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DECISION-SUPPORT TOOLS FOR SMART TRANSITION TO CIRCULAR ECONOMY

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ABSTRACT

The sustainable transition towards the circular economy requires the effective use of artificial intelligence (AI) and information technology (IT) techniques. As the sustainability targets for 2030–2050 increasingly become a tougher challenge, society, company managers and policymakers require more support from AI and IT in general. How can the AI-based and IT-based smart decision-support tools help implementation of circular economy principles from micro to macro scales?

This chapter provides a conceptual framework about the current status and future development of smart decision-support tools for facilitating the circular transition of smart industry, focussing on the implementation of the industrial symbiosis (IS) practice. IS, which is aimed at replacing production inputs of one company with wastes generated by a different company, is considered as a promising strategy towards closing the material, energy and waste loops. Based on the principles of a circular economy, the utility of such practices to close resource loops is analyzed from a functional and operational perspective. For each life cycle phase of IS businesses – e.g., opportunity identification for symbiotic business, assessment of the symbiotic business and sustainable operations of the business – the role played by decision-support tools is described and embedding smartness in these tools is discussed.

Based on the review of available tools and theoretical contributions in the field of IS, the characteristics, functionalities and utilities of smart decision-support tools are discussed within a circular economy transition framework. Tools based on recommender algorithms, machine learning techniques, multi-agent systems and life cycle analysis are critically assessed. Potential improvements are suggested for the resilience and sustainability of a smart circular transition.

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INTRODUCTION

Unsustainable development continues to endanger and threaten our future, while resource, water and energy scarcity gives a red alarm for the linear (take-make-use-dispose) economy. Examples are superfluous. One-third of the entire food produced in the world is wasted (FAO, 2011) with a global loss of 750 billion dollars annually (FAO, 2016). Around 90% of the electronic and electric equipment wastes (mobile phones, computers, headphones, etc.) are dumped in landfills (Savage, 2006), summing up to 53.6 million tons worldwide in 2019 (Forti, 2020). Greenhouse gas emissions and energy requirements increase the pressure on businesses and society while resource depletion points out further global problems. In energy production, considerable energy losses occur due to fluctuations in supply and demand. Carbon emissions continue to increase while researchers inspired by circular economy (CE) develop energy storage, carbon capture and conversion technologies and search for innovative and sustainable business models improving resource- and energy efficiency.

A quick impact on circular business improvement can be achieved via the adoption and better integration of artificial intelligence (AI) and information technologies (IT). Many examples in several industries could be mentioned. For example, AI and IT can drive several applications in the automotive industry, such as short loop recycling for manufacturing and robotic disassembly for remanufacturing, able to enhance the environmental performance of the production processes (Bai, Dallasega, Orzes, & Sarkis, 2020). In the food industry, blockchain technology is able to address major challenges, such as traceability, trust and accountability, which can increase transparency and reduce food waste (Kayikci, Subramanian, Dora, & Bhatia, 2020).

This chapter addresses the accelerative role of AI and IT in transition to smart and resilient CE focussing on industrial symbiosis (IS), the main skeleton of collaborative CE. The key principles behind smartness are adopted from Allen (2004) being the ability of a system to be self-monitoring, analyzing and reporting, and self-learning. While IT provides the necessary means to collect, process and communicate data, AI offers the techniques for self-learning ability.

According to Chertow (2000, p. 314), ‘IS engages traditionally separate entities in a collective approach to competitive advantage involving physical exchange of materials, energy, water and by-products’. Some studies simplify the concept of IS as the use of waste(s) of a company as a substitute of primary resources of another company. This directly contributes to waste diversion from landfills and reduction in virgin resource depletion. Furthermore, cost reductions for both companies involved in IS are achievable via savings on waste discharge cost and primary resource purchase cost. However, as wastes are not produced upon demand but emerge as secondary outputs of production, IS is different from the usual business models, further challenged by multiple uncertainties (Yazan, Romano, & Albino, 2016). First, identification of an IS opportunity among multiple companies is a challenge because the location, quality and quantity of wastes produced and required might be unclear. Second, assessing the business feasibility raises the question, ‘who is going to pay for running costs of IS, such as transportation, waste treatment or transaction costs?’ Third, a challenge emerges when companies need to sign long-term contracts, because waste markets are dynamic and turbulent, leading to the hesitation of company managers getting engaged with sharp contract rules (Yazdanpanah, Yazan, & Zijm, 2019). The next challenge is about the monitoring of the IS. Although IS can provide environmental and economic benefits, running IS brings in new processes which might also consume resources and cause new emissions. To tackle all of these challenges, IT and AI can play mitigative roles within the concept of Industry 4.0.

It can be argued that the search for smart technologies in product life cycle management has been accelerated by the discovery of the Industry 4.0 production paradigm (de Sousa Jabbour, Jabbour, Foropon, & GodinhoFilho, 2018). The key concept behind the Industry 4.0 paradigm is to make the supply chain 'smart'. This can be understood as the transition towards a system of product design and supply chain management that is controlled through real-time feedback provided by information and communication technology (Frank, Dalenogare, & Ayala, 2019). Such feedback is useful for different CE principles, i.e., from optimizing important manufacturing parameters to symbiosis identification for stimulating biological and technical cycles (de Sousa Jabbour et al., 2018).

This chapter has the following remainder. Section 'Industrial Symbiosis Development' describes the development of IS highlighting its five main phases. Section 'Techniques and Methodologies for Industrial Symbiosis Development' provides a detailed investigation of methodologies used for IS implementation and analysis. Section 'The Industrial Symbiosis Support Framework' proposes a smart decision-support framework for IS, based on the investigation conducted in Section 'Techniques and Methodologies for Industrial Symbiosis Development'. Section 'Conclusions' concludes the chapter with a short discussion on the future need of AI and IT for a smart CE transition.

INDUSTRIAL SYMBIOSIS DEVELOPMENT

The development of IS has been largely addressed in the last 20 years, mainly via case study developments. The literature has devoted a high interest in understanding the mechanisms for the emergence of IS relationships and IS networks – i.e., networks involving at least three companies that exchange at least two wastes (Chertow, 2007) and several models have been theorized – readers interested in deeper understanding on the topic are referred to Baas and Boons (2004), Chertow (2007), Doménech and Davies (2011), Chertow and Ehrenfeld (2012). Section 'The Industrial Symbiosis Dynamics' addresses the IS dynamics described by the literature and Section 'The Industrial Symbiosis Lifecycle' concerns the life cycle of IS relationships.

The Industrial Symbiosis Dynamics

Recently, Boons, Chertow, Park, Spekkink, and Shi (2017) have described seven main dynamics of IS: (1) self-organization, (2) organizational boundary change, (3) facilitation brokerage, (4) facilitation collective learning, (5) pilot facilitation and dissemination, (6) government planning and (7) eco-cluster development.

According to the *self-organization* pattern, independent companies try to establish IS relationships autonomously, driven by the willingness to achieve economic benefits. They search for suitable symbiotic partners: after finding a partner, the symbiotic contracts are negotiated and, if the negotiation succeeds, the IS relationship becomes operative.

IS networks might be created when companies make *changes in their organizational boundaries*. For instance, a company can expand its current business to include new production processes; opportunities for IS can emerge among the existing and the new processes integrated. Alternatively, a company can disintegrate part of the existing business which may transform from internal IS exchanges to external ones.

IS networks can emerge as a result of a *brokerage process* undertaken by a facilitator, i.e., a third-party entity (e.g., companies not involved in symbiotic exchanges, universities, research institutes, government agencies, non-profit associations). Facilitators can assist companies in finding suitable partners and developing a space for cooperation, thus contributing to overcome the waste quantity and quality mismatch problem (Fraccascia & Yazan, 2018). Facilitators can engage companies into a *collective learning* process, aimed at developing an IS network, or implementing dynamics of *pilot facilitation and dissemination*, aimed at spreading knowledge among companies via being responsible for a wide range of activities (e.g., collecting and spreading technical data, organizing workshops and meetings among companies, conducting feasibility studies, implementing follow-up activities for IS operation).

Local governments can facilitate the emergence of IS through the dynamics of *government planning* and *eco-cluster development*. As *governmental planning*, governmental actors formulate strategies and develop and implement plans of action using incentives and enforcement, such as the Eco-Industrial Park Development Programme in South Korea (Park, Park, & Park, 2016). Finally, according to the *eco-cluster development*, IS is implemented as part of a wider strategy, defined by different local actors (e.g., local governments, companies, associations) coming together around the goal of achieving economic development and/or technological innovation.

The Industrial Symbiosis Life Cycle

The life cycle of IS processes at the inter-company level can be divided into five phases, each characterized by a particular aim and a number of tasks firms typically encounter (Fig. 1). The first phase concerns the *identification* of the symbiotic opportunity and their potential eligible industries (e.g., searching for alternative materials, identifying industrial partners). In the second phase an *assessment* takes place to determine the feasibility of the synergy (e.g., identifying economic and environmental benefits, testing the technology readiness, assessing the sustainability of the collaboration, allocating the cost, risk analysis, checking legal issues, etc.). The third phase deals with the *implementation and coordination* of the synergy (e.g., contracting, arranging transport, deploying required conversion technology, etc.). Then, in the operational phase, the symbiotic relationship is *monitored* (e.g., collecting synergy data, re-assessing the sustainability of a synergy or configuration, etc.). Finally, changes to the environment in which the symbiosis is implemented may cause a *reconfiguration or a discontinuation* of the relationship or network (e.g., new entrants in an eco-park may require re-identification, assessment, implementation and monitoring of symbiotic relationships).

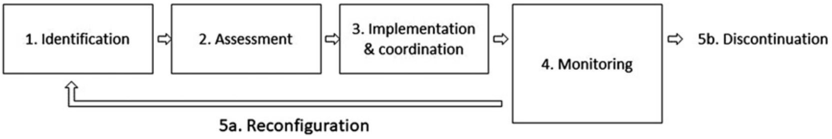

Fig. 1. Life Cycle Phases for Industrial Symbiosis.

TECHNIQUES AND METHODOLOGIES FOR INDUSTRIAL SYMBIOSIS DEVELOPMENT

The process of IS may be supported in various ways. Smart technologies can be effective in all of the previously explained life cycle phases of IS. The academic literature on this topic identified numerous methodologies and techniques to consider for IS facilitation (Lawal, Wan Alwi, Manan, & Ho, 2021; Lütje, Willenbacher, Möller, & Wohlgemuth, 2019; Maqbool, Mendez Alva, & Van Eetvelde, 2019; van Capelleveen, Amrit, & Yazan, 2018; Yeo et al., 2019a). This section is aimed at presenting these methodologies and techniques, together with their current application to the IS field. In particular, the following methods are discussed: agent-based modelling (ABM), material passports, environmental assessment and accounting methods, game theory, geographical information systems (GIS)-based exploration and scoring methods, machine learning and rule-based algorithms, material selection methods and optimization techniques.

Agent-Based Modelling

ABM is a methodology to study complex systems consisting of autonomous decision-making entities, which are modelled as independent agents. Each agent is described in terms of goals to be accomplished through interacting with other agents and rules of social engagement (Axelrod, 1997). The interactions among agents drive the spontaneous emergence of phenomena, structures and patterns, which are not defined a priori by the modeller. ABM is considered a useful approach to investigate the IS dynamics (Batten, 2009; Cao, Feng, & Wan, 2009; Demartini, Tonelli, & Bertani, 2018) but only in the recent 10 years such a methodology has been adopted to this aim – in fact, one of the first agent-based models for IS was proposed by Romero and Ruiz (2014), although the study does not carry out numerical simulations. ABM allows to reproduce and simulate the complex relationships among the companies involved in IS relationships, as well as the relationships between companies and the other stakeholders involved. Hence, the dynamics of identification, implementation and management of (potential) IS relationships can be easily simulated through ABM. A relevant advantage of ABM is that it can be used to simulate a specific system (e.g., industrial area) under different configurations (e.g., without IS and with IS), with the aim to investigate the marginal impact of each configuration (e.g., the benefits created in a given industrial area if IS is implemented). In fact, such an impact can be easily discovered by comparing the same system performance computed under different system configurations – for an overview of ISNs performance that can be computed through ABM, readers are referred to, e.g., Mantese and Amaral (2018). This characteristic makes ABM useful to investigate the impact that specific factors play on the emergence of IS.

From the operational perspective, the potential cooperation and competition strategies among companies involved in IS relationships were investigated through ABM (Abi Chahla & Zoughaib, 2019; Yazan, Fraccascia, Mes, & Zijm, 2018). In particular, the strategies of economic benefit-sharing in IS relationships were investigated by Albino, Fraccascia, and Giannoccaro (2016), who studied the impact of a contract scheme designed to foster the formation of stable symbiotic relationships and to guarantee that the IS is beneficial for all parties involved, and by Yazan, Yazdanpanah, and Fraccascia (2020), who studied the impact of adopting fair or opportunistic strategies when negotiating the contractual terms has on the establishment and operation of IS relationships over the long period. Fraccascia, Yazan, Albino, and Zijm (2020) investigated the impact of adopting a multiple sourcing strategy for wastes compared to the single-source strategy, which is traditionally adopted in the IS context. The impact of the mismatch between waste demand and supply, due to the fluctuations in the amounts of wastes produced and required, was investigated by Yazan and Fraccascia (2020). From the technological perspective, the extent to which online platforms for IS can support companies to find symbiotic partners, thanks to sharing information (e.g., the location of companies, the amounts of waste demanded and potentially supplied) among the platform users, is assessed by Fraccascia and Yazan (2018) and Fraccascia (2020). From the policy perspective, the effect of two measures – i.e., higher landfill taxes for industrial wastes and economic subsidies to companies operating IS – on the emergence of ISNs was investigated by Fraccascia, Giannoccaro, and Albino (2017). From the social perspective, Ghali, Frayret, and Ahabchane (2017) assessed the impact of social factors (i.e., social structure and dynamics, trust and knowledge diffusion on the spontaneous creation of symbiotic synergies among different companies. Finally, Zheng and Jia (2017) investigated the influence of promoting strategies associated with various dimensions of institutional capabilities, on the identification of opportunity sets for IS synergies.

The aforementioned studies each develop their own agent-based model and conduct numerical simulations by using software such as Netlogo and Matlab. This results in a significant limitation, since a comprehensive model to investigate all the aforementioned factors does not currently exist. All in all, ABM can support companies, IS facilitators and policymakers in two ways: (1) it allows to highlight factors impacting on the emergence and operation of IS and (2) it allows to investigate the business dynamics of companies involved in IS (e.g., the negotiation of contractual terms), thus facilitating the understanding of the complex phenomena underlined.

Material Passports

The current developments around material passports are expected to future benefit the identification and exchange of IS. In essence, a material passport is a tool that helps to keep track of all the materials of an object with the aim to identify the circular value of the object. A general application for material passports is currently developed in the building industry. The passport aims to provide different stakeholders in the construction supply chain the necessary information about a building to govern it as circularly as possible (Hansen, Braungart, & Mulhall, 2018). A more formal definition of a *material* passport is a digital interface to provide information about a single identifiable object over its life cycle that may be used to identify circular value and opportunities for its product and components (van Capelleveen, van Hillegersberg, Vegter, & Olthaar, n.d.). Among the characteristic properties that a material passport registers are a product's physical composition (i.e., material and component use), life expectancy, servicing history, quality of (sub) components, contaminations, separability of materials, value estimation for use, recovery and reuse, official declarations (e.g., hazardous statements), instruction manuals (e.g., dismantling guides) and CE performance indicators (e.g., energy certificates). There have been several passport variants proposed in the literature, some focussing on buildings (e.g., BAMB project reported in Debacker, Manshoven, & Denis, 2016), and others applied to discrete manufacturing (e.g., He & Bai, 2021) or developed for specific objects such as vessels (e.g., Danish Environmental Protection Agency, 2016). The value of these passports to IS facilitation is that that these provide the necessary information, typically in a standardized format, to object owners or object governance firms that enable these stakeholders with only few efforts to exchange this information with partners or (partly) disclose information on IS marketplaces (e.g., the Resource Passport of Excess Material Exchange, 2020). In conclusion, the two main goals of material passports are (1) to identify the value for use, recovery and reuse and (2) to support CE decision-making along the life cycle of a product.

Environmental Assessment and Accounting Tools

Environmental assessment and accounting tools are one of the most prevalent and long-lasted used tools to facilitate IS. The tools are core to industrial ecology, which studies the materials and energy flows through industrial systems. The tools aim to support the involved firms in a potential industrial symbiotic relation to understand the presumably environmental impacts generated by its implementation. Although impact calculation is an estimate or judgement of the significance and value of environmental effects, it can support decision-making by outlining the environmental gains and/or trade-offs that firms may evaluate with respect to environmental business or project objectives. While there are numerous methods for environmental assessment and accounting, there are a particular set of tools frequently used in IS, namely: (1) life cycle analysis (LCA), (2) input-output (IO) analysis, (3) material flow analysis (MFA), (4) eco-costing, (5) social network analysis and (6) biomimicry analysis. Many of the methods are based on the mass-balance principle and share the system approach, but differ in purpose, scope and data requirements. The methods addressed below support the process of IS in a number of ways: (1) analyzing environmental impacts, (2) expressing the environmental cost of environmental decisions in monetary terms and (3) analyzing the environmental stability of ecosystems.

Life Cycle Analysis

LCA is a methodology for assessing the environmental impacts that are associated with a product's life cycle (Finnveden et al., 2009). It is often used in the assessment of IS relationships to determine the environmental benefits of alternative symbiotic (network) configurations and product design (Daddi, Nucci, & Iraldo, 2017; Mattilla et al., 2010).

Input-Output Modelling

IO modelling is a methodology in economics that represents the interdependencies of different sectors of an economy. The method can also be used to analyze the interdependencies of material flows and can be applied at different levels. For example, enterprise IO modelling can be used to calculate the fit between the available waste and necessary primary input for the substitution under investigation (Yazan et al., 2016). Furthermore, efforts resulting from national IO modelling in the form of national IO tables have been used to identify the sectors that may be in need or can provide (waste) resources for IS applications (Chen & Ma, 2015).

Material Flow Analysis

MFA is an analytical method that quantifies the flow and stock of material, substance or products across an ecosystem, which is also used in several studies investigating the environmental benefits of IS (e.g., Sun et al., 2017; Van Berkel, Fujita, Hashimoto, & Fujii, 2009). The main drawback of MFA is the lacking view on the product cycle. Other variants of MFA differ by scale (e.g., by analyzing on a regional, national or worldwide level often referred to as material flow accounting) or by aspect scoping (e.g., by combining the costs associated with material flows often referred as Material Flow Cost Accounting (Ulhasanah & Goto, 2012).

Eco-costs

Eco-costs are a measure that expresses the financial investment required to be made to prevent environmental pollution or material depletion to reach the equilibrium between the environmental burden and the regenerative capacity of our earth (TU Delft, 2021). Eco-cost can be used as an extended instrument to express the financial costs related to environmental decision-making.

Biomimicry

Finally, *biomimicry* is a methodology to study how nature works by mimicking models from nature to study complex human problems. In the field of IS, biomimicry is studied using techniques such as social network analysis and food web analysis. This may reveal the properties and structures of IS networks in order to assess whether these correspond to natural ecosystems which may indicate the strength of network resilience (Genc, van Capelleveen, Erdis, Yildiz, & Yazan, 2019, 2020).

Game Theory

Game theory provides a set of tools to assist decision-makers in strategic decision-making environments. A game is defined as the interaction between players who are making decisions based on their individual goals and interests subject to environmental constraints. In game theory, it is usually assumed that players take rational decisions and consider the strategic behaviour of other players while making decisions.

By its strategic nature, game theory is a perfect tool to analyze IS and IS networks. This is due to the fact that IS is a ‘coopetition’ business model in which companies need to cooperate to create added value, reduce environmental burdens and dive into competition to pay a scant part of running costs of IS. However, the use of game theory for analyzing IS has been historically limited. Only few articles emerge in the literature particularly within the last five years. While most of the below-discussed literature deals with bottom-up IS, a recent article tackles the eco-industrial parks from the top-down perspective.

Yazdanpanah et al. (2019) set up an IS framework in which companies need to consider multiple dynamics of IS to properly filter the IS opportunities, i.e., Formal Industrial Symbiosis Opportunity Filtering. The paper refers to the environment in which IS might occur taking into account market and supply chain observability from the perspective of each player. Yazdanpanah and Yazan (2017) propose a cooperative game theory approach to assist companies on fair cost- and benefit-sharing and on stable IS relationship implementation. This is due to the fact the ‘coopetition’ nature of IS puts the stability and sustainability of IS under risk leading to interrupted IS relations. The authors demonstrate that the ‘Shapley value’ and the ‘Core of the game’ offer a space of cooperation in order to run fair and stable IS businesses. Yazan et al. (2020) combine enterprise IO modelling, non-cooperative game theory and agent-based simulation in order to demonstrate that cooperative behaviour can be learned over time by companies forming an IS network. The authors showcase an implementation of a cooperative network composed of companies who are initially reluctant to cooperate and learn emphatic and fair business strategy over time. In fact, the study suggests that opportunistic behaviour gets lost and companies fairly share costs and benefits with each other over time.

From the top-down perspective, a recent research by Jato-Espino and Ruez-Puente (2021) proposes game theory for facilitated IS in eco-industrial parks. The study offers a solution about how to strengthen the existing waste exchanges in a top-down designed network in order to mitigate the risk of operational failures or the departure of existing companies from the network.

Game theory in IS is in its infancy. More research should take place in order to tackle existing problems in already-running IS businesses and to provide future indications for company managers to adopt IS. In particular, game theory can be very useful to automate the initial feasibility assessment of IS for company managers who need more sophisticated tools to understand the best conditions offering the best economic, environmental and social outcomes. In fact, most of the studies relate only to economic assessment while proposing an environmental or social utility function is definitely needed. Such studies can be very helpful in particular for IS businesses that are environmentally and socially promising but economically challenging. Embedding game theory in AI and IT environments will reduce the uncertainty pressure on company managers who can look at the future with confidence in sustainable and circular business development.

Geographical Information Systems

The predominant type of *GIS* used in IS are IS region identification tools. IS region identification tools aim to support the strategic location of IS investments (van Capelleveen, Amrit, & Yazan, 2018). The key of such a system is its function to locate the regions that have a high economic viability for IS implementations. Aggregated data that reflect the regional economic, infrastructural or industrial characteristics are used to perform a multi-criteria evaluation (typically economic, environmental and social) to assess the viability of IS in that region. Examples of characteristics used include land destination, waste production projections, infrastructure density, urban development, industry diversity and access to nearby facilities such as power plants, boreholes and waste facilities (Aid, Brandt, Lysenkova, & Smedberg, 2015; Jensen, Basson, Hellawell, & Leach, 2012; Ruiz, Romero, Pérez, & Fernández, 2012). The multi-criteria evaluation systems typically rely on scoring methods such as analytic hierarchy process or fuzzy rule-based expert systems.

Another type of a GIS-based exploration tools are systems developed to determine the best location for a specific IS business case, for example, the spatial planning of district heating systems (Togawa, Fujita, Dong, Ohnishi, & Fujii, 2016) and the identification of waste heat potential of a region (Dou et al., 2018). Although this type of system has a different level of analysis than IS region identification tools, the technical function is similar, hence, these systems rely as well on a multi-criteria assessment using scoring methods. In summary, the GIS systems explained support to either (1) the strategic location to identify IS opportunities or (2) the optimized location to facilitate or implement a specific IS business case.

Rule-Based Matching

Rule-based matching is a popular technique used in IS markets. These systems support the process of connecting existing supply and demand. The match-making techniques in these platforms are often based on IO matching systems and make use of material or waste classification systems such as the European Waste Catalogue (EWC) and the Central Product Classification (CPC) to link the inputs and outputs. The literature reports a high failure of such systems and attributes these failures typically to a lack of sociability (Grant, Seager, Massard, & Nies, 2010). However, this dominant view on failures may also be the result of reported systems developed within research projects that were typically unable to overcome these barriers, e.g., the reviewed waste market platforms by Grant et al. (2010) and Maqbool et al. (2019). There also exist success stories in the literature (see van Capelleveen, Amrit, & Yazan, 2018), and there are corporate initiatives that are less visible in academic view (e.g., UCBCSD Materials Marketplace, Excess Materials Exchange, Synergie 4.0). There is an increasing interest in the application of machine learning techniques to support IS markets as a result of growing data availability and knowledge management (van Capelleveen, Amrit, Yazan, & Zijm, 2018).

Machine Learning

Machine learning is a methodology that improves computer algorithms automatically through the experience without explicit programmed rules. An Machine learning algorithm first identifies patterns in training data which it then uses to make predictions about new items or future data points (Bishop, 2006). Machine learning has been applied in a few applications of IS identification systems. Yeo et al. (2019b) suggest that a data-oriented approach could help build a knowledge repository that may reveal new IS opportunities. Their repository is built using natural language processing techniques that extract information about possible inputs and outputs from academic papers that can potentially form a symbiotic relationship. A further application of machine learning techniques is in recommendation systems for industrial symbiotic markets. The key strength of recommenders is the ability to support users in identifying item opportunities and proactively engage system use, resulting in both increased sales and a more active community. The work of van Capelleveen (2020) has identified three cases for recommender systems that can support the identification of IS. Firstly, a recommender system can reduce the search costs associated with identifying relevant IS ideas for a firm prior to revealing specific details of their operations (van Capelleveen, van Wieren, Amrit, Yazan, & Zijm, 2021). Secondly, a recommender can support the firm in classifying waste items with EWC code labels in order to support, for example, the search and matching process in IS platforms (van Capelleveen, Amrit, Zijm, Yazan, & Abdi, 2021). Finally, recommender systems can be employed to suggest the waste items in established marketplace platforms that match the firm's waste preference profile, e.g., by using the a priori and IO databases-based algorithms (van Capelleveen, Amrit, Yazan, & Zijm, 2018).

Material Selection Tools

Material selection tools are digital tools that support researchers, engineers and product designers in the material selection for a determined application considering the product constraints. A review performed by Ramalhete, Senos, and Aguiar (2010) identified and classified a number of tools that can support the material selection process. An example is the CES Selector, which is a software to support designers to select the most appropriate material candidate based on the technical properties of the materials. While there is a lack of reported use of these tools for the specific purpose of IS facilitation, there is a common use of the tools in product design, in particular in high-complex product design and products with stringent quality norms (Ramalhete et al., 2010). A plausible explanation for its currently low adaptation in IS design is the lacking database information about waste properties susceptible for reuse in product design. Capturing the growing knowledge around these waste characteristics into such databases would enrich such tooling by enabling the exploration of alternative use of 'waste material' in product design. While the primary aim of these tools is to support material selection for product design, there is a vast potential for use in IS identification as such tools may help to uncover potential alternative reuse streams for products.

Network Optimization

Quantitative tools are a popular methodology applied in eco-industrial parks used for *network optimization*. While there are a variety of mathematical optimization methods available from the literature, in the majority of cases mixed-integer linear programming (MILP) is used to optimize IS network configurations (Boix, Montastruc, Pibouleau, Azzaro-Pantel, & Domenech, 2011; Kastner, Lau, & Kraft, 2015; Montastruc, Boix, Pibouleau, Azzaro-Pantel, & Domenech, 2013). There are two major applications for the quantitative tools: network optimization and infrastructure optimization (Kastner et al., 2015). Network optimization attempts to search for, mostly from an economic or environmental point of view, the best configuration of interplant connections. Infrastructure optimization is concerned with searching for the most optimal infrastructure network that facilitates the transportation of by-product exchange. Typical network optimizations focus on energy and heat systems, water systems, material systems or combinations of different types of exchanges (e.g., Boix et al., 2011). Infrastructure optimization is often concerned with piping networks for steam, heat and water (Kastner et al., 2015). In conclusion, optimization methods can support companies, IS facilitators and policymakers: they allow to find the most optimal configuration of eco-parks based on multiple objects: environmental, economic and social.

THE INDUSTRIAL SYMBIOSIS SUPPORT FRAMEWORK

Table 1 displays the Industrial Symbiosis Framework developed in this section. The framework is developed as a matrix whose rows correspond to the techniques and methodologies that can be applied to IS and the columns to the IS phases where the methods can be applied. The framework reveals all the current and future tools that may be susceptible to develop smartness.

Techniques and Methodologies Aligned With IS Phases

With respect to the *IS identification phase*, machine learning is a useful technique to assist in determining the relevancy of potential opportunities for industries. Where humans would spend enormous amounts of time reviewing all potential opportunities for relevancy to a particular firm or industry, machines are able to identify this relevancy in short amounts of time. A prerequisite for many of these systems is the attribution of material and waste classifications (e.g., EWC, CPC) to items in IS marketplaces or synergies listed in knowledge bases. Also these tasks are experienced as time-consuming and provide an excellent opportunity for machine learning algorithms to be of support. Geographical location often plays a crucial role in the feasibility of IS. Therefore, GIS-based exploration and scoring methods provide a great ability for policymakers to reveal the areas susceptible for particular types of symbiosis and develop policy actions accordingly. Also for companies, GIS-based techniques are helpful, for example, to determine the strategic location of their facilities, or maybe by assessing the business climate for particular symbiotic opportunities. Material selection tools, often used by designers and process managers, can support the selection of appropriate alternative materials that may be waste-based, by reviewing the quality characteristics with respect to product requirements and other

Table 1. The Industrial Symbiosis (IS) Support Framework.

Techniques and Methodologies/ IS Phases	IS Identification	IS Assessment	IS Implementation	IS Monitoring
Agent-based modelling		• Investigating the factors impacting on the companies' willingness to cooperate and on the IS feasibility	• Explore factors affecting the IS emergence process • Explore the performance of operational practices	• Explore the operation of IS in the long period
Material passport	• Identify the value for use, recovery and reuse in a product	• Support CE decision-making along the life cycle of a product		• Monitor the circularity performance of the product and the implemented IS over the life cycle of a product
Environmental assessment and accounting		• Assess the presumable environmental impacts that will be generated by the implementation of IS		• Monitor the environmental impacts generated by the implementation of IS
Game theory		• Assess cost- and benefit-sharing options between companies	• Evaluate the potential consequences of fair and opportunistic behaviour for the stability of ISRs • automize decision-making for managers (future)	• Monitor the waste reduction and resource depletion mitigation within an eco-industrial park • Risk mitigation against operational failures in the design phase of eco-industrial parks (future)
GIS-based exploration and scoring methods	• Strategic location to identify IS opportunities • Determine the best location to facilitate or implement a specific IS business case • Quicker identification of opportunities through predicted geo-spacial relevancy (future)			

Machine learning and rule-based algorithms	• Quicker (waste taxonomy) tag assignment to waste items • Quicker identification of opportunities through predicted relevancy		• Analyze emergence patterns and their explanations (future)	• Suggest optimization strategies based on historical data analysis (future)
Material selection methods	• Uncover potential alternative reuse streams for products by reviewing the technical properties of the materials with respect to product requirements			
Optimization techniques		• Investigating the optimal configuration of interplant connections • Investigating the optimal infrastructure network for facilitating IS		• Control the optimal configuration of interplant connections through model parameters based on operational feedback (future) • Control the optimal configuration of infrastructure network for facilitating IS through model parameters based on operational feedback (future)

material options. Finally, material passports keep track of an object's composition, which may help to identify the value for use of those elements, recovery and potential reuse.

The *IS assessment phase* is characterized by determining the feasibility of a synergy. In this context, ABM can be a useful technique to explore which factors are able to impact on the feasibility of IS under specific circumstances. In this regard, companies' willingness to cooperate towards IS can be modelled as a fitness function, whose value depends on economic (e.g., prices and costs), environmental (e.g., the amounts of waste exchanged) and social factors (e.g., path dependence). Accordingly, the extent to which each factor can affect the companies' willingness to cooperate can be highlighted. The game theory approach can also facilitate the decision-making process for company managers in order to improve empathic thinking and observe long-term advantages of fairness in business strategy development. Optimization techniques, such as MILP, can help to investigate the optimal configuration of interplant connections in a park and infrastructure networks to facilitate IS. Of course, depending on the defined optimization goals (e.g., economic, environmental, social). Environmental assessment and accounting methods are critical tools in this phase to assess and balance different environmental impacts that are likely generated by the implementation of a symbiotic relationship. It provides support to the decision-making task if a symbiosis should be implemented from an environmental point of view, and what are the consequences of such implementation? In that regard, material passports may provide accurate data of an object that can be used in the environmental assessment described before in addition to its relation to circularity choices regarding the object (boundary shift assessment, understanding the effect of IS implementation on the objects circularity).

In the context of *IS implementation*, ABM can be used to explore a priori scenarios and practices not yet adopted. In particular, the factors that can influence the emergence of IS can be assessed and the effectiveness of policy measures aimed at supporting IS can be investigated. In this regard, the emergence of self-organized IS can be simulated under multiple scenarios under different economic, environmental, social and normative conditions. For example, the impact of economic incentives aimed at supporting the emergence of IS can be easily assessed via simulating the same IS system under two settings, i.e., one base scenario and one scenario where the incentive is implemented. The impact of the incentives can be assessed as the difference between the numerical performance of these scenarios. Through the same logic, also the effectiveness of operational practices (e.g., supply strategies, waste inventory practices) can be explored for specific industrial systems. Machine learning may provide a contribution by systematically analyzing data observation (e.g., governmental registers, news reports, etc.) of IS emergence in order to uncover patterns of IS synergies and IS network establishments. Cooperative game theory is particularly useful to analyze innovative circular business strategies to ensure the sustainability and stability of IS.

In the context of the *IS monitoring phase*, a practical critique sometimes mentioned towards many implemented symbiotic relationships or networks is that it may be resource-intensive and costly to monitor. Nevertheless, there are some advantages related to monitoring that may be highlighted that are or may become at some point beneficial. In the context of IS monitoring, ABM can be used to explore the operation of IS in the long period, in particular by assessing in advance the potential impact of changes in economic, environmental, social and normative factors on the potential waste flows among companies, as well as on the companies' willingness to cooperate. Environmental assessment and accounting techniques can not only be used to predict the environmental impacts of IS synergies but also to actually measure them while being operated. This is often more accurate and contributes to the body of knowledge regarding the effectiveness of IS implementation under practical conditions. Material passports help to identify the value for use, recovery and recycling and can thus potentially assist in specific cases in which the object makes use of an IS implementation. Then, the material passports can show, for example, how such implementation affects the CE performance of an object. Finally, a number of future suggestions to support the monitoring phase are driven by machine learning methods and optimization techniques. Machine learning may suggest optimization strategies based on historical data, and optimization techniques can be used for continued evaluation of model parameters, and control of implemented conditions of IS synergies, accordingly.

Embedding SMARTness Into IS Techniques and Methodologies

One of the main references for the use of the term 'SMART' originates from the acronym 'Self-Monitoring, Analysis and Reporting Technology', coined by IBM as a technology used in hard disk to monitor hard drive reliability with the aim of anticipating hardware failures (Allan, 2004). Regardless of being a direct result of SMART developed for hard drive, the principles behind SMART have been adopted in other areas and became known as SMART tech, e.g., smart wearables, smart TVs, smart devices, etc. The revolutionary innovation offered by SMART is to make these objects, devices and associated techniques aware of the its context by (1) directly linking the models to sensory input from the environment of real operation, (2) alerting the user to potential problems and guiding towards desirable and effective solutions and (3) learning from the new data provided to the model.

Nevertheless, many of the presented techniques discussed in the Section 'The Industrial Symbiosis Support Framework' are developed as tools which embed, hard coded in the models, the acquisitioned knowledge needed for operation. With the rise of possibilities provided by SMART innovations, we hypothesize that many tools may also benefit from a self-monitoring approach through sensors. For example, an opportunity arises for the material passports, where sensors can be used for measuring the state of an object, which can help to monitor the circular value and ultimately support in making maintenance decisions (Honic, Kovacic, Aschenbrenner, & Ragossnig, 2021). Although early studies show the applicability of the material passport, there is a considerable need for empirical evidence showcasing the environmental and societal effects of such a smart technology in context. Opportunities to embed SMART also arise in the development of GIS for facilitating waste transportation in IS processes (Yu, Yazan, Bhochhibhoya, & Volker, 2021).

Obviously, the potential for embedding smartness in IS tools is not limited to these examples provided but may be extended to the full framework of techniques displayed in Table 1. The SMART perspective, thus, opens new research avenues.

CONCLUSIONS

This section establishes a framework for AI and IT use to foster symbiotic relations between industries. Departing from the IS concept, several useful methodologies are synthesized from a functional perspective. Potential future improvements are critically discussed.

The twenty-first century is the era of sustainability and CE must be our future. We have made enough damage to our Earth, so our future efforts must focus on reversing this damage and constructing a livable world for all livelihoods. The ambition of profit must be minimized and economic gain must be spent on sustainable and circular technologies and business models; definitely not on investments pushing the society over-consumption. Therefore, the symbiosis should not only be implemented between industries but also between people, governments and industries. The concepts of rural and urban symbiosis must be well integrated into IS in order to achieve geographic complementarity and cooperation to accelerate CE transition.

In this big challenge, IT and AI must be our facilitators. Unfortunately, today the use of AI and IT to make companies and people consume more within the concept of linear economy is far more than the use of AI and IT to foster sustainable production and consumption. A circular and sustainable revolution is definitely needed to bring in quick and groundbreaking solutions, while an evolutionary approach is needed to assist companies, people and governments in order to achieve a smart CE transition.

To this aim, future research should be more interdisciplinary where the energy is spent through collective goals of companies and society by respecting the Earth's carrying capacity for human activities. This calls for education of students enrolled in programs such as AI, business IT, machine learning and engineering on the global sustainability challenges; thus, we can hope for future managers and researchers who are mathematically strong and environmentally and socially conscious. Next, fields such as business administration and management studies should provide students with non-conventional, sustainable and circular business models to achieve a *mental* transition in the industry and economic system. Furthermore, studies such as material science, nanotechnology, biology, ecology, electrical/electronic engineering, chemical engineering and energy systems which are dealing with resource use and consumption should provide students the necessary knowledge about resource- and energy efficiency. These educational improvements would facilitate industry-government-science collaboration which calls for a synergy among people with multiple skills and knowledge.

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