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A Framework and Taxonomy for Categorizing Industrial Symbiosis in Manufacturing

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Abstract. The industrial sector is a significant contributor to global waste, discarding vast amounts annually, which results in both environmental pollution and economic losses. A promising solution is industrial symbiosis (IS), where companies (often from different industries) identify synergies and engage in the exchange of materials, energy, water, and by-products, aiming to close the loop and enhance resource efficiency. Despite growing interest and numerous examples, comprehensive taxonomies for categorizing IS practices in manufacturing remain scarce, as existing studies often focus on individual case studies. This study addresses this gap by proposing a new general taxonomy for the manufacturing sector. Relevant studies were analyzed and synthesized through a systematic literature review of 61 studies, with 22 selected for in-depth analysis of existing IS taxonomies. The findings were refined and validated through iterative expert input, resulting in a three-level taxonomy comprising 4 primary categories, 26 secondary categories, and 119 tertiary categories. The proposed classification provides a holistic framework tailored to the manufacturing sector, enabling practitioners and researchers to gain deeper insights into IS networks and develop effective IS strategies. Future research should validate these categories through empirical studies and explore their practical applications in different manufacturing settings.

Keywords: sustainable manufacturing, Industry 5.0, industrial growth, circular economy, taxonomy.

1 Introduction

The industrial sector contributes significantly to global waste generation, producing substantial amounts annually. Besides the environmental impact, much of this waste results in the loss of valuable materials, highlighting the need for innovative solutions to mitigate economic losses while preserving the environment [1]. One promising approach is industrial symbiosis (IS), which facilitates the exchange of materials, energy, and by-products among different industries, thereby enhancing resource efficiency and reducing waste among industries [2]. Chertow [2] defines industrial symbiosis as a process in which companies, often operating in different industries, engage in the reciprocal exchange of materials, energy, water, and by-products, resulting in economic and environmental benefits. This concept is rooted in industrial ecology, which draws parallels between industrial systems and natural ecosystems, emphasizing the importance of collaboration and synergy among companies [3].

In this context, an industrial ecosystem functions analogously to a biological ecosystem [4]. Similar to the principles of biointelligence, industrial ecology applies natural processes to cultivate sustainable and symbiotic relationships within industrial systems. Frosch and Gallopoulos [5] suggested in 1989 that industries could learn from natural systems to create closed-loop systems where waste from one process becomes input for another to promote sustainability.

By leveraging synergies and fostering symbiotic interactions, industrial symbiosis seeks to improve efficiency and sustainability within industrial processes. Consequently, the significant environmental impact of the manufacturing industry can be mitigated through enhanced collaboration and resource efficiency [6].

Despite the increasing interest in and potential of industrial symbiosis, a significant gap remains in the literature regarding the categorization of IS practices both generally and within the manufacturing sector. Most existing studies tend to focus on specific industrial parks, each with unique characteristics and operational requirements, which complicates efforts to develop a universal classification framework [3, 7]. Therefore, a general taxonomy for IS networks does still not exist [8]. Thus, this work focuses on developing a classification framework generally applicable to manufacturing.

Further, it aims to address the existing research gap by proposing a new taxonomy for IS in the manufacturing industry. A holistic categorization tailored to the manufacturing sector will be developed by analyzing and synthesizing the information from a literature review. The proposed categories will serve as a valuable resource and provide them with a framework to better understand and implement IS strategies, ultimately accelerating closing the implementation gap of IS and overcoming the challenges associated with identifying and leveraging symbioses.

2 Literature Review

Over the past decades, the development of IS has gained increasing attention in both research and industry, primarily due to its potential to enhance resource efficiency and mitigate environmental impacts. Still, a significant gap remains in developing a general taxonomy and classification framework for IS practices among the manufacturing sectors. However, the absence of a universal classification system for IS practices, especially within the manufacturing sector, presents a significant challenge. This section delves into the existing efforts to categorize and classify IS, highlighting its challenges.

For the development of a taxonomy and classification, most studies, such as those by Chertow [9] and Lombardi and Laybourn [6], have focused on specific case studies such as the Kalundborg Eco-Industrial Park. However, the unique characteristics of each IS network complicate efforts to create a generalized framework because the synergies vary significantly depending on the specific context. The diverse nature of these synergies – spanning solid waste, liquids, emissions, and waste energy - adds complexity, as their value fluctuates depending on factors such as region, industry type, organizational boundaries, technologies, and timeframes. This variability highlights the necessity for comprehensively categorizing these interactions [10, 11].

As a result, much of the literature remains divided, with different terminologies and classifications based on resource types, industry sectors, or geographical proximity [12].

The absence of such a comprehensive system limits the broader application of IS, hindering practitioners and researchers from identifying best practices and drawing insights from successful implementations. A precise categorization can help address key challenges in identifying symbiotic opportunities and facilitate the implementation of industrial symbiosis [13]. Hereby, researchers such as Aid et al. [14] underline the need for a cohesive classification system to guide industries and policymakers. It helps companies identify potential symbiosis opportunities and helps policymakers design regulations that incentivize IS practices.

A comprehensive classification system offers companies a structured approach to understanding the composition of industrial networks and facilitates the mapping of resource exchanges. For example, one effective method for identifying potential symbioses is the ‘relationship mimicking’ mechanism, where organizations replicate successful collaborations observed in similar entities [7]. In this context, a classification system forms the foundation for identifying opportunities for replication. Furthermore, such a system could serve as the basis for developing digital tools and platforms to streamline identifying potential IS partners by matching available resources with organizational needs [1, 15].

Addressing this gap is particularly important in light of current political and economic developments, such as the European Union’s Green Deal, which seeks to accelerate the green transition and promote sustainability across industries. Hereby serves the EU taxonomy for sustainable activities as a key regulatory framework, aiming to standardize and promote sustainable practices across sectors. Developing an adequate classification system for IS practices is a key step in identifying and analyzing successful synergies, providing policymakers with valuable insights to design regulations that incentivize and support IS implementation. Furthermore, the Green Deal encompasses additional EU regulations that underscore the significance of this issue. For instance, the EU Circular Economy Action Plan emphasizes the necessity of sustainable resource efficiency. Simultaneously, the EU Corporate Sustainability Reporting Directive (CSRD) highlights the critical role of systematically collecting and comparing data to enhance transparency and support informed decision-making processes.

The most referenced taxonomy for IS was hereby developed by Chertow [2], highlighting five distinct types of exchanges: by-product exchanges, waste exchanges, energy exchanges, water exchanges, and service exchanges [2]. This foundational framework has not been universally adopted or expanded upon in subsequent research. Nevertheless, there is a need for a more refined classification system that considers the varying characteristics of IS networks across different geographical and industrial contexts [3].

Despite advancements, developing a standardized taxonomy for IS faces several key challenges. One of the significant issues is the diverse composition of companies and the varying nature of collaborations, such as by-product exchanges versus shared utilities. Regional and cultural differences in IS practices further enhance this complexity. IS networks vary significantly across different geographic areas, driven by variations in regulatory and market structures, making it challenging to apply a universal classification system [3]. Therefore, the taxonomy should be adaptable to varying contexts [16].

Additionally, governance structures play a crucial role in the classification of IS. How symbiotic exchanges are coordinated through centralized or decentralized systems affects how networks are categorized [17].

A comprehensive taxonomy should, therefore, address technical exchanges, e.g., material exchange, and the social and institutional dimensions that influence IS development [18, 19].

A further challenge is the lack of data transparency between companies, as companies often do not want to share information about their waste streams and resource flows due to competitive concerns that limit classification advances [20]. This issue highlights the need for a taxonomy that bridges the gap between the accurate categorization of IS networks and the limitations imposed by data transparency challenges.

The field of industrial symbiosis continues to evolve, with new methodologies, technologies, and case studies providing valuable insights into its potential. However, challenges remain in standardized classifying IS practices.

There is a need for cross-disciplinary collaboration between researchers, policymakers, and industry stakeholders to develop a comprehensive and universally applicable taxonomy for IS. This research takes an initial step toward developing a coherent and comprehensive taxonomy to understand industrial symbiosis practices in manufacturing by analyzing existing frameworks.

3 Research Methodology

This study employs a structured research methodology, beginning with a literature review to establish the theoretical foundation, followed by expert consultations with iterative feedback loops to refine the findings. This approach ensures both a robust theoretical basis and practical insights relevant to the manufacturing sector.

The initial phase involved conducting a comprehensive literature review to analyze and synthesize relevant research. In July 2024, a systematic search was performed using Scopus, a widely recognized database for scientific publications, to identify pertinent literature.

The first phase involves conducting a literature review to analyze relevant research. A following search query was applied in July 2024 in Scopus, a database for scientific publications to identify the literature: "(TITLE-ABS-KEY ("industrial symbioses") AND TITLE-ABS-KEY ("classification" OR "categorization" OR "taxonomy" OR "typology"))".

This search yielded 61 results, subsequently screened and evaluated for relevance, as illustrated in Figure 1.

Only studies published in English are considered a valuable output of the inquiry. The search is not limited to any specific field since IS is mainly applied among different industries.

To ensure the inclusion of only relevant literature, an initial screening is performed by reviewing the titles of the identified works. This is followed by a second round, in which the abstracts are analyzed for relevance. In the third round, the full papers are analyzed to assess their relevance and contribution to the research topic.

Sources were excluded if they were overly specific or deemed insufficiently relevant for developing a general taxonomy applicable to IS in the manufacturing sector.

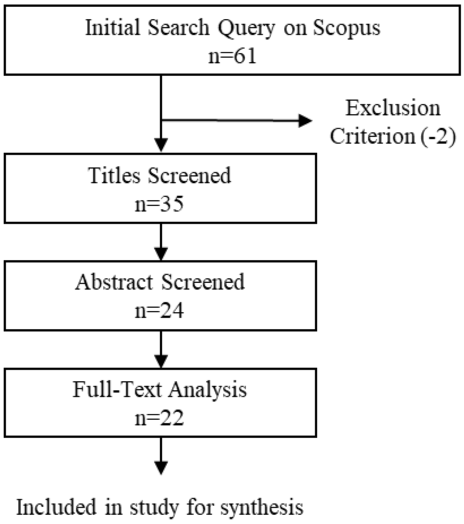

Figure 1 – A visual representation of the literature review

Also, papers with a narrow focus on specific case studies without broader applicability are removed from consideration. After applying the exclusion criterion and conducting all three stages of review, a final selection of 22 relevant sources is identified.

Table 1 summarizes the selected entities to provide an overview of the identified literature. The review reveals that no general framework has been proposed, with most studies deriving their proposed framework from specific ecosystems or case studies.

Although the literature reviewed exhibits a variety of focus areas, all sources propose different focus of categorizations. As outlined in the state of the art (see Section 2, no general classification exists. However, these sources contribute valuable input for developing a new classification framework. The analysis and review of studies forms the basis for identifying clusters, which will be used to develop a structured approach for classification.

Therefore, the clusters proposed in the literature are first collected and subsequently synthesized and restructured to align with the objectives of this study. This process involves consolidating, merging, and refining the identified clusters, which serve as the foundation for developing a first structured framework. After that, multiple feedback loops with experts from both industry and academia are conducted to further refine and eventually validate the proposed framework. These iterative feedback loops ensure that the framework is both scientific and practically applicable. The following Section presents the proposed taxonomy along with its defined categories. Each category is supported by references to existing approaches, underscoring their relevance and shows the existing state of research.

Table 1 – Overview of the selected literature

Source	Focus area
[1]	Introduces symbiosys, a web-based tool designed to identify synergies, manage resources, and facilitate networking.
[2]	Review IS literature and highlight collaboration, geographic proximity, input-output matching, and materials budgeting as key to eco-industrial parks.
[3]	Map IS in Europe. It highlights typical waste streams and discusses economic and legal aspects while emphasizing IS for the circular economy.
[4]	Emphasizes the importance of geographic proximity and advocates for precise land-use management in IS, comparing self-organized and planned models.
[7]	A novel IS knowledge repository approach is presented based on various methods, such as mimicking and input-output matching approaches.
[8]	A classification model for strategic IS networks was elaborated based on input-output matching, focusing on material and energy recovery.
[10]	Proposes a new regional resource synergies framework based on economic and environmental benefits.
[11]	Reviews the development of IS theory and methodology and suggests future research directions for improving quantitative classification and system monitoring.
[17]	Identifies a taxonomy of IS and four business models, focusing on system governance through coordination and control centralization.
[21]	Suggests a taxonomy for numerical indicators to measure IS, focusing on measuring IS systems' environmental, economic, and social benefits.
[22]	A method for evaluating IS's environmental and economic benefits and a classification based on in-depth analysis of various symbioses is proposed.
[23]	Classifies IS models, analyzing bottom-up districts, top-down eco-industrial parks, and network-based approaches.
[24]	Discusses the application of mixed industrial parks with SMEs, highlighting environmental challenges and proposing solutions for sustainable development.
[25]	Reviews European eco-industrial parks highlighting the importance of company diversity and proposing an algorithm to evaluate IS potential
[26]	Analyzes IS in chemicals, steel, and cement sectors using open databases. It classifies synergies by the most shared resources, offering a methodology for circular economy projects.
[27]	Proposes a classification model for IS networks using an input-output approach to guide company strategies and government policies.
[28]	Based on case studies, develop a classification of six business models for IS.
[29]	Proposes a framework for comparative analysis of IS and identifies IS terminology as well as provides a typology of IS dynamic
[30]	Using a web platform could support the application of IS for the waste and processing technology classifications.
[31]	Examines how IS emergence, synergy governance, actor serendipity, and bioeconomy enhance sustainability.
[32]	Explores digital transformation in IS using the viable systems approach.

4 Results

The proposed IS categorization framework is structured across three levels to provide a comprehensive categorization and taxonomy. Four primary categories have been established at the first level, which are further subdivided into 26 secondary categories at the second level. These secondary categories are then expanded into 119 specific classifications at the third level. The following sections offer a detailed explanation of each level and its corresponding categories.

The first category, "Network Typology", describes an IS network's general structure and dynamics. The related description is summarized in Table 2.

Table 2 – Typology of industrial symbiosis networks

Emergence	Internal
	Hybrid
	External
Development approach	Greenfield
	Brownfield
Governance	Self-organized/bottom-up
	Facilitated
	Planned/top down
Coordination	Centralized coordination
	Distributed coordination
	Initial coordination
	Ongoing coordination
	Policy framework
Facilitator	None
	Park manager
	External
	Internal
Network partners	Companies
	Facilitator
	Public entities
	Research facilities
	Business associations
	Technology provider
	Non-governmental organizations
	Financial institutions
	Communities
	Others
Number of companies	Bilateral partnership
	< 5
	5–20
	> 20
Size of companies	Micro < 9 employees
	Small < 50 employees
	Medium < 250 employees
	Large > 250 employees
Exchange structure	One to one
	One to n
	M to one
	N to m
Level of cooperation	Simple exchange
	Information sharing
	Coordinate process
	Strategic partnership
	Joint business model

Geographical proximity	Within a facility, company, or organization
	Small range (< 5 km)
	Medium range (5–20 km)
	Large range (20–50 km)
	Over 50 km
Industry Structure	Among industry / sector-specific / vertical symbiosis
	Across industries / sector-integrated / horizontal symbiosis
Investments	Initial
	Operational
	Private investments
	Public funding
Type of relationship	Exploitation
	Control
	Competition
	Commensalism
	Mutualism
Dependencies	Equality-oriented parks
	Dependency-oriented parks
	Single-dependency parks
	Multiple-dependency parks
	Nested parks
Symbiosis Context	Industrial
	Urban
	Rural

It integrates several key dimensions to provide a holistic framework for understanding the organization, relationships, and collaboration within the network. The networks can emerge through different mechanisms, e.g., internal when the network emerges between companies without external intervention. Simultaneously, external emergence is driven by outside forces such as regulatory frameworks or policymakers, as described by Doménech et al. [3] and Bijon et al. [31]. Hybrid emergence arises when both internal and external factors contribute to the development of the network. The emerging networks can hereby be developed from scratch (greenfield projects) or evolve from pre-existing infrastructures (brownfield) [4, 24, 25].

Alongside these emergence mechanisms, the governance of the network plays a central role in shaping its development. It can range from more self-organized to planned, top-down approaches, primarily stated in the literature. Self-organized governance allows the network participants to collaborate organically without centralized control, whereas planned, top-down governance relies on structured frameworks and policies imposed by authorities or central organizations, resulting in a more regulated approach [3, 4, 21, 25]. In between, facilitated governance involves a third party that helps guide and coordinate the network, providing support while allowing some flexibility [9].

For the network to function effectively, coordination might be needed, which can be either centralized or distributed and may vary between the initial and ongoing phases of the collaboration [17]. Coordination can be supported by an existing policy framework among companies [3].

Facilitators act as mediators to coordinate and manage diverse networks, playing a key role in engaging companies within the network since they can help overcome barriers such as a lack of trust between partners and foster collaborations [1, 33]. They can be internal, directly from the companies, or dedicated park managers. Facilitators may also come externally, such as government bodies, business associations, or research institutions [29]. In some cases, facilitators may not be applicable [7].

Facilitators are key in coordinating the diverse composition of IS networks, which often include companies, governmental bodies, and other stakeholders [32]. However, the network also extends to a broader range of stakeholders, including research institutions, NGOs, financial institutions, and others, all of which play key roles but have not been extensively covered in the literature.

The number of participants, particularly companies involved, varies widely from a bilateral partnership between two entities to broader networks [3, 10]. Networks with up to 5, up to 20, and larger ones with more than 20 participants become increasingly complex, offering more significant collaboration potential [29].
Among these participating companies, the size can vary significantly [1, 7]. To classify them, a general framework based on the number of employees ranging from micro-enterprises with fewer than 9 employees to small (under 50), medium (under 250), and large organizations (over 250) is used [34].

The number of participants in a network significantly influences its structure and the complexity of interactions. It can range from simple one-to-one relationships with only two companies to more complex models like n-to-m configurations involving multiple partners, as described by Albino et al. [8].

These exchanges can occur at different levels of cooperation, ranging from simple exchanges of resources to information sharing for better collaboration. Further partners may coordinate processes to align operations or form strategic partnerships for long-term goals as proposed. At the utmost level of cooperation, companies move toward adopting a joint business model, fully integrating their operations and strategies. This dimension has not been extensively covered in the identified literature but was briefly addressed by [25]. However, through expert feedback, it has emerged as a significant topic.

In industrial symbiosis, the geographical proximity of participants plays a key role and is widely discussed in the literature, as seen in studies such as [1–3, 11, 25], and defines the different spatial scales where exchanges occur. Some studies, e.g. [2], already define IS as being within a single company, whereas most studies relate to a broader range. A general classification proposed by [31] categorizes small ranges under 5 km, medium distances of 5–20 km, and extensive ranges extending up to 50 km and beyond.

Some authors, such as [11], refer to smaller ranges as co-located eco-industrial parks and wider ranges as virtual eco-industrial parks.

With several companies involved, the industry structure can be distinguished between sector-specific, where collaborations occur within the same industry, or sector-integrated, where collaboration happens among different industries [1, 10, 11]. It is proposed to list and categorize these industries according to the NACE system, as described by Benedetti et al. [7].

New business opportunities in IS often require initial and/or operational investments to foster and sustain the synergies, with funding typically coming from private, public, or combined sources [3, 21].

The dynamics and relationships between participants can significantly differ based on the variety of interactions within the networks. Exploitative relationships may occur when one company benefits disproportionately, whereas mutualistic relationships foster equal benefits for all participants. Control relationships emerge when one company significantly influences its partners, while competitive relationships arise when companies compete, e.g., with resources within the network. Additionally, commensal relationships are characterized by one party benefiting without affecting others, either positively or negatively [11, 21].

These relationships come with dependencies where participants in equality-oriented relationships have equal roles, while dominant companies drive dependency-oriented networks. Single-dependency networks rely on one key company, while multiple-dependency parks have two or more central companies. Nested parks hereby integrate both models with equal roles and dependencies [11].

To conclude the analysis of network properties, the symbiosis context further distinguishes whether the network operates exclusively in industrial areas or also extends to urban (e.g., with municipalities) or rural (e.g., involving agricultural industry) environments [21].

This multi-dimensional approach to categorizing the network typology highlights the diverse structures, relationships, and contexts that define industrial symbiosis networks, which will be further explored in the categories.

The next cluster is described in Table 3 in the following paragraph, focusing on the symbiosis and resource exchange within the network.

Upstream resources refer to the essential inputs needed for production, while Downstream resources represent the outputs of these processes. Most studies hereby named raw materials, water, and energy as key components for industrial symbiosis [1, 2, 10, 11, 21–23, 25, 35]. This study does not aim to delve deeper into defining specific materials. However, Álvarez et al. [1] propose to classify products using classifications of products classified by activity (CPA) for better identification.

Focusing on the downstream side, various categories have been listed in the literature, such as waste, process waste, by-products, heat, energy, emissions, and wastewater [1, 2, 7, 10, 11, 21, 23, 25, 26, 28, 32].

Table 3 – Exchange type within industrial symbiosis networks

Upstream resources (material inputs)	Materials
	Water
	Energy
Downstream resources (waste outputs)	Waste
	Process waste
	By-products
	Heat
	Energy
	Emissions
	Wastewater
Infrastructure, knowledge, and data sharing	Joint provision of services
	Utilities/infrastructure
	Knowledge
	Data, information
Resource exchange and processing	Direct use/reuse
	Internally processed
	With intermediary/ processed by third party

Studies such as [7] and [1] propose using the European Waste Catalogue (EWC) to standardize its identification for waste classification. Additionally, concerning water, [11] distinguishes between various types of water in the downstream process, such as wastewater, cooling water, or process water, which helps to provide a clearer understanding of how different resources are managed within these networks.

Managing these outputs has been the central element of the concept of IS, where the goal is to minimize waste and repurpose by-products into usable inputs for other processes, fostering circularity and resource efficiency [36, 37]. It historically focused hereby on the exchange of materials, but the scope has since expanded to include also others such as the joint provision of services, e.g., transport, shared utilities/infrastructure such as offices, or the exchange of knowledge, data, and information, enhancing collaboration and efficiency [2, 8, 11, 23, 38].

Resource exchange within the network can be managed through different approaches. Although direct use or reuse is sometimes feasible, resources typically require internal processing by companies, intermediaries, or third parties, depending on the context [7, 10, 31].

After building on the previous focus on exchange structure and resource exchanges, it is equally important to understand the broader implications of these IS networks. Therefore, the next cluster (Table 4) presents an approach to classify their impact on social, ecological, and economic dimensions, following the Triple Bottom Line framework proposed by Elkington [39].

Although this aspect has not been as extensively analyzed in the literature as others, it is essential for understanding industrial symbiosis networks comprehensively. In the social dimension, which tends to be underrepresented in both sustainability discussions and IS research, industrial symbiosis contributes to job creation by generating new opportunities and supports job retention by maintaining existing positions [3, 21].

Table 4 – Benefits of industrial symbiosis networks

Social	Job creation
	Job retention
Ecological	Emission reduction
	Resource efficiency
	Energy recovery
	Waste reduction
	Water conservation
	Biodiversity
	Land use
Economic	Cost saving
	Revenue generated
	Competitive advantage

The ecological dimension, often one of the main goals of IS, offers significant benefits such as emission reduction, improved resource efficiency, energy recovery, waste reduction, water conservation, the protection of biodiversity, and the prevention of land use [1, 3, 4, 10, 11, 23, 27]. The economic dimension, central to our current economic system and a key driver for industrial symbiosis, can lead to tangible cost savings or new revenues as described by [3, 21]. Furthermore, industrial symbiosis can provide a competitive advantage, offering diverse benefits for the involved companies [28].

The next cluster presented in Table 5 refers to a key research field within IS, as there remains a significant implementation gap between the benefits of IS and the actual implementation in practice.

Table 5 – Frameworks and tools for IS networks

Identification of IS	Software tools and platforms
	Input output matching
	Relationship mimicking
	Spontaneous/coincidence
	Engage with neighboring companies
	Other
Network Analysis	Material flow analysis
	Information flow
	Materials budgeting
	Stakeholder value
	Lifecycle assessment (LCA)
	Financial analysis
	Social interaction
	Other network analysis methodologies
Digital Support	Resource exchange platform
	IS matchmaking platform
	Waste management platform
	Big data for IS

This gap is primarily due to challenges in identifying symbiotic opportunities, making discovery and identification a key area of focus for advancing IS networks. Various methods are proposed in the literature for identifying IS, including software tools and platforms, input-output matching, and relationship mimicking, where successful symbiosis models with a comparable setting are replicated [2, 7, 35]. IS can also emerge through spontaneous or coincidental interactions or engaging with neighboring companies [3, 7]. Other approaches may exist, captured under other methods. Network analysis helps to understand networks concerning a specific area better. In the context of IS, key methods include material flow analysis, information flow assessment, and materials budgeting. Techniques like stakeholder value assessment, life cycle analysis (LCA), and financial and social interaction impact evaluations are further potential analyses based on the network's specific aspects. Other network analysis methodologies may also be applied depending on the specific network context [2, 21, 22].

Digitalization support plays an increasingly vital role in overcoming identification barriers, not only for the analyses of networks but for IS in general. Tools like resource exchange platforms, IS matchmaking platforms, and waste management platforms facilitate the coordination of exchanges as described in [1, 17, 23, 30, 32]. Moreover, applying big data for IS can potentially optimize networks and improve decision-making, enhancing the overall effectiveness of formed symbiotic relationships [1, 23, 24].

The presented clusters provide a comprehensive framework for understanding the different dimensions affecting IS networks (Figure 2).

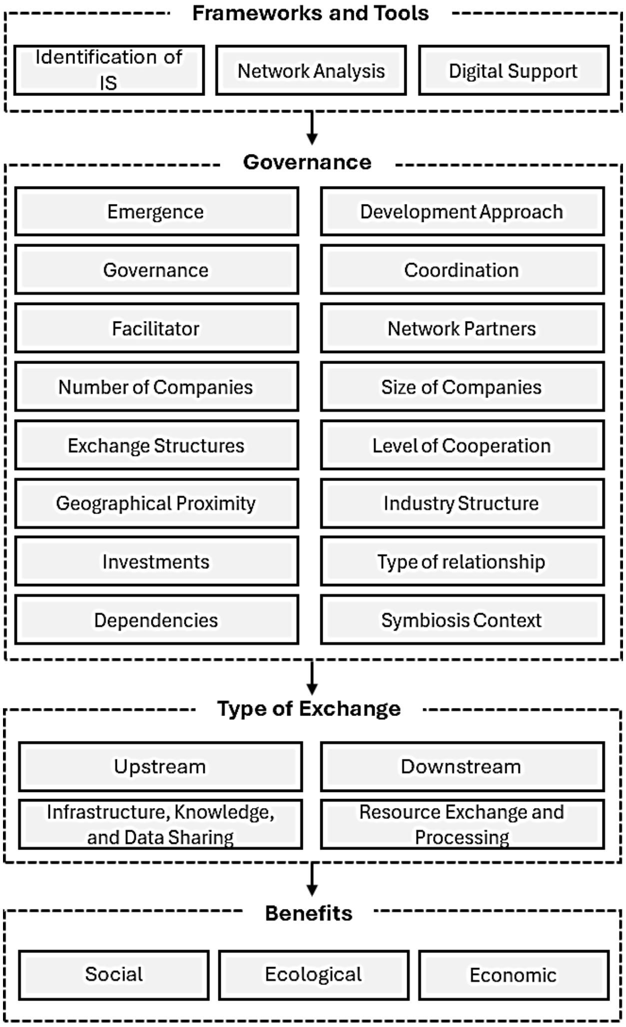

Figure 2 – Taxonomy framework for industrial symbiosis

From the structure and governance of the network to resource exchanges to its broader social, ecological, and economic impacts, each cluster contributes to a deeper understanding of how industrial symbiosis functions. Key methods such as network analysis and digital tools are essential in identifying, managing, and optimizing these symbiotic relationships. These insights offer a holistic view of industrial symbiosis, highlighting both its potential and the complexities involved in its implementation.

5 Discussion

The presented work addresses the significant gap in the literature regarding the lack of a universal classification framework for IS, particularly within the manufacturing sector. By providing the classification, this study helps to overcome some of the existing challenges of IS and facilitate its more widespread adoption. The developed taxonomy offers significant implications for researchers, practitioners, and policymakers while presenting particular challenges.

A key benefit of the structured approach is that it enables practitioners and research to understand better and analyze existing synergies and defined networks, which helps define new ones. It shows the different influencing factors, such as regional, technological, and organizational.

Besides the improved analyses, the absence of such a categorization framework has been limiting the identification of best practices and, for example, the replication of successful implementations across industries. This "relationship mimicking" mechanism enables organizations to replicate successful symbioses observed in similar contexts. Combined with digital tools and an established database, it could play a crucial role in streamlining the identification of IS partners and fostering collaboration.

IS presents a promising pathway to mitigate environmental impacts and contribute to the green transition of the economy. Therefore, it is highly relevant to policymakers. The proposed taxonomy can help create targeted incentives and regulations that align to support and facilitate the identification of IS. Improving understanding of IS enables more effective policy interventions to promote company collaboration.

However, several limitations must be acknowledged. The complexity and context-specific nature of IS synergies makes it challenging to develop a universal classification that is comprehensive both in detail and among all industries. This taxonomy serves as a general overview and network understanding. For a more in-depth analysis, each category must be examined further, such as the EWC for waste classification.

Moreover, while the taxonomy provides a helpful tool for understanding IS, it is not a direct means of identifying symbiotic opportunities. However, it helps to indirectly identify and replicate successful synergies observed in similar contexts. Furthermore, the taxonomy does not claim to be collectively exhaustive in specific categories, as additional ideas and dimensions may not be fully explored. The taxonomy has been developed based on existing literature and enriched by expert input. For example, social implications are currently underrepresented in literature; therefore, further research is needed in this area to capture all potential benefits. The other category has been added to allow for flexibility and the inclusion of other possibilities.

A limitation of the proposed framework is the lack of industrial validation. While it was developed with input from industry and the literature was mainly based on case studies, a final validation is needed. Further, its application in other industries should be reviewed to ensure its applicability beyond manufacturing.

By addressing these limitations, the taxonomy presented in this study can serve as a foundation for further advancements in industrial symbiosis and sustainable industrial practices.

6 Conclusions

This study proposes a structured taxonomy comprising 4 primary categories, further divided into 26 secondary categories and 119 tertiary classifications, to enable a more comprehensive analysis of industrial symbiosis focusing on the manufacturing sector.

First, a literature review was conducted to provide an overview of existing classification frameworks. It shows the research gap regarding a general taxonomy for the manufacturing sector. Based on the literature and the identified studies, the information is analyzed and synthesized, which results in the proposed framework.

After the development, various feedback rounds with industry and research experts were conducted, and the framework was adapted and validated. The final taxonomy helps to categorize and better understand the diverse synergies within industrial ecosystems.

The development taxonomy hereby offers advantages but also has certain limitations that can be subject to further research. Firstly, the taxonomy should be tested and validated with various case studies. Through tests within focus on different industries, the framework and its applicability can be expanded.

It could be of interest to further explore the development of a database based on the proposed classification which would facilitate can facilitate the identification and expansion of new symbiotic opportunities.

In conclusion, while this study provides a foundation for a general understanding and categorizing IS practices, various topics for further research remain due to the inherent complexity of IS systems. By addressing these gaps, the proposed taxonomy has the potential to play a pivotal role in facilitating IS and promoting sustainable industrial practices on a larger scale.

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However, the views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union.

References

1. Álvarez, R., Ruiz-Puente, C. (2017). Development of the tool symbiosys to support the transition towards a circular economy based on industrial symbiosis strategies. *Waste and Biomass Valorization*, Vol. 8(5), pp. 1521–1530. https://doi.org/10.1007/s12649-016-9748-1
2. Chertow, M.R. (2000). Industrial symbiosis: Literature and taxonomy. *Annual Review of Energy and the Environment*, Vol. 25, pp. 313–337. https://doi.org/10.1146/annurev.energy.25.1.313
3. Doménech, T., Bleischwitz, R., Doranova, A., Panayotopoulos, D., Roman, L. (2019). Mapping industrial symbiosis development in Europe_ typologies of networks, characteristics, performance and contribution to the circular economy. *Resources, Conservation and Recycling*, Vol. 141, pp. 76–98. https://doi.org/10.1016/j.resconrec.2018.09.016
4. Momirski, L.A. (2019). Industrial symbiosis and land use. *IOP Conference Series: Materials Science and Engineering*, Vol. 471(11), 112089. https://dx.doi.org/10.1088/1757-899X/471/11/112089
5. Frosch, R.A., Gallopoulos, N.E. (1989). Strategies for manufacturing. *Scientific American*, Vol. 261(3), pp. 144–153.
6. Lombardi, D.R., Laybourn, P. (2012). Redefining industrial symbiosis. *Journal of Industrial Ecology*, Vol. 16, pp. 28–37. https://doi.org/10.1111/j.1530-9290.2011.00444.x
7. Benedetti, M., Holgado, M., Evans, S. (2017). A novel knowledge repository to support industrial symbiosis. *IFIP Advances in Information and Communication Technology*, Vol. 514, pp. 443–451. https://doi.org/10.1007/978-3-319-66926-7_51
8. Albino, V., Garavelli, A.C., Romano, V.A. (2013). A classification of industrial symbiosis networks: A focus on materials and energy recovery. *IFIP Advances in Information and Communication Technology*, Vol. 397(1), pp. 216–223. https://doi.org/10.1007/978-3-642-40352-1_28
9. Chertow, M.R. (2007). “Uncovering” industrial symbiosis. *Journal of Industrial Ecology*, Vol. 11, pp. 11–30. https://doi.org/10.1162/jiec.2007.1110
10. Golev, A., Corder, G.D. (2012). Developing a classification system for regional resource synergies. *Minerals Engineering*, Vol. 29, pp. 58–64. https://doi.org/10.1016/j.mineng.2011.10.018
11. Zhang, Y., Zheng, H., Chen, B., Su, M., Liu, G. (2015). A review of industrial symbiosis research: theory and methodology. *Frontiers of Earth Science*, Vol. 9(1), pp. 91–104. https://doi.org/10.1007/s11707-014-0445-8
12. Jacobsen, N.B. (2006). Industrial symbiosis in Kalundborg, Denmark: A quantitative assessment of economic and environmental aspects. *Journal of Industrial Ecology*, Vol. 10, pp. 239–255. https://doi.org/10.1162/108819806775545411
13. Paquin, R.L., Howard-Grenville, J. (2012). The evolution of facilitated industrial symbiosis. *Journal of Industrial Ecology*, Vol. 16, pp. 83–93. https://doi.org/10.1111/j.1530-9290.2011.00437.x
14. Aid, G., Eklund, M., Anderberg, S., Baas, L. (2017). Expanding roles for the Swedish waste management sector in inter-organizational resource management. *Resources, Conservation and Recycling*, Vol. 124, pp. 85–97. https://doi.org/10.1016/j.resconrec.2017.04.007
15. Mirata, M. (2004). Experiences from early stages of a national industrial symbiosis programme in the UK: Determinants and coordination challenges. *Journal of Cleaner production*, Vol. 12(8–10), pp. 967–983. https://doi.org/10.1016/j.jclepro.2004.02.031
16. Albino, V., Dangelico, R. M., Pontrandolfo, P. (2012). Do inter-organizational collaborations enhance a firm’s environmental performance? A study of the largest U.S. companies. *Journal of Cleaner Production*, Vol. 37, pp 304–315. https://doi.org/10.1016/j.jclepro.2012.07.033
17. Fraccascia, L., Giannoccaro, I., Albino, V. (2019). Business models for industrial symbiosis: A taxonomy focused on the form of governance. *Resources, Conservation and Recycling*, Vol. 146, pp. 114–126. https://doi.org/10.1016/j.resconrec.2019.03.016
18. Hoffman, A.J. (2003). Linking social systems analysis to the industrial ecology framework. *Organization & Environment*, Vol. 16(1), pp. 66–86. https://doi.org/10.1177/1086026602250219
19. Angelis-Dimakis, A., Arampatzis, G., Alexopoulos, A., Vyrkou, A., Pantazopoulos, A., Angelis, V. (2023). Industrial symbiosis in the balkan-mediterranean region: The case of solid waste. *Environments*, Vol. 10(1), 1. https://doi.org/10.3390/environments10010001
20. Van Beers, D., Flammini, A., Meylan, F.D., Stucki, J. (2019). Lessons learned from the application of the UNIDO eco-industrial park toolbox in Viet Nam and other countries. *Sustainability*, Vol. 11(17), 4687. https://doi.org/10.3390/su11174687
21. Fraccascia, L., Giannoccaro, I. (2020). What, where, and how measuring industrial symbiosis: A reasoned taxonomy of relevant indicators. *Resources, Conservation and Recycling*, Vol. 157, 104799. https://doi.org/10.1016/j.resconrec.2020.104799

22. Chen, X., Dong, M., Zhang, L., Luan, X., Cui, X., Cui, Z. (2022). Comprehensive evaluation of environmental and economic benefits of industrial symbiosis in industrial parks. *Journal of Cleaner Production*, Vol. 354, 131635. https://doi.org/10.1016/j.jclepro.2022.131635
23. Scafà, M., Marconi, M., Germani, M. (2018). A critical review of industrial symbiosis models. *Advances in Transdisciplinary Engineering*, Vol. 7, pp.1184–1193. https://doi.org/10.3233/978-1-61499-898-3-1184
24. Lambert, A.J.D., Boons, F.A. (2002). Eco-industrial parks: Stimulating sustainable development in mixed industrial parks. *Technovation*, Vol. 22(8), pp. 471–484. https://doi.org/10.1016/S0166-4972(01)00040-2
25. Liwarska-Bizukojc, E., Bizukojc, M. (2018). Overview of european eco-industrial parks: Evaluation of industrial symbiosis potential. *Environmental Engineering and Management Journal*, Vol. 17(2), pp. 477–490. https://doi.org/10.30638/eemj.2018.049
26. Mendez-Alva, F., Cervo, H., Krese, G., Van Eetvelde, G. (2021) Industrial symbiosis profiles in energy-intensive industries: Sectoral insights from open databases. *Journal of Cleaner Production*, Vol. 314, 128031. https://doi.org/10.1016/j.jclepro.2021.128031
27. Fichtner, W., Tietze-Stöckinger, I., Rentz, O. (2004). On industrial symbiosis networks and their classification. *Progress in Industrial Ecology*, Vol. 1(1–3), pp. 130–142. https://doi.org/10.1504/pie.2004.004675
28. Albino, V., Fraccascia, L. (2015). The industrial symbiosis approach: A classification of business models. *Procedia Environmental Science, Engineering and Management*, Vol. 2(3), pp. 217–223.
29. Boons, F., Chertow, M., Park, J., Spekkink, W., Shi H. (2017). Industrial symbiosis dynamics and the problem of equivalence: proposal for a comparative framework. *Journal of Industrial Ecology*, Vol. 21(4), pp. 938–952. https://doi.org/10.1111/jiec.12468
30. Raafat, T., Trokanas, N., Cecelja, F., Kokossis, A., Yang, A. (2012). Semantically-enabled formalisation to support and automate the application of industrial symbiosis. *Computer Aided Chemical Engineering*, Vol. 31, pp. 1055–1059. https://doi.org/10.1016/B978-0-444-59506-5.50042-0
31. Bijon, N., Wassenaar, T., Junqua, G., Dechesne, M. (2022). Towards a sustainable bioeconomy through industrial symbiosis: current situation and perspectives. *Sustainability*, Vol. 14(3), 1605. https://doi.org/10.3390/su14031605
32. Barile, S., Bassano, C., D'Amore, R., Piciocchi, P., Saviano, M., Vito, P. (2021). Insights of digital transformation processes in industrial symbiosis from the viable systems approach (vSa). *Sustainability*, Vol. 13(17), 9696. https://doi.org/10.3390/su13179696
33. Moser, S., Rodin, V. (2021). The 'Industrial Symbiosis Gap': Information asymmetries are the main challenge for industrial symbiosis – evidence from four Austrian testbeds with a focus on heat exchange. *Elektrotechnik und Informationstechnik*, Vol. 138(4–5), pp. 264–268. https://doi.org/10.1007/s00502-021-00897-y
34. Eurostat (2016). Glossary:Enterprise size – Statistics Explained. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Enterprise_size
35. Raafat, T., Trokanas, N., Cecelja, F., Bimi, X. (2013). An ontological approach towards enabling processing technologies participation in industrial symbiosis. *Computers and Chemical Engineering*, Vol. 59, pp. 33–46. https://doi.org/10.1016/j.compchemeng.2013.03.022
36. Dallasega, P., Rauch, E. (2017). Sustainable construction supply chains through synchronized production planning and control in engineer-to-order enterprises. *Sustainability*, Vol. 9, pp. 1888–1913. https://doi.org/10.3390/su9101888
37. Despeisse, M., Acerbi, F. (2022). Toward eco-efficient and circular industrial systems: ten years of advances in production management systems and a thematic framework. *Manufacturing Research*, Vol. 10(1), pp. 354–382. https://doi.org/10.1080/21693277.2022.2088634
38. Matt, D.T., Dallasega, P., Rauch, E. (2014). Synchronization of the manufacturing process and on-site installation in ETO companies. *Procedia CIRP*, Vol. 17, pp. 457–462. https://doi.org/10.1016/j.procir.2014.01.058
39. Elkington, J. (2004). Enter the triple bottom line. In: *The Triple Bottom Line*, pp. 1–16, Routledge, Taylor & Francis Group, Thames, Oxfordshire, UK. https://doi.org/10.4324/9781849773348