A Socio-Technical Perspective of Industrial Symbiosis*

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Abstract

Industrial symbiosis (IS) is an inter-organisational arrangement designed to pursue environmental sustainability outcomes and circular economy practices. While the extant literature extensively reports the environmental and economic benefits that IS can generate, there remains a notable shortage of studies systematically summarising its enablers from a socio-technical perspective. Therefore, this study addresses this gap by conducting an extensive literature review. The results reveal three main technical system enablers: information systems, cleaner production technologies, and Industry 4.0 technologies. Three social system enablers are also identified: top management commitment to developing inter-organisational sustainable production, the establishment of an integration role between government and the IS organisation, and the development of knowledgeable workers.

Keywords

industrial symbiosis, socio-technical theory, literature review, sustainability, circular economy

1. Introduction

Manufacturing organisations worldwide are increasingly called upon to achieve environmental sustainability, defined as the systematic decrease in organisational consumption of natural resources combined with the adoption of practices that enhance the overall health of the planet [19]. Achieving environmental sustainability requires not only the incremental greening of existing processes, but also fundamental redesigns of how firms organise their production and interact with their industrial neighbours. Environmentally friendly and efficient production and circular economy practices represent one avenue for pursuing this goal [28].

Within the landscape of inter-organisational arrangements oriented toward sustainability, Industrial Symbiosis (IS) has attracted sustained scholarly attention over the past two decades [9, 37]. IS refers to a strategy in which two or more organisations engage in the deliberate exchange of materials, energy, water, by-products, and even knowledge, so that the waste of one company becomes the productive input of another [22]. By closing the production cycle in this way, IS simultaneously reduces the environmental footprint of each participant and may generate economic savings through reduced raw material procurement and waste disposal costs. The environmental gains from IS are well-documented: they include decreased global

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warming potential, reduced landfill use, diminished water pollution, and significant energy savings [32, 37].

Despite the recognised promise of IS, its implementation remains challenging. A growing body of literature explores the drivers and barriers to IS adoption [14, 15], yet existing studies tend to be either narrowly focused on specific enabling factors such as geographic proximity or trust [44], or limited to single case studies that impede generalisation [10, 43]. More comprehensive syntheses of the literature on IS enablers exist [37], but they focus predominantly on managerial and process-layout dimensions without sufficiently integrating the role of technologies.

Thus, this study addresses these gaps by conducting an extensive review on IS literature through the lens of socio-technical theory [39, 42]. The literature review systematically identifies and synthesises the factors that enable IS and uses ST theory as the theoretical framework for their interpretation and classification. Specifically, ST theory provides a dual analytical structure that distinguishes between the social system, encompassing people, organisational roles, and inter-organisational relationships, and the technical system, encompassing technologies, automated tasks, and information flows [24, 25]. Rather than treating these dimensions independently, the socio-technical perspective emphasises their interdependence in shaping inter-organisational goals [7]. Accordingly, the identified IS enablers are analysed and mapped according to their social and technical dimensions, allowing the study to examine how their interplay supports successful IS initiatives. The study is thus guided by the following research question: *"What are the socio-technical enablers of industrial symbiosis?"*

2. Theoretical Framing: Socio-Technical Theory

Socio-technical (ST) theory was first developed in the 1950s by researchers at the Tavistock Institute in London, most notably Trist and Bamforth [42], who studied the organisational disruptions caused by the mechanisation of coal mining. Their seminal insight was that technological change does not occur in isolation from social arrangements: the introduction of new machinery without adequate attention to the human and organisational context systematically produces suboptimal outcomes [42].

From this observation emerged the principle of "joint optimisation", namely, that the technical and social systems of an organisation must be designed together to achieve sustained performance [24].

In this study, we follow the information systems tradition of applying ST theory [5, 39], which offers a particularly apt framework for analysing the role of technologies alongside individual and organisational factors in enabling complex organisational strategies. Within this tradition, the technical system encapsulates the technological artefacts in use and the tasks they automate or augment, while the social system refers to the organisational members, their roles and competences, and the inter-organisational structures within which they are embedded [24]. Moreover, within an IS network, which represents an inter-organisational arrangement, joint optimisation occurs at the inter-organisational level.

Because IS inherently involves two or more organisations in a coordinated exchange, the social and technical interfaces between partner firms must also be designed and managed. As de Bruijn and Herder [5, p. 981] note, IS participants are part of "systems that involve both complex physical-technical systems and networks of interdependent actors." Moreover, this perspective aligns with the nature of contemporary information systems, whose use is no longer confined to the boundaries of a single organisation but increasingly extends across organisational boundaries [3]. Such systems enable organisations to exchange information, coordinate activities, and manage interdependencies even when actors are geographically dispersed. This is particularly relevant to IS, where the exchange of by-products requires continuous information sharing and coordination among participating firms [36]. Therefore, ST theory offers a nuanced framework for understanding IS enablers: the social system must be designed to cultivate competent, environmentally aware, and strategically aligned actors at both managerial and worker levels, while the technical system must provide information systems and production technologies capable of supporting the complex logistical and operational demands of IS.

3. Methodology

This study adopted an extensive literature review methodology. The aim of the review was to identify and analyse empirical and conceptual articles on IS in order to understand the socio-technical enablers. Data collection was carried out in Scopus in January 2026 using the query: "industrial symbiosi*" OR "eco-industrial park" [45]. These keywords were selected because they represent the core concepts underpinning IS research [36]. The search was limited to English-language journal articles published between 2000 and 2025, considering that contemporary IS literature largely originates from Chertow's taxonomy [9]. Following the procedure proposed by Webster and Watson [45], we conducted an extensive literature review to enhance the rigor and transparency of the review process. The initial search yielded approximately 600 records. The search was restricted to the 'Business, Management and Accounting' subject area to maintain consistency with the organisational and socio-technical focus of the study, resulting in 150 records. Titles and abstracts were then screened to assess their relevance to the study, specifically whether they addressed enablers of IS. At this stage, 50 records were excluded. The remaining articles underwent full-text screening to assess whether they provided evidence or conceptual insights concerning IS enablers, resulting in a final corpus of 40 articles [45]. All articles were analysed using ST theory as a sensitising framework [25], whereby the dimensions of social and technical systems guided the coding and interpretation of IS enablers.

4. Results

4.1. Industrial Symbiosis: An Overview

IS emerges within the broader field of industrial ecology, which examines industrial systems from a systemic perspective with the aim of improving environmental sustainability through more efficient resource use [2]. While industrial ecology provides this overarching perspective, IS focuses more specifically on inter-firm cooperation in production processes, aiming to enhance environmental sustainability by reducing resource consumption and minimising waste

through the exchange of resources, such as materials, energy, water, and by-products, among otherwise separate firms [36]. Classic examples of IS, such as the network in Kalundborg, Denmark, emphasised geographic proximity and locally developed inter-organisational relationships [43]. Contemporary IS frameworks, however, increasingly rely on socio-technical alignment and data-driven coordination, highlighting the growing interplay between technological infrastructures and social and organisational relationships [36].

The literature provides multiple definitions of IS, reflecting the concept's evolution and multidisciplinarity. The most widely cited definition, proposed by Chertow [9], characterises IS as a collective approach in which traditionally separate industries engage in the physical exchange of materials, energy, water, and by-products to achieve competitive advantage. The empirical literature on IS is largely organised around case studies [36]. The most celebrated and frequently cited example is the IS in Kalundborg, Denmark, which developed organically from informal interactions among a small cluster of firms sharing water resources and grew, over several decades, into a sophisticated network involving 19 participants exchanging diverse streams of waste heat, steam, fly ash, sulfur, sludge, and other by-products [12, 13].

4.2. Industrial Symbiosis Social System Enablers

The literature elucidates three social system enablers for IS: (i) top management commitment to developing inter-organisational sustainable production; (ii) the establishment of an integration role between the IS network and the government; and (iii) the development of knowledgeable workers. In this study, these enablers are examined from an inter-organisational perspective, focusing on how they facilitate coordination, collaboration, and resource exchange among organisations participating in the IS network.

The first enabler, top management commitment to developing inter-organisational sustainable production, encompasses the attitudes, strategic dispositions, and practical decisions of senior managers that support the development and maintenance of collaborative relationships within the IS network [43]. Top managers who champion IS typically possess a high level of environmental awareness and are willing to invest in sustainability-oriented inter-organisational strategies even when the financial returns are uncertain or long-term [11]. Various case studies corroborate this: in Kalundborg, the IS developed largely through the personal relationships and environmental commitments of a small group of top managers, whose trust in one another was built gradually through repeated social interactions over several years [36]. From an inter-organisational perspective, such trust enables cooperation across organisational boundaries and facilitates the development and continuity of resource-exchange relationships [36].

Once a foundational IS is established, top managers must continue to actively support its inter-organisational development by contributing to the definition and refinement of shared IS strategies. This involves coordinating decisions among participating organisations about which by-products to include in the exchange, how to price them, how to attract new partners, and how to respond to changes in production volumes or composition. Top managers must also maintain an openness to innovation: successful ISs evolve over time, incorporating new firms, new types of by-product, and new exchange mechanisms. The willingness to accept novel entrants into the IS and to experiment with different ways of using by-products is therefore a dynamic dimension of top management commitment [43]. In this sense, top management

commitment to IS is not a one-off decision but an ongoing organisational disposition that requires active cultivation.

The second social system enabler concerns the management of relationships between the IS network and governmental actors at the municipal, regional, and national levels [37]. Government bodies can profoundly shape the incentive environment for IS by creating barriers — for example, through strict waste classification regulations that impede the legal transfer of by-products between firms, or through unclear land-use policies that complicate the development of shared infrastructure — or by providing incentives, such as subsidies for IS-enabling technologies, grants for feasibility studies, or facilitated access to eco-industrial parks [20, 30]. Government bodies may also play a more active facilitation role, organising workshops, disseminating best practice information, or funding research into new symbiotic opportunities [1].

Given the centrality of government actions for IS development, each IS participant organisation must establish a dedicated integration role — whether a specific manager or a unit — whose responsibility is to continuously monitor government policies and regulatory developments, communicate proactively with relevant government agencies, and relay this information across the IS network so that participating organisations can coordinate and adapt their strategies accordingly [37]. Rather than being viewed solely as an internal organisational function, this integration role is therefore conceptualised here in terms of its inter-organisational function: facilitating alignment between the network of IS participants and governmental actors. Its effectiveness is a key determinant of the IS's long-term resilience and adaptability. Without such a role, IS networks risk being blindsided by regulatory changes or missing opportunities to leverage government support [37].

The third social system enabler is the development of knowledgeable workers [41]. Workers occupy a central position in IS operations because they are the individuals who, day-to-day, conduct the production activities that generate or consume by-products, operate the technologies that monitor and manage these flows, and interact with workers from partner firms to support resource exchange and inter-organisational coordination [43]. The knowledge required of IS workers is therefore multifaceted: they must be technically proficient in the production processes that underpin the IS; they must understand the logistical requirements of by-product exchange, including the scheduling, transportation, and quality management of by-product streams; and they must possess environmental awareness sufficient to motivate their engagement with sustainability-oriented practices [11, 38]. From the inter-organisational perspective adopted in this study, these competences are particularly relevant as they enable workers to coordinate activities, exchange knowledge, and solve operational problems across organisational boundaries.

Beyond these operational competences, workers also have the potential to act as innovators within the IS. By virtue of their proximity to the production process, workers are well-positioned to identify inefficiencies, propose improvements, and provide bottom-up feedback to managers on how the IS could be developed or refined [11]. This innovative potential is most likely to be realised when firms invest in training and when organisational culture supports workers in developing an environmentally conscious mindset [38]. Branson [6] further notes that workers themselves can be understood as a shared resource within the IS:

their knowledge of IS practices, technologies, and inter-firm relationships constitutes a form of organisational capital that, when shared and diffused across participating organisations, supports inter-organisational learning and enhances the collective capacity of the IS network to adapt and evolve.

4.3. Industrial Symbiosis Technical System Enablers

Alongside the social system enablers, the literature identifies three main technical system enablers for IS: (i) information systems; (ii) cleaner production technologies; and (iii) Industry 4.0 (I4.0) technologies.

Information systems constitute the first technical enabler of IS, providing the informational infrastructure that makes coordinated by-product exchange operationally feasible [21]. For an IS to function effectively, each participating firm must know, at any given time, what by-products are available from its partners, in what quantities, of what quality, and at what locations [16, 31]. Without this information, the by-product exchange process degenerates into an ad hoc and unreliable arrangement that cannot be integrated into firms' production planning. Information systems address this need by collecting, storing, and visualising data about the input-output profiles of IS participants, enabling firms to plan their production processes around the availability of secondary raw materials and by-products [16, 31].

In addition to internal production data management, geographic information systems are also identified in the literature as a key technical enabler. A geographic information system overlays by-product availability and firm location data on a spatial map, allowing existing IS members to visualise the geographic distribution of by-product sources and sinks within the IS, and enabling potential new entrants to assess whether IS participation is feasible and advantageous for their production processes [23]. In this way, the geographic information system reduces information asymmetries that would otherwise impede IS formation and expansion, and it lowers the search and evaluation costs associated with identifying new symbiotic partnerships [34, 37]. The development and maintenance of these information systems therefore represent a strategic investment that enhances the long-term robustness and growth potential of the IS.

Cleaner production technologies constitute the second technical enabler of IS. This category encompasses a diverse range of technologies whose common feature is their ability to reduce the environmental impact of production processes, either by minimising the generation of waste and emissions per unit of output, or by enabling the transformation of waste streams from one production process into usable inputs for another [4, 8]. Advanced materials and production technologies improve resource efficiency by enabling more precise control of raw material use and by reducing the by-product streams generated per unit of output. Cleaner transportation technologies — including low-emission vehicles and route-optimisation systems — reduce the environmental costs of moving by-products between IS participants and make the overall IS more logistically efficient [30]. Technologies related to the development of clean energy, biofuels, and waste valorisation also fall within this category, as they directly enable the conversion of waste materials and energy into productive inputs for IS participants [8].

Industry 4.0 (I4.0) technologies represent the third, and most recently emphasised, technical enabler of IS [40]. The I4.0 paradigm encompasses a suite of digital and automation technologies — including the Internet of Things (IoT), artificial intelligence, big data analytics, cloud computing, and collaborative robotics — whose collective effect is to dramatically increase the digitalisation and automation of production and logistics processes [27]. When applied to IS, I4.0 technologies offer two principal contributions.

First, they enhance the informational infrastructure of IS through real-time data collection and analysis. IoT sensors embedded in production equipment and logistics systems enable the continuous monitoring of by-product generation, quality, and availability, providing IS participants with up-to-date production data that supports more precise and responsive by-product exchange scheduling [26]. This real-time visibility reduces the uncertainty associated with by-product availability and quality, which is a key barrier to effective IS coordination [17]. Second, I4.0 technologies for automation — particularly collaborative robots (cobots) designed to work alongside human operators — improve the efficiency and flexibility of production processes, reducing error rates, increasing throughput, and enabling more agile responses to changes in by-product availability [40]. Together, these I4.0 capabilities extend and deepen the informational and operational infrastructure that IS requires, making the technical system more adaptive and resilient [40].

5. Discussion and conclusion

This study discusses the importance of socio-technical enablers for IS, a strategy whose potential contribution to environmental sustainability and circular economy goals is widely acknowledged but whose implementation remains complex and demanding. By conducting an extensive literature review of the IS literature and analysing its findings through the ST lens, the study identifies three technical and three social system enablers for IS. Therefore, the main contribution to the literature is a ST reflection on the development of IS that complements those studies that focus on managing by-product exchange from a commodity science perspective [23, 33].

Specifically, organisations should consider three main social-systems enablers: workers, managers of the various organisations, and the integration role between IS and the government [37]. Each contributes to the development of IS in different ways. Top management establishes inter-organisational partnerships for IS to achieve environmental sustainability and sustainable production [34, 43]. Within an IS, organisations may establish an integration role with the government in order to develop an IS strategy for environmental sustainability aligned with government policies [37]. Still, workers should be capable of using the relevant IS technologies and conducting environmentally friendly and efficient production [4, 18, 31]. Moreover, three groups of technologies should be implemented for an efficient IS: information systems, cleaner production technologies, and I4.0 technologies [23, 40]. Information systems for IS support by-product exchanges [21, 23]. Cleaner production technologies enable sustainable production, reducing energy and raw material consumption [37, 43]. Finally, I4.0 technologies are technical-system enablers that provide increased digitalisation that facilitates exchanges among IS organisations [17, 40]. Therefore, considering these enablers in relation to one another, we propose an interacting ST system for IS: top management is the actor

responsible for selecting the strategy, partners, and technologies for IS. They may use information systems to support the by-product exchange strategy and allow new partners to enter IS. Workers are those who conduct operations and use cleaner and I4.0 technologies for production, aiming at environmental sustainability. Lastly, the integration role between the IS network and government serves to address potential barriers that government policies may create and to secure funding. In this way, this integration role contributes to the joint optimisation of the social and technical systems by supporting the alignment of technology-related decisions with government policies and facilitating access to public funding for technological investments.

5.1. Implications for managers

This study generates several actionable implications for managers seeking to develop or join IS initiatives. First, managers should proactively identify and cultivate relationships with suitable partner firms, focusing on complementarities between their waste streams and the raw material needs of potential partners, while considering geographic proximity where it provides logistical and relational advantages. As illustrated by the Kalundborg case, trust-building through repeated informal interactions is a sustained effort, not a one-off search.

Second, managers must invest in information systems that make information on by-product availability, quality, and logistics visible to all IS participants. Geographic IS tools, which overlay this data on spatial maps, are particularly valuable for networks seeking to expand, functioning as strategic assets rather than mere operational tools.

Third, a dedicated integration role or unit should be established to manage relationships with government bodies at all levels, monitor policy developments, and mobilise support for IS. Beyond securing financial incentives, this role is essential for pre-empting regulatory risks that could disrupt operations.

Fourth, managers must invest in worker training that builds both technical competences and environmental awareness. A collaborative, innovation-oriented culture that encourages workers to provide bottom-up feedback is a key determinant of long-term IS success.

Finally, managers should adopt a phased approach to technology investment: cleaner production technologies are an important enabler for IS participation, while the subsequent adoption of I4.0 tools — particularly IoT and collaborative robotics — enhances coordination and responsiveness. Awareness of these complementarities is essential for effective technology planning. More broadly, managers should avoid treating these social and technical interventions independently. Effective IS development requires their joint optimisation, ensuring that technology investments are aligned with workers' competences, inter-organisational relationships, and the institutional conditions shaped by government actors [35].

5.2. Limitations and future research avenues

This study has several limitations that provide opportunities for future research. The literature review relies on the quality and coverage of the studies identified through the search process, and the use of Scopus, while comprehensive, may have excluded relevant work published in less accessible venues. The ST framework applied here is based on secondary data;

future research should validate and extend it using primary data from IS participants. Moreover, geographic proximity is frequently considered an IS enabler, but its relevance may vary depending on logistical and technological conditions. Future research should therefore examine whether digital technologies can reduce the constraints associated with geographical distance. Also, the predominance of European IS cases may limit the generalisability of the identified enablers. In developing economies or regions characterised by different regulatory and institutional frameworks, these enablers may manifest differently. For instance, the role of government and the availability of technological infrastructure may vary considerably across contexts, affecting both the social and technical conditions enabling IS. Future research should therefore examine and validate the identified enablers across different geographical and institutional settings. Finally, this study adopts I4.0 as its analytical boundary, reflecting the technological enablers identified in the reviewed literature. However, this perspective may underrepresent the increasing emphasis on human–technology collaboration associated with Industry 5.0 [29]. Future research could therefore extend the proposed socio-technical perspective by examining how Industry 5.0 principles, particularly human-centricity, may influence the development of IS.

Declaration on Generative AI

During the preparation of this work, the author used ChatGPT to check grammar and spelling. After using the tool, the author reviewed and edited the content as needed and takes full responsibility for the publication's content.

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