern Denmark, Odense, Denmark

Email address: med@iti.sdu.dk

Abstract The aim of this paper is to understand how to model industrial symbiosis networks in order to favour its implementation and provide a framework to guide companies and policy makers towards it. Industrial symbiosis is a clear example of complex adaptive systems and traditional approaches (i.e., Input/Output analysis, Material flow analysis) are not capable to capture these dynamics behaviours. Therefore, the aim of this literature review is to investigate: i) the most used modelling and simulation approaches to analyse industrial symbiosis and ii) their characteristics in terms of simulation methods, interaction mechanisms and simulations software. Findings from our research suggest that a hybrid modelling and simulation approach, based on agent-based and system dynamics, could be an appropriate method for industrial symbiosis analysis and design.

Keywords industrial symbiosis, hybrid modelling and simulation approach, literature review, system dynamics, agent based modelling

1. Introduction

In recent years, businesses have shown an increasing interest in moving towards resource efficient business models to reduce costs and improve their sustainability (Elia et al., 2017;

Schaltegger et al, 2014; Tonelli et al., 2013). This transformation calls for awareness and a complete process change to reduce resource consumption and emissions with a shift towards a circular economy paradigm (Govindan and Hasanagic, 2018). This requires the companies' engagement in more efficient behaviours, by adopting both a value creation and triple bottom line (TBL) approach to achieve long-term competitive advantage, (Elkington, 1998). As a consequence, policy makers, industry leaders, societies and academics are trying to understand how this affects traditional ways of doing business, and how traditional businesses are affected by sustainability (Formentini and Taticchi, 2016). How to develop organizations with a sense of purpose and how to build a sustainable competitive advantage are key challenges. Policy makers can play a fundamental role amplifying or reducing these effects by means of public investments and/or tax incentives, removing legislation, technological or financial barriers through effective policy measures, leading to steady economic growth with business opportunities across the whole economy. However, it is important to underline that there is a critical element that should be carefully analysed, this is the development of policy considering the technological advancement in recycling and waste processing and the interaction between the negative (i.e., pollution, emission) and positive (i.e., technological innovation) externalities. Additionally, the complexity of laws and different regulations throughout the world can harm circular economy. Policy makers should encourage cooperation and partnerships between companies promoting circular economy and sustainable business models. One of these prominent strategies is Industrial Symbiosis (IS) where two or more companies cooperate by making sustainable business decisions to utilize common resources, so that the waste of one company becomes the raw material of the other, (Chertow, 2000). All kinds of resources be it energy, labour, knowledge, logistics and expertise are efficiently shared. Innovation and learning capabilities which are at the core of IS represent important factors for improving competitiveness and environmental sustainability. Policy makers can favour IS by creating a

proactive environment for the spontaneous development of this sustainable business model. They can push companies to implement IS both from regulation and economical point of views, such as banning specific wastes, forcing companies to implement new strategies for their waste or increasing incentives (Fraccascia et al., 2017). The literature distinguishes between two different kinds of IS: i) the self-organizing symbiosis model (bottom-up), and ii) the Planned Eco-Industrial park model (top- down). This distinction is grounded on the formation mechanism which determines the birth of the synergies themselves; the top-down typology is related to a central authority planning, while the bottom-up arises spontaneously, thanks to the companies' self-organization promoted by government (Chertow, 1998). The interaction of IS between industry, resources and policy is complex, requiring the maximization of synergies from industrial and policy perspectives within the economy. IS exhibits both detailed and dynamic complexity due to the degree of circularity and uncertainty on forward-reverse logistics modelling and optimization levels. It represents a form of Complex Adaptive System (CAS) involving multiple domains and agents and displaying non-linear and non-rational interacting behaviours (Demartini et al, 2018). Furthermore, the system mutates and changes over time by self-organizing and adapting its structure in order to increase its well-being and the adaptivity is influenced only by the interaction among agents, (Albino et al., 2016; Chertow and Ehrenfeld, 2012). Traditional approaches such as Material Flow Analysis or Input / Output analysis are not capable of understanding these dynamic behaviours, (Demartini et al., 2019). Therefore, new paradigms, which are able to capture the complexity of such a system and focus their efforts on modelling and designing the IS processes, are necessary. Within this context, modelling innovative methods could increase insight and understanding of the intrinsic complexity related to IS transformative strategies. Therefore, the aim of this paper is to review the literature to investigate: i) the most used modelling approaches to analyse IS and ii) their characteristics in terms of simulation methods, interaction mechanisms and simulations

software. This research can contribute by providing a list of the most used modelling approaches for IS in order to support researchers and practitioners approaching the study and modelling of IS. For this purpose, the authors performed both a narrative and a systematic review in order to capture qualitative evidence from literature and rigorous facts. The next section presents the methodology adopted to review the literature while Section 3 identifies the most relevant modelling approaches for IS, and an in-depth analysis is provided. This will be followed by Section 4 with a discussion on the key findings, finally, conclusions are drawn in Section 5.

2. Literature methodology

Dataset creation

In this research, two datasets have been created with different scopes. The first dataset (now on called the "comprehensive dataset") was constructed from the Scopus database as it is one of the most consistent repositories of business and management papers. The authors populated the comprehensive dataset 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 articles published in English;
- Excluding Journal articles published in the following Scopus subject areas: Medicine, Phycology, Arts, Biochemistry, Chemical, Physics and Neuroscience;
- Excluding Conference proceedings.

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

- A number of articles were removed as the focus was not relevant for the objective of this research (e.g., chemical focus, or 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, the authors decided to study with greater depth the papers focusing on hybrid modelling and simulation approaches which are considered relevant to to model and understand IS problems (Demartini et al, 2018; Demartini et al, 2019). This second dataset (now on called the "relevant dataset") was constructed again from the Scopus database 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 second keyword instead of "industrial symbiosis" to capture more papers as possible on this topic. An initial selection was performed by using the following criteria:

- Journal articles published in English;
- Excluding Journal articles published in the following Scopus subject areas: Medicine, Phycology, Arts, Biochemistry, Chemical, Physics and Neuroscience;
- Excluding Conference proceedings.

Such an initial interrogation resulted in a set of 99 papers that were downloaded. At this point, the authors read the abstracts of all articles and applied an additional filter 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.

Analysis techniques

The systematic literature review was performed using classic bibliometric techniques, in accordance with previous work performed by other scholars in this field. It consists of three related investigations:

1. Analysis of publication;
2. Classification of modelling approaches used to model IS;
3. Characterization of hybrid approach.

For the analysis of publications, we adopted a framework which consists of 3 dimensions of analysis that relate to a specific investigative rationale as presented in Table 1.

Grouping	**Dimensions**	**Rationale (identify -)**
1. Analysis of publication data (comprehensive dataset)	Number of publications	Size of research field
	Time distribution of publications	Trends in the research field
	Most popular journals for publication	Journals where research is published

Table 1 – Framework used to analyse publication and citation data

For the purpose of understanding the most used approaches to model IS and their core characteristics, the authors developed a framework (Table 2) to perform a characterisation of the approaches in use.

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

Table 2 – Framework used to characterise modelling approaches in use.

3. Analysis of modelling approaches for Industrial Symbiosis

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

3.1 Comprehensive dataset

In this section, the selected papers are examined in detail in terms of year of publication, journal, modelling approaches adopted to study IS. Figure 1 depicts the year-wise frequency of research papers considered in this study published from 2008 to 2020. The number of publications has increased rapidly from 2015 and has appeared in a close variety of journals (Figure 1).

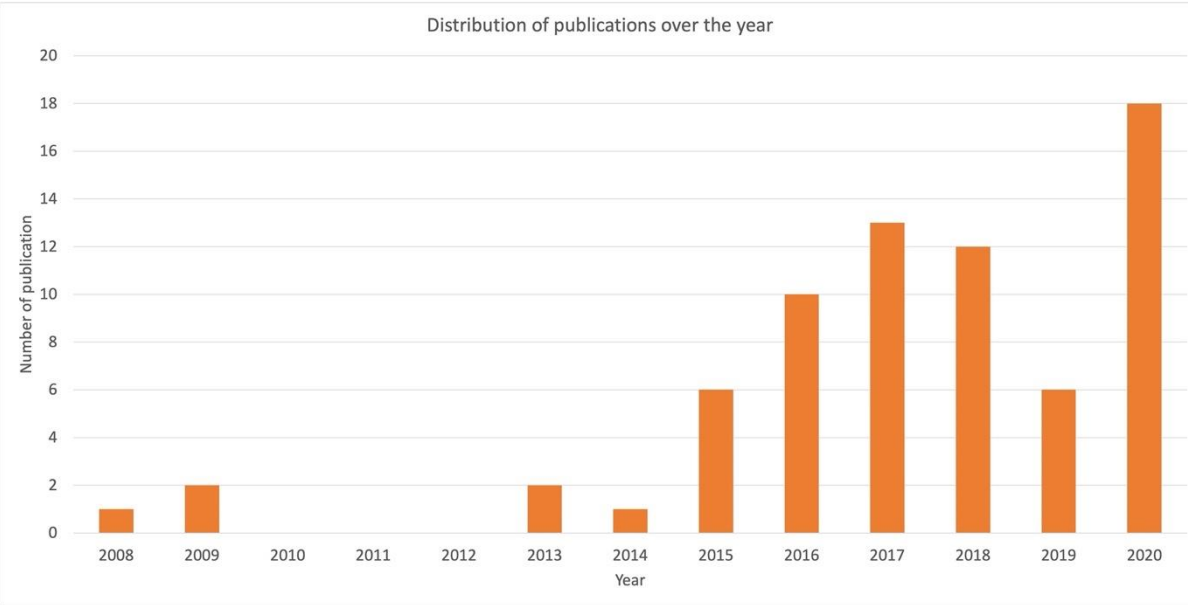

Figure 1 Distribution of publications over the years

Figure 2 shows the number of papers published in a particular journal. The maximum number of publications is reported in “Journal of Cleaner Production” followed by “Sustainability”, “Resource Conservation and Recycling”, “Journal of Industrial Ecology” and “International Journal of Production Economics”. From Figure 2, it is evident that this area is popular among different fields of research, from engineering and ecology, up to economics.

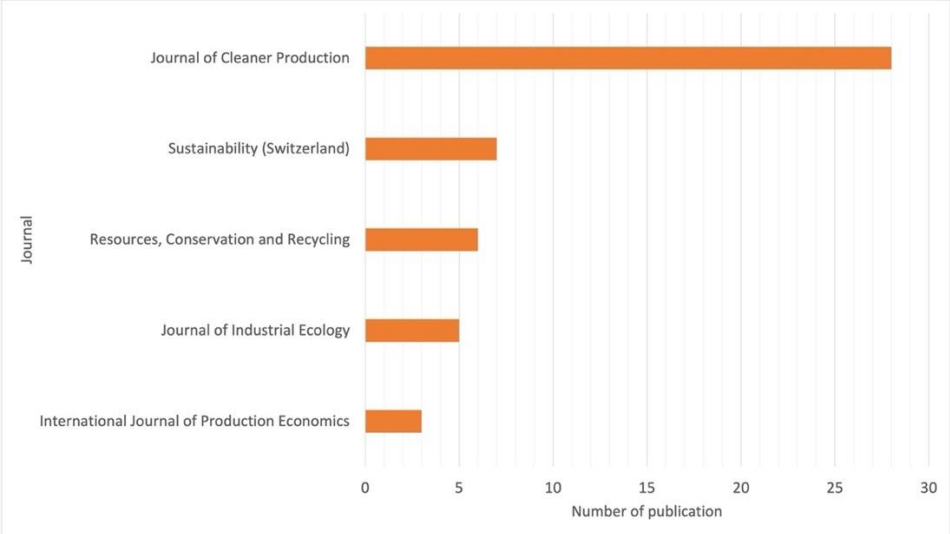

Figure 2 Distribution of publications over the journals

Figure 3 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) (6 publications), Lifecycle Assessment (LCA), Material Flow Analysis (MFA), Network Analysis (NA), Mixed Integer Linear Programming (MILP) with 4 publications respectively, DEMATEL, Ecological network analysis (ENA) and System Dynamics (SD) with 2 publications respectively.

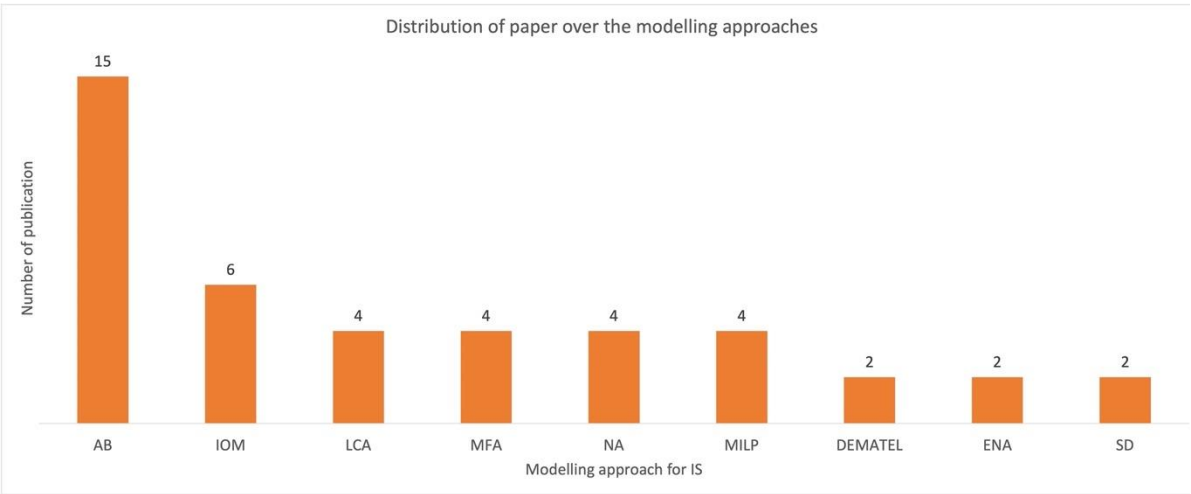

Figure 3 Distribution of most used modelling approaches for industrial symbiosis

The following is an overview of each modelling approach presented from the most frequently used to the least frequently used.

Agent Based

AB modelling has increased its popularity in different disciplines in the last few years. It describes behaviours of complex systems through the interaction of agents. Agents are independent, heterogeneous and can communicate and cooperate with each other (Castro et al, 2020). Mantese and Amaral (2018) develop an AB model to evaluate IS indicators related to Symbiotic Utilization, Eco-Efficiency, Resource Productivity and Environmental Impact. Two scenarios have been studied in order to evaluate different conditions: i) the presence of IS networks in a stable condition - Eco Industrial Park and ii) in an unstable condition, no fixed rules in the Eco Industrial Park with companies entering and leaving the park constantly. The goal of the second scenario is to analyse how indicators behave in environments where there are drastic changes in number of companies. In Fraccascia et al. (2020), AB is 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-organized IS is modelled. AB has been chosen as modelling approach for its ability to capture heterogeneity and it is used in combination with Enterprise input-output and Path dependence theory.

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 GHG emissions (environmental extended input–output analysis)" (Yazan et al, 2016). It is frequently used to analyse carbon footprint at different level of analysis. Zhang et al. (2018) adopt an environmental IOM to analyse usage pattern of material resources and carbon footprint emission considering the symbiotic cooperation. This analysis is used as an input for defining

economic and environmental constrains in the optimization model developed with a fuzzy programming approach. Fraccascia et al. (2017) propose an enterprise IOM to model production flows in terms of waste generated and exchanged. Particularly, different types of IS have been modelled according to supply and demand of waste: i) the waste absorbing scenario in which waste supply is much lower than the waste demand; ii) the primary input scenario in which waste supply is much higher than the waste demand; and iii) the balanced scenario in which there is an equilibrium between the waste supply and the waste demand. For all scenarios, usage and disposed waste rate is measured.

Life Cycle Assessment

LCA is a tool to measure the number of resources - material and energy- and the environmental impacts produced during a product's life cycle, from raw material extraction up to product's end of life (Finnveden et al, 2009). Mohammed et al. (2016) deal with the problem of emissions in nitric acid plants – the paper analyses the effect in using by-products produced during chemical absorption for the production of potassium nitrate fertilizer. LCA is adopted to evaluate the environmental impacts of this symbiotic pattern. In this study therefore, LCA has been used for setting an optimum and environmentally friendly pathway for IS. Dong et al. (2017) adopt a hybrid approach composed of LCA and IOM to evaluate the benefits of an urban IS in China. LCA provides information about material consumptions and emissions while IOM has been developed to analyse up-stream and down-stream flows of information.

Material Flow Analysis

MFA is an analytical method to quantify stocks and flow of materials, energy and assess environmental sustainability. It is based on the concept of "mass conservation", and it uses input/output flows, including both material and economic data. Li et al. (2015) adopt a MFA to evaluate the environmental benefits of an industrial and regional symbiosis located in China

to face the goal of creating a "resource dependent city". MFA in combination with urban statistics is used to analyse the impact of IS on cities, in particular urban waste can be used as input to industries and in return heat is guaranteed to citizens. The study underlines the importance of connecting cities and industries in facing the problem of resource consumption and pollution. Dong et al. (2013) implement a MFA to evaluate the environmental and economic benefits on an IS based on steel and iron industries. It takes into account material flows in terms of virgin materials, energy, by-product and waste in scenarios with and without IS. According to this analysis two indicators have been developed: i) environmental gains and ii) economic gains.

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 Ulanovicz, 1987). Zhang et al. (2015) implement 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 consists 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. Fraccascia et al. (2017) focus on the resiliency dimension of IS, which is conceptualized using NA and network diversity concepts. The IS is represented through a network where nodes are factories and links between nodes represent exchanges of resources within the IS. 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.

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. Karlsson and Wolf (2008) adopt 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 underlines that MILP is a particularly useful tool in evaluating IS by searching the optimum operational strategy and to compare the results with different systems. In this specific case, MILP is used to support companies in the decision-making process and in the IS planning. The model demonstrates that there are economic and operational benefits related to IS implementation. Afshari et al. (2020) propose a MILP to manage energy demand fluctuations and promote energy symbiosis. The model optimizes total cost, environmental impact, and social value.

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. Bacudio et al. (2016) use a DEMATEL model to identify the main barriers in IS implementation. A specific eco-industrial park in Laguna Philippine has been considered. According to the DEMATEL model, the main barriers in IS implementation are: “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”.

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. Wu and Jin (2020) adopt an ENA to evaluate the IS between iron and carbon industries. It allows the evaluation of both structural and functional considerations within the network and studies the interrelationships between actors. It describes the characteristics of the direct and indirect pairwise relationship and highlights the nodes connected by indirect flow.

System Dynamics

SD is an approach to understand the nonlinear behaviour of complex systems over time using stocks, flows, and feedback loops. Norbert et al. (2020) adopt SD to assess both the economic and environmental impacts arisen over time from any IS scenarios applied to a typical integrated iron and steel plant. The research methodology maps the system structure, from which the behaviour of the system arises, according to the core principle of SD.

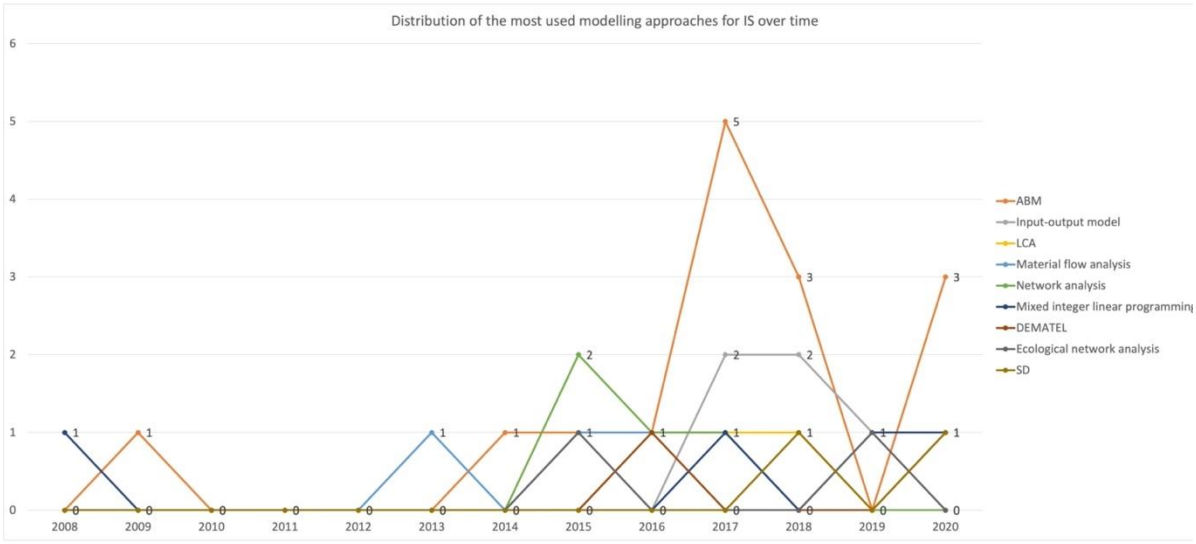

Figure 4 Time distribution of most frequently used modelling approaches for IS

Figure 4 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 the 90% of these approaches are applied starting from 2015, before 2015 only MILP, AB and MFA have been implemented to analyse IS. A peak has been achieved in 2017 with the application of 11 modelling approaches (25%). From 2015 the approaches that have grown faster are AB and IOM. Finally, the 50% of publications which adopt MILP and SD for IS are mainly used in the last few years (2018-2020).

Figure 5 shows the editorial positioning of the modelling approaches for IS. The top three journals, in terms of number of papers published, are "Journal of Cleaner production", "International Journal of Production Economics", "Resources, Conservation and Recycling". The full classification of publications is shown in Figure 5.

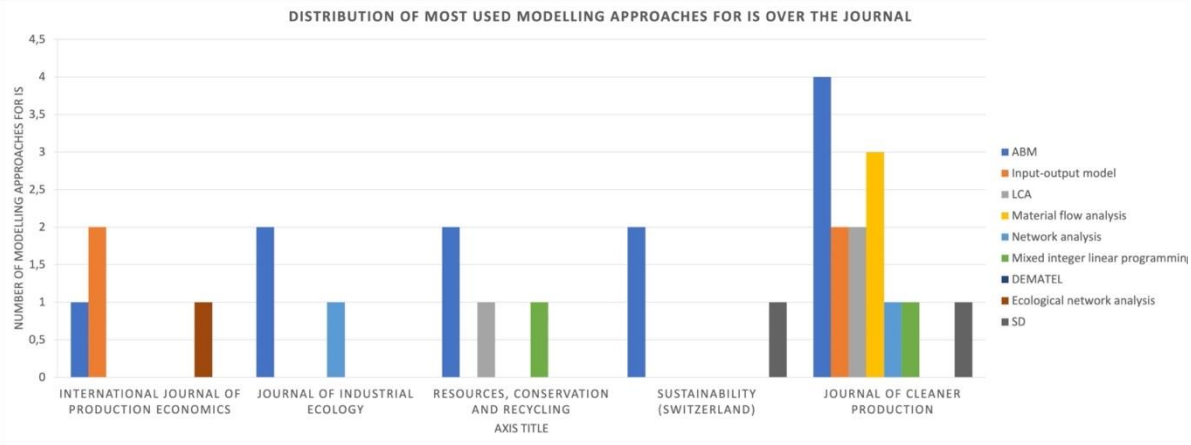

Figure 5 - Most frequently used modelling approaches for IS in the most cited journals

In line with the interdisciplinary objectives of the journal, Journal of Cleaner Production provides the greatest variety of modelling approaches used to investigate IS. In fact, as stated in its aims and scope, this journal addresses both theoretically and practically "cleaner production" issues (i.e., preventing the production of waste, while increasing the efficient use of resources) that encompass environmental and sustainability in corporations,

governments, education institutions, regions, and societies. The main used modelling approaches in this journal are AB and MFA.

The International Journal of Production Economics (IJPE) focuses primarily on topics at the interface of engineering and management. Despite not mentioning in their aims and scope the focus on environmental and social sustainability, instead stressing the impact of the economic environment, IJPE serves as an important outlet for modelling approaches. It encounters for a total of 4 papers, 2 of them adopt ENA.

Finally, Resources, Conservation and Recycling focuses on contributions from research, which consider sustainable management and conservation of resources. The journal emphasizes the transformation processes involved in a transition toward more sustainable production and consumption systems. The main modelling approach used in this journal is AB, followed by LCA and MILP.

3.2 Relevant dataset

The review of particularly relevant literature leads to several insights. The dataset consists of 39 papers published between 2010 and 2020. Figure 6 depicts the distribution of the relevant database over the years – it shows that there are peaks in 2016, and 2019.

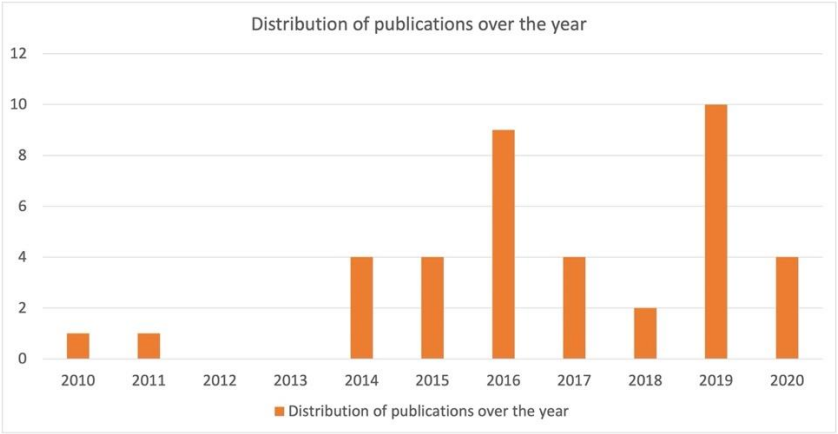

Figure 6 Distribution of the relevant dataset over the years

Figure 7 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.

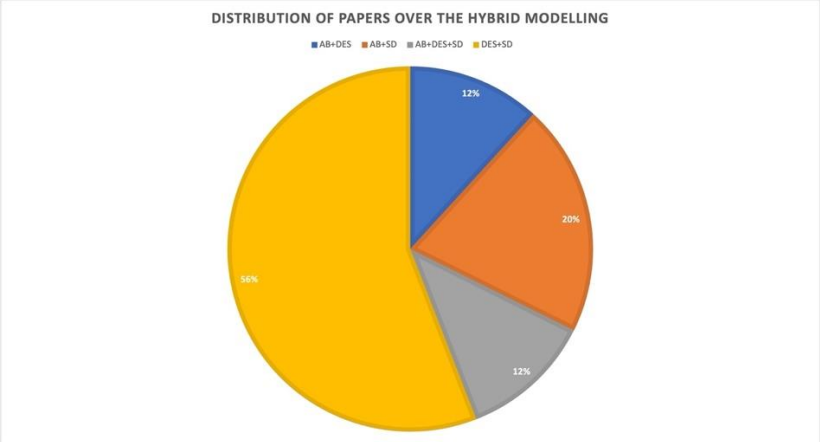

Figure 7 Distribution of publications over the most used hybrid modelling

DES-SD

This hybrid approach is the most used to study sustainability problems. None of the papers face IS problems. Doluweera et al. (2020) focus on the topic of electric vehicles; it analyses the impact of electric vehicle energy and greenhouse emissions by developing a hybrid model which allows to manage the electric fleets. The model consists of: i) SD which takes into account demand and power flows and ii) DES which models specific events to analyse control decisions in specific discrete points. The model is applied in the Canadian context to gain insights into the impacts of transitioning from gasoline-fuelled conventional vehicles to battery electric vehicles. Oleghe (2019) develops a hybrid model to test different strategies in an aquaculture company which wants to expand its production capacity without reducing performance of its value chain. The SD model represents the aquaculture supply chain highlighting materials and cash flows. A DES sub-model has been linked to the main SD

model in order to test different capacity scenarios and understand how throughput rate varies with respect to capacity. The choice of DES is justified due to the discrete nature of starting and completion rates of fish shops. The two models (DES and SD) interact and share data through the usage of shadow variables. This study highlights two main facts related to hybrid approaches: i) the importance of using a multi-method simulation modelling software in order to facilitate the integration between different simulation methods and that ii) these findings could not have been revealed without a hybrid approach able to capture the time-related dynamics of the system. DES and SD have been extensively used to analyse sustainable 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 the 47% of the publications, while the 30% of publications adopt a DES-SD hybrid model to deal with specific supply and industrial sustainable issues (Doluweera et al, 2020; Oleghe, 2019; Fakhimi et al, 2015; Rabelo et al, 2015; Abduaziz et al, 2015; Sigurðardóttir et al, 2014).

AB-SD

This hybrid approach is the second most used. All the papers which applied this hybrid approach focus on industrial sustainability issues and one paper proposes AB-SD as a suitable method for IS. Romero and Ruiz (2014) analyse pro and cons of AB and SD and conclude that AB and SD "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". Sitepu et al. (2016) develop an AB-SD model - applied to natural rubber industry for decision making purposes - to reduce environmental, social and economic impacts of its industrial activities. In particular, the framework is employed for the

allocation of rubber replanting for different districts in one province in Indonesia. The SD model is used to capture high level industrial sector dynamics, and the relationships between different entities within the sector such as rubber smallholder, private plantation, state-owned plantation, land area, latex, stepper, village collector, district supplier and trader. The AB model is built to analyse individual behaviours, locations and decision making performed by heterogeneous agents. Concerning the integration of the two models, it is highlighted the importance of data sharing, particularly, the AB model needs data related to material stocks which are modelled in the SD. So, the two models need to share and exchange data, however no additional information is provided for the interaction mechanisms adopted. Golroudbary et al. (2019) develop an AB-SD model applied to logistics issue to reduce congestion, air pollution and noise, which affect traffic safety and quality of life. AB and SD are 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. SD focuses on the influence of intelligent factors on system behaviour, while AB analyses deliverer's behaviours. Finally, customer service rate and customer satisfaction are examined by both.

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). Farsi et al. (2019) develops an AB-DES model applied to complex manufacturing system based on parallel multi agent discrete events. In the AB–DES frameworks, AB is employed to model the manufacturing system (macro level) and components (micro level). However, manufacturing systems can also be split into multiple sub-systems, which can interact with each other in a parallel manner. Each sub-system has an individual dynamical DES structure composed of multiple repeating modules. Then, the framework has been validated by using data of a specific

company from the cell and gene therapy industry. Mittal and Krejci (2015) build an AB-DES model to determine the effects of incorporating various efficiency-enhancing practices into food hub warehousing operations. The hybrid model employs AB to capture producers' delivery scheduling decisions and behaviours and a DES model to represent the food hub's receiving process. "The hybrid simulation begins with the ABM. The producer agent arrival times are determined and are then written to an output file to become inputs for the DES model. At this point, the simulation switches to the DES model of the food hub warehouse's inbound operations. 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".

AB - DES - SD

Finally, a few papers use all the three simulation methods (AB, DES and SD) (Gu and Kunc, 2019; Elia et al, 2016, Wang et al, 2014). Wang et al. (2014) develop a hybrid approach in order to improve a traditional LCA. It is considered as a useful high-level tool, but unable to deal with dynamics and uncertainties. The framework consists of different parts and it is tested in the beverage sector: i) SD is used to model the beverage supply chain with a specific focus on bottled water production and distribution highlighting energy and material flows; ii) AB and DES are used to design customer and market preferences, particularly DES "is 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". Gu and Kunc (2019) develop a hybrid approach to compare different strategies, the model is then tested with a case study - a supermarket which aims to increase market share and sales. The model simulates financial operations and research and development with the SD sub-model; the DES model represents operational process and supply chain system; while AB models the market sector and individual customer behaviours.

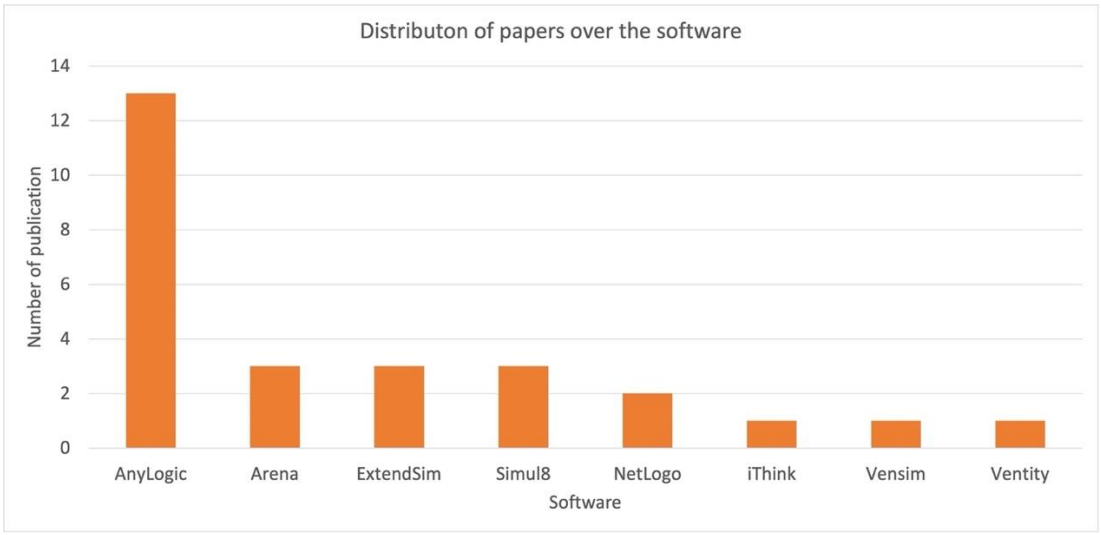

Figure 8 Distribution of publications over the most used software

Figure 8 depicts the most used simulation software for hybrid approach. The most used is Anylogic which is used in the 49% of the publications, the second most used are Arena, ExtendSim and Simul8 which represent the 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.

4. Discussions of findings

This paper employs a systematic and methodologically rigorous process to review the existing and potential modelling approaches for IS. Two different datasets have been considered:

- The *comprehensive dataset* to perform a high-level analysis related to modelling approaches for IS;
- The *relevant dataset* to focus on potentialities of hybrid approaches for IS.

The comprehensive dataset highlighted that AB is the most used modelling approach to analyze IS. Starting from this result, the authors investigated the potentialities to adopt hybrid

approaches to model IS. Results from the analysis of the relevant dataset reveled that different combinations of the three main simulations methods (AB, DES and SD) can be used for sustainability purposes, but only one paper relies on IS and suggested an AB-SD hybridization similarly to the Authors' approach.

Another interesting contribution related to hybrid approach comes from another sector – the healthcare. Abdelghany and Eltawil (2017) analyzed the different modelling and simulation approaches in the healthcare domain. Advantages and limitations of AB and SD have been studied, highlighting that AB is a bottom-up approach, which mainly concentrates on interactions between agents; however, for its development, it requires a lot of data and knowledge. SD is a top-down approach, which doesn't require many data, but it is mainly deterministic, and is not able to capture individual behaviors. Even if healthcare and IS are very different domains, it is possible to state that they have some aspects in common – both exhibit detail and dynamic complexity – in healthcare most divisions/units are interrelated and therefore, it is difficult to study any division/unit in isolation from the others; this is especially true for IS too where it is fundamental to analyze the interactions between the different companies and stakeholders involved in the process.

Even if hybrid approach is not the most prevailing method to model IS, there are many examples of its application in sustainable issues (as highlighted in section 3.2).

Van Baal (2019) proposed an AB-SD hybrid approach for the energy transition in Switzerland – he highlighted that AB and SD can be applied to study energy systems as they work with "tailored assumptions based on the case at hand" and because they enable the possibility to combine system perspective with agent level interactions. Muravev et al (2020) developed an AB-SD model in port management to optimize the balance between ship owners and terminal managers. They stated that "simulation modeling is better than analytical modeling in

representing the random and complex environment of the port facilities with minimal time and labor costs". The internal structure of the agents, which represent the main parameters of the intermodal terminal, is modelled using SD. This model simulates the change of stock depending on changes in the reserves of the stocks of all interrelated agents. Golroudbary et al, (2019) built a hybrid model based on AB and SD to face sustainability in logistics management. They highlighted that the choice of developing an AB-SD model lies in the complexity of logistics, indeed the model is able to capture behavioral and sustainable technical systems. A specific focus is then posed on different hybridization mechanisms: i) *Hierarchical* - two distinct models simply pass date from one to the other, ii) *Process environment* - two distinct models, but one model sits inside the other and models a small segment of the system and iii) *Integrated* - there is one single hybrid model with no clear distinction between the models.

Aly and Managia (2018) provided a hybrid model for evaluating the impact of energy infrastructure projects on the trajectory of wealth. They applied a hybrid approach to compensate for the limitations in each approach and to build a model that is reliable and robust to evaluate whether technology choices. SD's main focus is building models to explore the evolutionary behavior of systems and how that behavior is linked to the system structure. Using AB enables evaluators to examine different scenarios by 'plugging-in' different agents to the framework and monitor the evolution of the system under each scenario. Zhao et al (2011) provided an interesting comparison between SD and AB-SD hybrid approach applied to policy evaluation of solar power generation systems. "The hybrid model is shown to offer significant advantages in simulating the randomness and emergent issues than the SD-only model".

Therefore, advantages and limitations of individual methods are the motive for the emergence of integrated simulation approaches. They exploit the strengths of both models, while minimize the drawbacks.

In light of the above, the Authors propose a hybrid approach based on AB and SD as a suitable tool for IS. This decision is justified by the fact that AB is a powerful tool to analyze both micro and macro dynamic behaviors by capturing heterogeneous details. However, the increased detail comes at the cost of introducing large numbers of parameters. It can be difficult to analyze the behavior of an AB model, and the computing resources required to carry out sensitivity tests can be prohibitive (Rahmandad and Sterman, 2008). Because resources are limited, the individuality of AB should be used for those variables that need it. Therefore, the Authors propose to adopt AB to describe the emerging, complex and dynamic behaviors which characterize IS as AB has been recognized as a proper and the most frequent method (Figure 3) (Albino and Fraccascia, 2015; Fraccascia et al 2020; Ghali et al, 2017).

While SD is suggested to be used to model the internal structure of the agents, as it is largely diffused in modelling supply chains and factories (Venkateswaran and Son, 2005; Venkateswaran et al, 2006; Rabelo et al, 2015). The goal is to simplify the AB structure adopting the aggregation capability of SD as internal structure of agents. The combination of SD, which uses a top-down modelling approach with a high level of aggregation, and AB modelling, which uses a bottom-up approach to capture heterogeneities, enables such comprehensive IS analysis.

5. Conclusions

This paper proposes a literature review to identify the most used modelling approaches for IS. After an initial introduction to the topic, bibliometric techniques were used to analyze the evolution of the literature. Findings highlighted the growing number of publications, leading journals and modelling approaches for IS. Additionally, the authors provide an in-depth analysis of hybrid approaches. The application of a hybrid approach to focus efforts towards the modelling of IS processes and effects on the transition towards a zero- waste economy has

been highlighted. In particular, Authors state that the interaction between AB and SD is a suitable method to understand emerging, dynamic and complex behaviors which characterize IS. The IS modelling approach proposed in this paper found some confirmations on the available literature:

- Romero and Ruiz, (2014) stated that AB-SD hybrid approach is a feasible paradigm to model IS (eco industrial park).
- Zhao et al (2011) claimed that the AB-SD hybrid model is "shown to offer significant advantages in simulating the randomness and emergent issues than the SD-only model".
- Muravev et al (2020), Van Baal (2019), Golroudbary et al (2019), Aly and Managia (2018), Sitepu et al, (2016), Zhao et al (2011) adopted an AB-SD hybrid approach to model sustainability issues.

For these reasons, the authors are working on a model-based research established on the development of a hybrid AB-SD framework to capture the complexity of IS. The model tests different assumptions in the industrial system while generating a top- down perspective to take effective policies towards a circular economy. In order to evaluate the effectiveness of IS in terms of environmental impact and economic benefits, a case study related to three different industrial sectors has been designed.

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