Industrial Symbiosis and Industry 4.0: Literature Review and Research Steps Toward Sustainability

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Abstract. The recognition of Industry 4.0 (I4.0) technologies as enablers of Circular Economy (CE) is a debated topic throughout the last decade. Material flows and operations within circular cross-industry networks require information sharing platforms and supporting digital tools to improve resource optimisation and to aim at CE principles. As a branch of CE, Industrial Symbiosis (IS) connects traditionally separated entities for sharing and exchanging by-products, energy, information and know-how. Practical implementations of IS are still limited. Several factors currently hamper the implementation of IS exchanges, i.e., technical, managerial, legislative, social, and I4.0 technologies, especially sensors, IoT and data analytics, can contribute to address them. However, in current literature few studies explore this promising tandem. According to this vision, this paper presents an updated review of the literature about the concepts of "Industry 4.0" and "Industrial Symbiosis", focusing, firstly, on the analysis of the authors keywords, and then, on the identification of methods and applications used. Finally, potential areas of interest for future agendas of researchers and practitioners in this field are proposed.

Keywords: Industrial symbiosis · Industry 4.0 · Literature review

1 Introduction

Digitalisation and sustainability are two of the most debated topics driving international discussions during the last decades. Although they have been commonly investigated as separated research themes, several synergies can be identified by overlapping them [1]. Within an industrial perspective, the digitalisation of production systems is associated to Industry 4.0 (I4.0), whilst sustainability suggests a more efficient use of natural resources and closed loop supply chains, related to principles regulating the so-called Circular Economy (CE) [2].

The term "Industrie 4.0" emerged in 2011 into a high-tech strategy project of German government regarding manufacturing computerisation, and then it was publicly introduced during the Hannover Fair. I4.0 transforms traditional production systems with the

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use of advanced digital technologies and Internet, aiming at the full automation and digitalisation. In 2015 the Boston Consulting Group recognises nine enabling technologies of I4.0: big data and analytics, autonomous robots, additive manufacturing, simulation, augmented and virtual reality, horizontal and vertical system integration, the Industrial Internet of Things (IoT), cloud, and cyber-security [3, 4].

On the other hand, overcoming the conventional "take-make-dispose" industrial paradigm, the CE concept promotes the closing of resources loops by aiming at zero waste production and harmful emissions reduction, extending the life cycle of a product or a service. Instead of thinking to a finite supply of resources, products and components are redesigned and rethought to adopt a returned and renewed culture, and to ease disassembly and recycling after their first usage [5].

To implement CE principles, Industrial Symbiosis (IS) can positively contribute to optimise the use of material and energy resources within a specific geographical area. It engages distinct organisations in an industrial network where by-products and outputs of a company represent potential inputs and raw materials for another business [6]. Allowing companies and entities that traditionally are separated to cooperate by sharing resources, sustainability is enhanced in terms of environmental, economic and social benefits [7]. However, the practical implementation of an IS network is hampered by several factors. First, taking part in an IS network (ISN) is an investment of financial resources and time. Then, a variety of cultural, managerial, technological, legislative issues affects decision making [8]. In addition, the efficient simultaneous management of physical and informational flows in cross-industry networks requires the integration of different skills. Industry 4.0 technologies, especially sensors, IoT and data analytics, are expected to boost the efficiency of circular material flows by data [9].

The aim of this paper is to present an updated literature review on the merging of the topics of IS and I4.0. According to this background, the reminder of this paper is structured as follows: the next Sect. 2 analyses the authors keywords and targets addressed, whilst Sect. 3 discusses the methodologies and applications. Finally, Sect. 4 draws conclusions and potential research steps.

2 Database Creation, Keywords Analysis and Research Targets

The review process focused on titles, abstracts, and author keywords by using Scopus and Web of Science as sources of scientific papers. First, a keyword search was conducted in Scopus. Second, Web of Science was consulted as a renowned database for assuring the consistency of the analysis. During the article screening, search strings contained only the two main terms: "Industry 4.0" and "Industrial Symbiosis". The analysis allowed finding 21 articles and collecting data about title, authors, years, keywords, and research targets. The analysis included relevant contributions published after 2016. Nevertheless, all the papers are dated from 2017 onward, confirming the novelty of the research. The subject areas cover engineering, environmental science, business management and accounting, and computer science. While the number of studies addressing CE and I4.0, jointly, is wide, few explore the link between IS, rose as a branch of CE, and I4.0 [5].

The retrieved papers are analysed by authors keywords to comprehend the synergies between IS, I4.0 and other related topics. Table 1 shows the most frequently used keywords, present in at least two papers within the selected set of articles.

Table 1. Author keywords (present in at least two papers out of the total).

		Author Keywords										Ref
Author(s)	Year	I4.0	I.S	C.E	Sust.Manuf	Sustainab	A.I	C.B.M	Eco Eff	Ind.Ecol	Waste.M	
Ferrera et al	2017	X	X		X				X			[10]
Baptista et al	2018								X			[11]
Tseng et al	2018	X		X								[12]
Garcia-Muiña et al	2019	X	X	X		X		X				[13]
Hertwig et al	2019		X									[14]
Kalyan et al	2019		X							X	X	[15]
Kerdlap et al	2019	X	X		X							[16]
Naderi et al	2019	X			X		X					[17]
Colla et al	2020	X					X					[18]
Gurjanov et al	2020		X	X								[19]
Ponis	2020			X				X		X		[8]
Scafà et al	2020	X	X									[20]
Cohen and Gil	2021	X		X							X	[21]
Jamwal et al	2021	X			X	X						[22]
Järvenpää et al	2021	X	X	X								[9]
Mendez-Alva et al	2021		X	X		X						[23]
Norouzi et al	2021			X								[24]
Pizzi et al	2021			X								[25]
Pyakurel and Wright	2021		X									[26]
Cappelletti et al	2022	X		X								[27]
Chari et al	2022	X	X	X								[28]
Total		12	11	11	4	3	2	2	2	2	2	21

The sparsity of the keywords distribution in Table 1 demonstrates the lack of established commons streams under investigation. The keywords "Industry 4.0", "Industrial Symbiosis" and "Circular Economy" are the most widely adopted by the authors, with a frequency of 12, 11 and 11 respectively, out of a total of 21 papers. A Pareto chart is used to order by occurrence all the keywords of the retrieved contributions (Fig. 1).

Starting from this analysis, the selected articles are examined by considering how authors address the topics associated to the three most used keywords (I4.0, IS, CE) and what common threads emerge in papers research targets.

2.1 Shared Features

The contributions jointly considering the three most adopted keywords, i.e., I4.0, IS, CE, are by Garcia-Muiña et al. [13], Järvenpää et al. [9] and Chari et al. [28]. Garcia-Muiña et al. [13] tested eco-design phase and IoT technologies in the ceramic tile production for promoting a circular business model as a tool of competitiveness in enterprises. Eco-design allowed to assess different industrial solutions and to forecast their performance by an environmental, socio-economic and technological perspective. Järvenpää et al. [9] explored the information sharing related to IS material flow and how I4.0 can facilitate waste or by-product flows. A case study composed by three sub-cases, three materials and eight Finnish companies was used for conducting qualitative interviews. The research revealed difficulties in investing in I4.0 technologies compared to the information value, and it suggested that significant benefits can be achieved considering the whole network of actors. Finally, Chari et al. [28] conducted qualitative research to assess how dynamic capabilities (DCs) enable manufacturing supply chains to build resilience and transition to CE. Three steps constituted the research process: a literature review, with the keywords "resilience", "Circular Economy", "Industrial Symbiosis", "DCs" and "capabilities", the participation of a European project to investigate the potential of IS in Europe, and interviews to experts. The role of I4.0 in the development of DCs was also investigated since it emerged from the review.

Other relevant contributions about I4.0 and IS are proposed by Tseng et al. [12], Colla et al. [18], Ponis [8] and Pyakurel and Wright [26]. Tseng et al. [12] discussed the mitigation of the complexity of cross-industry networks in multiple supply chains with I4.0 tools, including data-driven methods and big-data analysis. In this context, research opportunities included the identification of sustainability gains from empirical assessment of I4.0, the optimisation of IS practices through mathematical models for providing decision-making support, data-driven analysis among industrial networks, the development of universally applicable metrics for IS and big-data driven analysis for the benchmarking of different IS parameters. Colla et al. [18] presented a set of application examples in the steel industry with the aim of implementing digital enablers for CE and IS solutions, such as big data techniques, Machine Learning (ML) and Artificial Intelligence (AI). The heterogeneity of data sources, the different available volumes and the unpredictable frequency of data sampling require advanced decision-methods to support managers and to improve the environmental footprint of production processes. Ponis [8] introduced an innovative business model supported by a B2B marketplace based on blockchain technology to mitigate IS barriers and to enable the creation of symbiotic relationships among cross-sectoral manufacturing firms in Greece, i.e., ISN, Industrial Symbiosis Network. In this context, blockchain acts both as a trust mechanism and an exchange platform. The model has technical and social limitations due to the lack of trusts among participants and the technology adoption. Pyakurel and Wright [26] proposed a framework and a methodology for the implementation of energy and resources cooperation combining related topics of IS, sharing economy and CE. Authors highlighted the significance of potential applications of blockchain technology and I4.0 in coordination and information sharing, and in enhancing trust among IS entities.

The performed analysis reveals that the main issues faced concern the management of information flows and the analysis of large amounts of heterogeneous data. The branch of I4.0 technologies related to Information Technology (IT), i.e., AI, big data and analytics, IoT, cloud, and cyber-security, is the most debated for addressing IS networks complexity. Frameworks and procedures that test I4.0 technologies especially within real industrial cases and circular supply chains cover most of the scientific papers.

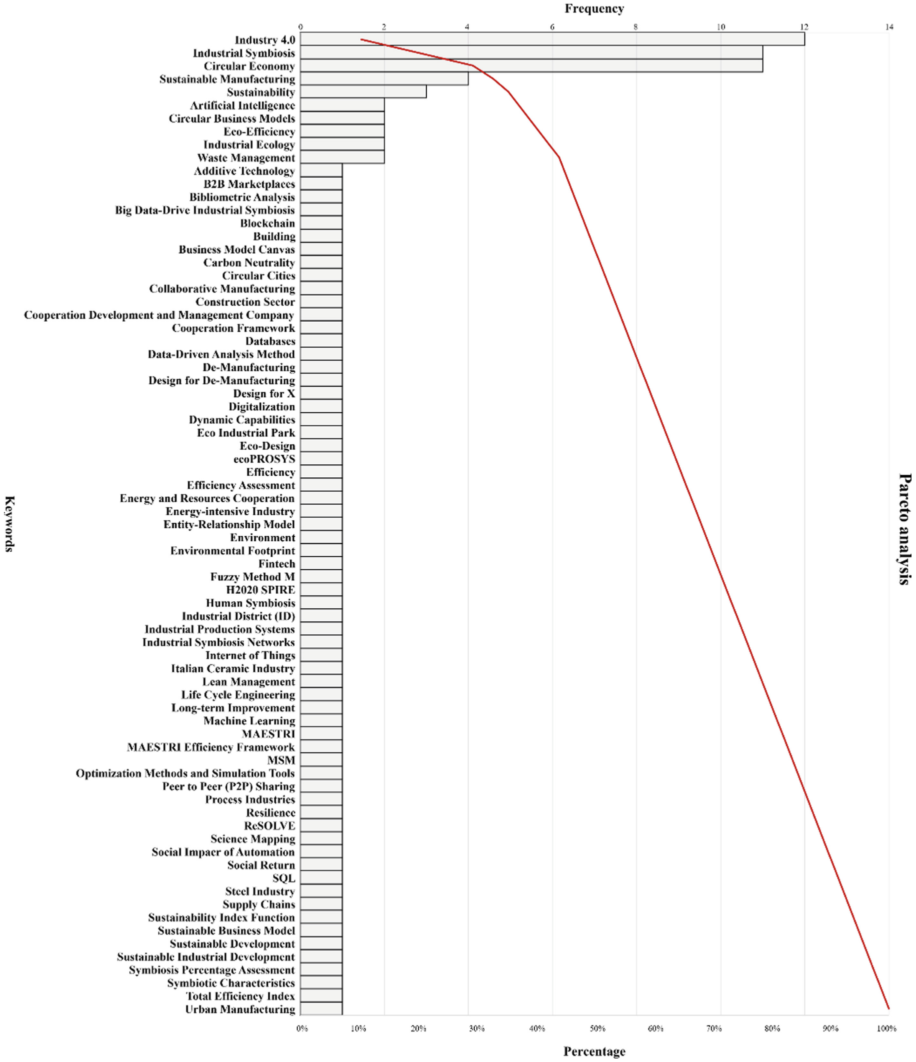

Fig. 1. Pareto analysis of the keywords frequency.

Next section will explore more in depth the methods and applications of the retrieved contributions.

3 Methodologies and Applications

This section is devoted to analysing papers by methodology adopted and by possible applications. Table 2 illustrates a classification of the articles according to the methodologies and the type of application used. Methods are divided into literature review, frameworks and procedures and algorithms. Frameworks are qualitative methodologies represented by logical schemes, such as conceptual or operative. Procedures and algorithms include quantitative methodologies, optimal or heuristic, consisting in a finite sequence of instructions to achieve a result. About the applications, illustrative examples and industrial real case studies are considered.

Table 2. Contributions classification by methodology and application.

Author(s)	Year	Paper methodology			Application		Ref
		Review	Frame-work	Procedures & Algorithms	Illustrative example	Industrial case study	
Ferrera et al	2017		X				[10]
Baptista et al	2018		X			X	[11]
Tseng et al	2018	X					[12]
Garcia-Muiña et al	2019			X		X	[13]
Hertwig et al	2019			X		X	[14]
Kalyan et al	2019			X		X	[15]
Kerdlap et al	2019	X	X			X	[16]
Naderi et al	2019			X		X	[17]
Colla et al	2020	X					[18]
Gurjanov et al	2020		X		X		[19]
Ponis	2020		X				[8]
Scafà et al	2020	X					[20]
Cohen and Gil	2021		X		X		[21]
Jamwal et al	2021	X					[22]
Järvenpää et al	2021			X		X	[9]
Mendez-Alva et al	2021			X		X	[23]
Norouzi et al	2021	X					[24]
Pizzi et al	2021		X				[25]
Pyakurel and Wright	2021		X	X			[26]
Cappelletti et al	2022	X					[27]
Chari et al	2022		X			X	[28]
Total		7	9	7	2	9	

As shown in Table 2, the use of qualitative approaches within paper methodologies, i.e., literature reviews and frameworks, exceeds the use of quantitative ones, i.e., procedures and algorithms. In addition, by analysing scientific methods, mathematical models, e.g., optimisation models, still constitute a small portion of the total. Regarding applications, industrial cases represent the majority compared to illustrative examples. The validation of several methods and procedures in real business contexts is very significant and promising for the future development of the analysed research topic in Academia and Industry.

4 Conclusions and Next Steps

Nowadays, digitalisation and sustainability represent two of the most debated topics in Academia and Industry. Within industrial contexts, the opportunities provided by Industry 4.0 (I4.0) technologies can address environmental challenges. Material flows and operations within circular cross-industry networks, i.e., Industrial Symbiosis (IS), require information sharing platforms and supporting digital tools to improve resource optimisation and to aim at Circular Economy (CE) principles.

The aim of this paper is to present an updated literature review on the merging of the concepts of IS and I4.0. The review allowed to retrieve 21 scientific papers. The analysis of the papers pointed out mainly the variety of contributions by keywords, methodologies and applications. This emphasises bibliometric evidence of the sparsity of scientific literature and the lack of common threads. The main issues faced concern information flow management and data analysis for decision-making support within IS contexts. AI, big data and analytics, IoT, cloud, and cyber-security are the most debated I4.0 technologies for addressing IS networks complexity. Qualitative frameworks are preferred, whilst regarding applications, methodologies are tested and validated through industrial case studies.

The limitations of the study concern the restricted set of keywords selected. There may be related articles that the review does not cover, but the extension of the research to other keyworks would have expose to the risk of including articles not strictly related to I4.0 and IS. A possible future research development will comprehend related keywords for both IS, such as CE, waste management, circular supply chain networks, and I4.0, including the key enabling technologies.

Given the evident potential of I4.0 technologies within IS, future research agendas are encouraged to deeply investigate these two topics from an applied perspective, also implementing quantitative approaches. A "smart" IS is the target to achieve, supported by digital platform based on I4.0 technologies, e.g., blockchain or cloud computing, and that leverage the energy and resources cooperation among firms or entities to reduce emissions and optimise the circular networks.

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