Environmental Technology & Innovation 37 (2025) 104026

Contents lists available at ScienceDirect

Environmental Technology & Innovation

journal homepage: www.elsevier.com/locate/eti

Industrial symbiosis networks supporting circularity: Understanding complexity, cyclicality and resilience

Urška Fric [a,b,*], Zoran Levnajić [a], Dolores Modic [b,c], Borut Rončević [a,b]

[a] Faculty of Information Studies in Novo mesto, Slovenia
[b] Rudolfovo – Science and Technology Centre Novo mesto, Slovenia
[c] Nord University Business School, Nord University, Norway

A R T I C L E I N F O

Keywords:
Circular economy
Industrial symbiosis networks
Typology
Complexity
Cyclicality
Resilience

A B S T R A C T

The aim of this study is to provide a more nuanced understanding of the industrial symbiosis networks supporting the circular economy. We do so through an evolutionary dynamics lens, viewing these networks as adaptive complex systems. This approach allows us to address the limited research attention that has resulted in insufficient understanding of the underlying networks in the circular economy literature, particularly regarding collaboration for waste resource exchange. i.e. the circular economy closing of the resource loops. This paper draws on empirically obtained data from industrial symbiosis networks in five countries: Croatia, Slovenia, Austria, Denmark and Finland. Through network analysis, we find that the structure of these symbiosis networks has evolved to varying extents. This evolution takes into account the complexity of leveraging opportunities based on waste resource exchange, cyclicality with numerous feedback loops, and resilience against disruptions and failures. Based on these findings, we propose three types of symbiosis networks that support circularity: mature, evolving, and emerging. Concurrently, we further develop conceptual and empirical diagnostic tools for future research by showcasing the utility of newly developed measures. Additionally, we outline several practical implications for both system-level, and organization-level managers.

1. Introduction

Circular economy (CE) represents a reaction to the pressures that a developing economy and the increasing consumption pose on the limited resources and environmental capacity (Ellen MacArthur Foundation and McKinsey, 2015; European Commission, 2020). CE thus proposes an alternative model – systemic, restorative and regenerative by design – aimed at keeping materials and products in use and entailing all levels, including the mezzo level (Kirchherr et al., 2017; Stahel, 2016). There are several strategies to reach circularity goals, i.e., closing, narrowing, slowing, and regenerating (Bocken et al., 2016; Konietzko et al., 2020). We focus in this paper on the CE's closing strategy and connected with it, industrial symbiosis (IS), emphasising the networks of independent organisations that exchange resources (Chertow, 2000, 2004, 2007; Deutz, 2014; Neves et al., 2020), which is in the CE literature connected to the mezzo-level (Gonzalez-Moreno et al., 2024).

CE's core principle is one of designing out waste whilst having a wide understanding of the concept of waste (Esposito et al., 2018),

* Corresponding author at: Faculty of Information Studies in Novo mesto, Slovenia.
E-mail addresses: urska.fric@fis.unm.si (U. Fric), zoran.levnajic@fis.unm.si (Z. Levnajić), dolores.modic@nord.no (D. Modic), borut.roncevic@rudolfovo.eu (B. Rončević).

https://doi.org/10.1016/j.eti.2025.104026
Received 31 May 2024; Received in revised form 3 January 2025; Accepted 9 January 2025
Available online 10 January 2025

a strong emphasis on closing the loops (Bocken et al., 2016) and eliminating residuals within the systems. IS supports this (Domenech et al., 2019; Wen and Meng, 2015), since it represents an important business process for transforming waste into a source in terms of circular economy (Baldassarre et al., 2019). Concurrent derivation of ecological, economic, and social benefits through the reuse of secondary raw materials has thus established industrial symbiosis and its resulting formation of industrial symbiosis networks as an extremely important mechanism to contribute to circular economy goals (Džajić Uršič 2020).

The CE literature has pointed out collaboration as one of the key enabling elements (beside innovation) of CE implementation and development (Sudusinghe and Seuring, 2022; Berardi and de Brito, 2021, Jakobsen et al., 2021). But in terms of closed loop networks, the focus has been more on selected issues such as closing the loops locally (Christensen et al., 2022; Vanhamäki et al., 2020; Bassi et al., 2021). Less attention has been given to the type and maturity of these loops from a systems perspective, such as involving diverse resources and incorporating redundancies to withstand shocks from node disappearances, thereby strengthening network resilience. On the other hand, the IS literature focuses mainly on the emergence – either spontaneous or ad-hoc – of IS networks, measuring their performance or on its impact (Kumar Behera et al., 2012; Boons et al., 2011; Wen and Meng, 2015). Another stream in IS literature is related to individual elements such as resilience (Chopra and Khanna, 2014; Baldassarre et al., 2019), but less focus is given to understanding the composition of elements within developing IS systems.

We conceptualise IS as complex adaptive systems, where the actors and their relationships are constituted in diverse constellations that are also adaptive to changes that emanate from internal (or external) conditions (Holling, 2001; Ashton, 2009). Thus, we focus on the issues of IS development, i.e. their maturity. Interestingly, that albeit IS has looked into development of IS networks (Korhonen and Snäkin, 2005) and has also been seen as business model-oriented (Baldassarre et al., 2019), still issues that would look into more complex understanding of business opportunities being harnessed – such as both providing resources (byproducts, etc.) to others and taking them in, i.e. looking both at circular inputs as well as opportunities arising from own wastages and by-products – remained unexplored.

In contrast to the above, this paper focuses in particular on the evolutionary dynamics of industrial symbiosis (IS) networks, i.e. their **maturity**, simultaneously spotlighting the varying engagement of actors within the IS (their **complexity**), the feedback loops (their **cyclicality**) as well as showcasing the potential vulnerability of CE loops' **resilience** through observing redundancies in the IS networks. We do so by engaging in a network analysis, which is an established method for studying IS (Neves et al., 2020).

Our contributions are thus threefold. Based on an original dataset of five industrial symbiosis networks, where our selection of the cases included the diversity of cases – both related to the industry parks and not as most evidence is based on studying industry parks networks (Atanasovska et al., 2022; Gonzalez-Moreno et al., 2024) – we are able to address selected issues permeating the circular economy literature in terms of collaboration for waste resource exchange (i.e., exchange of waste material, water, and energy). We showcase how IS can also inform the newer literature stream related to collaboration for CE, and vice-versa. Next, using the network analysis we are then able to propose a taxonomy of industrial symbiosis networks supporting circularity, i.e. emerging, evolving and mature, including specific network characteristics for each type in terms of complexity, cyclicality and resilience. Therewith we contribute to a challenge present across many fields of categorising the objects of interest into taxonomies (mostly empirically derived, such as ours) and typologies (derived purely conceptually) (Bailey, 1994; Sokal, 1966). At the same time, we develop both conceptualization and empirical diagnostic tools to support future research and policymaking.

The idea of a closed loop economy has been prevalent at least since the late 1960s with the work of Boulding (1966) and furthered by works such as the seminar work Jobs for tomorrow: the potential for substituting manpower for energy (Stahel and Reday-Mulvey, 1981). Stahel (1984) then extended the idea in relation to a self-replenishing economy, based on a loop system that results in the circulation of materials through sequential product-life extension activities, which he subsequently connected also to the ideas of circular economy. "A 'circular economy'," he writes in his seminar article on CE in Nature, "would turn goods that are at the end of their service life into resources for others, closing loops in industrial ecosystems and minimising waste" (Stahel, 2016: 435).

But the conceptual clarity of circular economy is still debated (Kirchherr et al., 2017, 2023; Corvellec et al., 2022; Lavtizar et al., 2023). That notwithstanding, the recent analysis focusing on delineating the concept (Kirchherr et al., 2023), Points out an additional element of the concept – typically seen as focused on a regenerative system, using R strategies to promote value retention and aiming at sustainable development (Kirchherr et al., 2017) – CE being enabled by a collaboration between various actors (Kirchherr et al., 2023), which puts focus also on industrial symbiosis networks as enablers of circularity.

A strong policy push towards CE (Tura et al., 2019; Hina et al., 2022) is present, with the recognition that waste is a source of value for business (Perey et al., 2018) rising, and several CE strategies, i.e. CE Rs, pointed out such as reuse, remanufacture, and recycling of materials (Reike et al., 2018; Uvarova et al., 2023). The activities supporting individual Rs were often seen as incremental and fragmented, and not holistic. Subsequently albeit innovating the related circular business models (Urbinati et al., 2017; Geissdoerfer et al., 2018; Lüdeke-Freund et al., 2018), these are criticized as not sufficiently transformative (Lavtizar et al., 2023). This is also related to firms still struggling to view CE as a revenue-making paradigm (Cristoni and Tonelli, 2018) leading to both the uptake and general levels of circular economy activities remaining overall low (The Circularity Gap Report, 2024). There were several potential reasons identified thereof, with some of them derived from the fact that companies not only need to be adopting internal CE strategies to advance circularity, but also that they are required to connect and collaborate with other stakeholders as well (Barros et al., 2021).

Collaboration in the value chains and value networks (Ricciotti, 2020), spontaneous or designed, is a key factor for CE development (Köhler et al., 2022; Sudusinghe and Seuring, 2022; Berardi and de Brito, 2021; Genovese et al., 2017). Transitioning from linear to circular production systems requires a wide collaborative effort with distinct stakeholders engaging in both resource exchange and other circular economy activities, including cross-sectoral collaboration in networks (Köhler et al., 2022). This collaboration is often plagued with coordination and orchestration issues, since CE requires simultaneous and coordinated action from multiple actors (Aspelund et al., 2021) in smaller or larger geographical proximity.

The literature mentions a wide range of diverse actors but often points out also the role of waste companies and recycling facilities (Bartolacci et al., 2017; Salmenperä et al., 2021). These two types of stakeholders support seeing circular economy as a strategic focus, which entails the reframing and re-organising of material (as well as information and energy) flows to achieve greater resource efficiency (Puntillo et al., 2021). The latter can also support the opportunities related to industry convergence, defined by Bröring et al. (2006): 488) as "the blurring of boundaries between formerly distinct industries due to converging value propositions, technologies, and markets". In particular, these cross-sectoral collaborations, which strengthen the circularity, can support inter-industry convergence (Schmenner, 2009), whilst these can be driven by environmental policies and a drive to achieve environmental sustainability, i.e. resulting in so-called policy-driven environmental enhancer industry convergence (Geum et al., 2016).

The circular literature in particular focuses on the benefits of closing the loops locally, using examples as diverse as the construction industry (Christensen et al., 2022) and the cork industry (Parejo-Moruno et al., 2024-forthcoming). The latter case, for example, showcases how new flows were created between actors once the industry was able to close the loops in-region. Establishing local networks that enable collaboration in the value chains is often seen as essential (Christensen et al., 2022; Besednjak Valič et al., 2022, 2023). The required shift in design planning, perception and activities related to the CE takes time to implement and the results are incremental; however, to promote this, closed loops can be harnessed using an IS approach, thus extending the lifetime of waste resources for as long as possible (Barrau et al., 2024).

Turning now to the IS literature, which showcases a particular type of collaborative efforts in terms of waste resources, similar to the CE literature. Industrial symbiosis, in essence, represents a flow of untapped resources, starting with stakeholders who would otherwise have discarded the unused resources and ending with stakeholders who can use these resources as substitutes or primary resources (Deutz, 2014). In a strict sense, industrial symbiosis (IS) is a collaborative approach among firms involving physical exchanges of materials, energy, and wastes, which creates economic advantages for firms and environmental benefits for society – representing synergies between the stakeholders (Fraccascia et al., 2021). To distinguish IS from general "resource exchange," the criteria for IS proposed by Chertow (2007) are to incorporate a minimum of three different organisational entities and a minimum of two different resources. Hence, the IS literature was somewhat more concerned with the topologies of the networks in question.

Although there is a recognition of the need for the constant evolution of networks (Berardi and de Brito, 2021), the CE literature has focused less on issues related to the type and maturity of related loops. This lack of focus is evident when considering actors through the lenses of a systemic view. CE opportunities remain far from fully exploited (Circularity Gap Report, 2024), particularly in IS as adaptive complex systems (Ashton, 2009). Addressing the evolution of IS networks supporting circularity is therefore of key importance.

The topologies as related to evolution of the networks, i.e. what we understand as **maturity,** can examine issues such as more systemic thinking in terms of both providing resources to others and taking them in (what we term as complexity); seeing how many of these networks are really closed, i.e. cyclical (what we term as cyclicality); as well as incorporating redundancies that can withstand shocks of a node disappearance, i.e. strengthening the resilience of these networks. This is particularly important since most industrial symbiosis networks are spontaneous and not strategically planned (Chopra and Khanna, 2014) in spite of a very significant policy focus on CE (Džajič Ursic et al., 2024).

In IS networks for circularity, as complex adaptive systems, agents are able to autonomously interact with each other to increase their performance (Goldstein, 1999). The limitations could come from the interests and planning of the central organisational entity if existing inside the IS. The latter is especially true for those IS that are spatially bound to an industry park. Nonetheless, the **complexity** of the IS interactions are especially dependent on the internal strategies related to CE Rs (Reike et al., 2018) and diverse circular business models (CBM) applied (Urbinati et al., 2017; Geissdoerfer et al., 2018; Lüdeke-Freund et al., 2018). In this sense, the IS can consist of several companies that pursue only CBMs geared towards certain opportunities, e.g. solely circular inputs, but not simultaneously enhancing other business model opportunities related, e.g., to end-of-life or similar. However as within the IS there is not only flow of material resources, but also the knowledge flows, having more firms that simultaneously focus both on providing the inputs to others and understanding how resources of waste materials of others can be harnessed, leads to diverse industrial networks truly promoting the effect of resource utilisation (Ormazabal et al., 2018). This results most likely also having some spillover effects with other IS network members in term of the knowledge of the CE potentials and in regard to how to engage in harnessing them.

The focus of the CE is not only on dyad relationships and paths leading from one actor to another, but also in general closed loops (consisting of triads or more) appearing within networks (Stahel, 2016). Hand in hand with this, network science literature has been interested in methods for finding short loops (cycles) in empirical networks. These can both address the incompleteness of short parts, increase information spreading and sharing, provide robust information within these closed loops (Sorkhoh et al., 2012) as well as introduce an 'ignored' property: the feedback (Zhou et al., 2018). Hence, we focus in this work on the evolution of more complex constellations inside the networks than linear pathways (relationships), i.e., on what we call **cyclicality**. This property provides insights on the potential of information sharing on new opportunities within networks of actors that are connected through resource sharing and are thus potentially still socially proximate to one another. The latter implies an increased presence of trust or easier trust building; since the size of the loop denotes that spread of information, e.g. on new circular business model potentials, or higher waste valorization potentials, can be wider. Furthermore, the existence of more loops with more numerous members, has also been connected to stronger robustness (Sorkhoh et al., 2012), albeit we posit in this paper that robustness is more connected to redundancies.

Furthermore, **resilience** represents the ability of adaptive systems, such as IS, to respond to disruptions by re-establishing a stable state (Holling, 1973), whereas the system can bounce back to the same original state or evolve to a new stable state (Annarelli and Nonino, 2016). This also somewhat widens the ideas related to the robustness of networks (Christopher and Peck, 2004; Zeballos, et al., 2012). The topic of CE and resilience has however been relatively scarce and focused more on organisational level (Bag et al., 2019), especially in connection to reducing reliance on virgin input materials (Baars et al., 2021). But on a network level Fraccascia et al. (2020) provided indications (based on an agent-based modeling), that a high redundancy could increase the overall resilience of the network. However, Fraccascia et al. (2020) focus more on the individual strategy (i.e. exchange with several partners) than on the overall IS resilience. We believe this to be an oversight, as redundancies need to be studied on the whole network level, since the match between supply and demand quantities of byproducts and waste are not easily controllable, as they are not produced upon demand but emerge as secondary outputs of main production activities (Yazan et al., 2016). A disturbance in the system can have a domino effect on the whole IS supporting circularity (Chopra and Khanna, 2014). We focus on the disappearance of an actor inside IS networks supporting circularity, the disappearance of an actor, especially if central, can be quite detrimental to the continuing valorization of waste and byproducts.

2. Materials and methods

2.1. Dataset construction and research setting

During the data collection phase, we assembled secondary and primary data. Secondary data was gathered from relevant international collections, studies and research and included information on the geographical extent of industrial symbiosis manifestations. The scientific journals, studies and research have been searched using keywords. The authors have combined keywords using Boolean operators, quotation marks, order, and search strings in various combinations. The secondary sources (original and review papers) have been evaluated using the Currency, Relevance, Authority, Accuracy, and Purpose (CRAAP) method.

Afterwards, primary data was obtained in real-life environments on four geographical levels (Domenech, 2010; Onita, 2006; Chertow, 2007) – local, regional, national and international – which were defined according to the presence of symbiosis networks. Data collection was done using semi-structured interviews (Saunders et al., 2009) either live or through video conference calls between April and August 2017. Network architecture, structural-analytical characteristics of the networks, and social network analysis refer to this period. The semi-structured interview proved to be suitable mainly due to the combination of open and closed questions, the interviewees' answers, which can be narrative or short, and its usefulness for the case studies included in our research. Semi-structured interviews were conducted with relevant interviewees in the selected organisation, namely interviewees who worked as managers in the field of environmental protection, ecology or waste management and interviewees who worked in the management of the organisation.

Additionally, we gathered information through email, where we utilised the snowball effect (Doreian and Woodard, 1994) to receive the contact information of relevant university researchers who helped identify industrial symbiosis networks in their countries.

Before starting the data collection, four minimum conditions were defined and pursued during the data collection phase, using a snowball effect (Doreian and Woodard, 1994: 279–280):

1. We included at least one 'facilitator' or coordinator of each industrial symbiosis network.
2. We determined that the relevant nodes were those between which multiple links or multiple collaborations take place – by fulfilling this condition, we avoided nodes that would randomly become nodes in an industrial symbiosis network with the intention of collaborating once.
3. By observing the first condition of multiple collaboration, we have treated all nodes equally according to their size, which applies to micro, small, medium and large organisations.
4. Considering the second condition on the size of the stakeholder, we minimally included at least one stakeholder from the existing four sizes.

The first phase of data collection involved identifying utility companies that are authorised for waste material handling in different EU states, focusing on companies that act as a link between stakeholders depositing waste and those demanding waste. We were looking for and selecting utilities acting as points-of-contact between providers and demanders of waste mainly because these companies possessed the largest collection of information on waste material flows in their country. The questionnaires were divided into two parts. In the first part, we asked participating organisations about their demographic data, whereas the second set of questions contained information on the implementation of industrial symbiosis in their organisation (Table 1).

Twenty-five semi-structured interviews were conducted live, and two were conducted through video conference calls with organisations acting as nodes in the same network. Data on industrial symbiosis networks in Austria and Finland was also gathered through email, where we utilised the snowball effect (Doreian and Woodard, 1994) to receive contact information of relevant university researchers who helped identify industrial symbiosis networks in their countries. As seen from Table 1 above, we gathered the data on

Table 1
Data collection.

Case no.	Country	Primary data collection method(s)	Respondents
1	Croatia	9 semi-structured interviews	Utility company Companies
2	Slovenia	15 semi-structured interviews	Utility company Companies
3	Austria	2 semi-structured interviews	Utility company Companies
4	Denmark	2 questionnaires via email correspondence	Facilitator organisation
5	Finland	1 semi-structured interview 3 questionnaires via email correspondence	Utility company Companies

five networks corresponding to networks in five distinct countries. The network representing case 1 and 2 operates at international level (the network includes one node outside the country's borders), while the network representing case 3, 4 and 5 operates at national level.

3. Methods

Social networks offer insights into complex social systems phenomena in which many individuals or entities collaborate towards a common goal (De Nooy et al., 2011; Estrada, 2012; Barabási, 2016; Zweig, 2016; Newman, 2018; Menczer et al., 2020; Coscia, 2021). Researchers in this field rely on diverse methodologies ranging from mathematics and statistics to computer science and even physics (Doreian and Woodard, 1994; Pržulj, 2007; Levnajicć and Pikovsky, 2011; Yaveroğlu et al., 2014; Barabási, 2016). Being a strongly interdisciplinary endeavour, social networks are also used to model and understand phenomena in economics and sustainability, in terms of both theoretical models and empirical insights (Easley and Kleinberg, 2010; Albizua et al., 2021). Specifically, social networks can be used to study goal-oriented collaborations that require sharing knowledge and/or resources (Easley and Kleinberg, 2010; Modic et al., 2023). Such collaborations are the foundation for circular economy and industrial symbiosis, where the framework of social networks is already in use (Wang et al., 2017; Song et al., 2018; Albizua et al., 2021; Vranić et al., 2023).

Our industrial symbiosis networks represent companies (or other organisations) as nodes. Modeling the exchange of waste resources among them is captured by directed links connecting these nodes. A link pointing from one stakeholder (node) towards another stakeholder pictures the empirical fact that the first stakeholder is exporting one (or more) waste resources to the second stakeholder. These are the networks (graphs) we are interested in here. As we show in what follows, their structures can be classified as either linear or circular, which is indicative of linear and circular economy, respectively.

In the analysis we label the networks via countries they belong to. Each network includes only some (and not all) companies from the country it is labelled by. Some networks include companies from more than one country (case 1 and 2). Starting with companies in a selected country, in some cases leads to including one or more companies from the neighbouring countries since they exchange materials. In such cases, networks were labelled by the country where the majority of companies are located.

We arranged the data and analysed it using PAJEK software (De Nooy et al., 2011). The analysis provided us with design-structural parameters and performance characteristics of the industrial symbiosis networks. We began by computing basic network measures such as number of nodes, number of links (edges), in-degree, out-degree, link density, statistics of (directed) shortest paths, and diameter. These measures are very common in network analysis and are easy to interpret, also in the case of directed networks (Estrada, 2012; Barabási, 2016; Zweig, 2016; Newman, 2018; Menczer et al., 2020; Coscia, 2021). The latter constituted the basic starting point for further analysis.

Next we constructed a measure we called *node flow*. To define it, we first note that each node can be characterised by its in-degree and out-degree (Menczer et al., 2020; Coscia, 2021). The former denotes the number of links pointing towards a node (i.e., the number of different waste resources imported by a company from the neighbouring companies). The latter stays for the number of links pointing away from a node (i.e., the number of waste resources exported by a company to the neighbouring companies). So, for any given node i, we call node flow the product of its in-degree and out-degree, and denote it as node flow (i). It measures how much waste resources 'flows' through the node i. For instance, a node corresponding to a stakeholder that imports no waste material will have node flow equal to zero, regardless of how much waste resources it exports. Node flow equal to one means that this node imports and exports exactly one waste resource. This is readily expressed by the formula:

$$\text{node flow (i)} = \text{in-degree (i)} \times \text{out-degree (i)}$$

where in-degree (i) and out-degree (i), respectively, denote in-degree and out-degree of the node i. This network measure has a clear and simple interpretation suited for our analysis. It can also be understood in the context of centrality measures, which are routinely used to quantify a node's centrality is a way adequate for any specific analytical task (Estrada, 2012; Zweig, 2016; Newman, 2018; Coscia, 2021).

Moreover, we designed another set of network measures tailored to our aims that are inspired by the literature on graphlets (Pržulj, 2007; Yaveroğlu et al., 2014; Sarajlić et al., 2016). Namely, counting the presence of small subgraphs with few nodes (often called graphlets or motifs) in the studied network is a novel and important avenue in network analysis. Rather than considering the full set of small, connected, non-isomorphic, induced subgraphs (Pržulj, 2007; Yaveroğlu et al., 2014; Sarajlić et al., 2016), we focus only on several such subgraphs, whose count statistics lends itself into interpretable measure for our analysis purposes. Note that in contrast to the usual studies, our graphlets (small subgraphs) are directed (Sarajlić et al., 2016).

There are two groups of such subgraphs, the first of which we call *cyclical subgraphs*. Their presence in a symbiosis network indicates

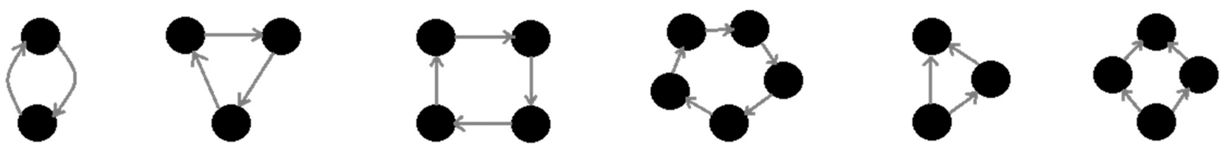

Fig. 1. Pictorial illustrations of cyclical subgraphs and redundancy graphlets used in our analysis of symbiosis networks. From left to right: 2-cycle, 3-cycle, 4-cycle, 5-cycle, single redundancy graphlet, and double redundancy graphlet.

cyclicality in its structure. For example, mutual bi-directional interaction between two nodes is captured by the presence of (one or more) 2-cycle subgraph(s) in a given network. By the same token, a cyclical flow involving three nodes (flow goes from node 1 to node 2, from node 2 to node 3, and then back from node 3 to node 1) is represented by a 3-cycle subgraph. If the structure of some network contains several such subgraphs, this suggests that cyclicality of this sort is pronounced in that network. Same logic applies to 4-cycle and 5-cycle. Counting cyclical subgraphs in a given symbiosis network informs and quantifies the cyclicality of that network. The first four graphs in Fig. 1 illustrate these four cyclical subgraphs.

In addition to the cyclicality, we are also interested in redundancies. They happen when there are multiple independent paths between pairs of nodes and capture the fact that some flows are more robust than others. We capture these via two different subgraphs, which we call *redundancy graphlets*. Single redundancy graphlet and double redundancy graphlet capture the intuition that there are, respectively, one and two alternative paths between a pair of nodes, as depicted in the Fig. 1 (last two graphs on the right). Presence of redundancy graphlets in any network is counted in the same way as for cyclical subgraphs. This measure expresses how much is the overall flow in that network robust and resilient to interruptions or failures.

All above described values and network measures were computed for all five symbiosis networks that we study. The results are presented in the next section.

4. Results

4.1. Descriptive results

In this section we present the results of network analysis of industrial symbiosis networks. To first get an appreciation of their structures, we begin by providing the basic network measures for all networks, continue by visualising each of the five networks (using PAJEK) and lastly focusing on comparative analysis of the structures of all five networks (Table 2).

Table 2 highlights the relative diversity in terms of the network sizes, measured as the number of nodes. In our sample we have set the cases from the largest sized network (Case 1) to the smallest sized one (Case 5). In terms of number of edges (links), networks can be roughly arranged in the same way. Next, we focus on network density, which is nothing but the number of edges divided by the number of nodes (i.e., number of edges per node). High value of density means that nodes are more cohesive and better connected, whilst a low-density value suggests a less connected (sparse) network. The first two networks have rather low densities, whereas the last two networks have relatively high densities. Case 3 network has medium density close to one half, meaning that nearly half of possible edges are present. Lastly, we measure the network diameter, which expresses how far apart (in terms of network distance) are the two nodes in a network which are farthest apart. Small values of network diameter indicate that the network is compact, whereas large diameters are associated with dispersed networks. We find that all networks have medium diameters values, with Case 3 being the most compact network, and Cases 4 and 5 most dispersed ones. All the networks considered are small in terms of the number of nodes,

Table 2
Basic characteristics of the industrial symbiosis networks.

	Case 1 (CRO)	Case 2 (SI)	Case 3 (A)	Case 4 (DK)	Case 5 (FI)
Number of nodes/ stakeholders	23	18	11	11	9
Number of edges/links	54	42	26	33	22
Network density	0,21	0,27	0,47	0,60	0,61
Network diameter	4	5	3	5	5
Size of network	Small	Small	Small	Small	Small
Waste resources	Glass Textiles Metals Paper Biomass Rubber Cardboard	Water Biomass Paper Cardboard Fly ash Glass Wood Rubber Fibre rejects Candles Electronic and electrical equipment Biomass Metals Mixed municipal waste	Wood Paper Rubber Fibre rejects Oils Iron Sand	Water Steam Biomass Ethanol Bioethanol Gypsum	Glass Biomass Slaughterhouse waste Sludge Paper Cardboard Ammonium sulphate
Economic sector/type of industry	Metal industry Textile industry Glass industry Utilities Support services	Paper industry Wood industry chemical industry Utilities Support services	Metal industry Automotive industry Wood industry Paper industry Construction industry Utilities Support services	Pharmaceutical industry Biotechnology industry Energy industry Utilities Support services	Agriculture Food industry Energy industry Construction industry Utilities Support services

with fewer than 100 nodes/stakeholders (Borgatti et al., 2013).

The flows that are the subject of the links are dominated by material waste resources, which are mainly exchanges of biological, glass, paper, cardboard, and metal waste. However, given the specific nature of each stakeholder's primary activity, some more specific material resources (e.g., sludge, fibre rejects) are also the subject of the links. In the case of direct material flows, the stakeholders are mainly industrial enterprises, which in principle have waste resources, and industrial enterprises, which need these waste resources. In addition to the direct and indirect stakeholders, indirect stakeholders other than the providers or seekers of waste resources play a key role in industrial symbiosis networks. These are the so-called intermediaries, who act as a link between the providers and seekers of waste resources, providing information about one and the other stakeholders and seeking and presenting solutions in industrial symbiosis.

The challenges most commonly faced by stakeholders in case 1 are outdated legislation governing waste management, logistical challenges including inadequate stock planning strategies and lack of closer cooperation at the level of the stakeholder. In case 2, stakeholders face the challenges of new environmental regulations and their compliance. In case 3, there are logistical challenges, which include price volatility of indirect or support services and time-dependent availability of inputs, where price volatility is also present. In case 4, there are no specific challenges. This is not surprising as it is the most developed network in terms of structural characteristics (cyclicality and resilience) compared to the other four cases. However, the challenges faced by stakeholders in case 5 relate to the legal and formal reorganisations of the stakeholders involved, to the new waste management legislation and its lack of adaptation to primary activities, and logistical challenges dealing with the spatial constraints of the raw material receiving and dispatch units.

The industrial symbiosis network for Croatia consists of utility companies in and around Zagreb, in the so-called region of Inland Croatia, extended to some companies from the Austrian region of Styria. The network hence operates on a local, regional and international level. The network includes 23 companies (networks nodes) that exchange 54 waste materials (networks links) among them (Table 2). We find a public utility company as one of most central players, together with two recycling centres connecting the most distant nodes.

Next, the industrial symbiosis network for Slovenia includes the utility companies from Slovenian regions of Lower Sava, Savinja, Central Slovenia, Southeast Slovenia, Drava, Upper Carniola, Gorizia, together with the Austrian region of Vienna. Similarly, as the network in Croatia, this network hence operates on local, regional, country and international level. The network includes 18 companies (nodes) that exchange 42 waste materials (links) among them (Table 2). Interestingly, beside public utility companies and recycling centres, we also find a paper factory at the core of the network.

The industrial symbiosis network for Austria includes the utility companies from the Austrian region of Styria. Unlike the prior two, this network operates on local and regional level only. The network includes 11 companies (nodes) that exchange 26 waste materials (links) among them, and the shortest network diameter (Table 2). Companies from traditional sectors, such as the paper factory and a cement plant interestingly can be seen as bridging the two parts of the network.

The industrial symbiosis network for Denmark includes the utility companies from the Danish region of Zealand. As with the case of Austria, the network operates on local and regional level only. The network includes – same as the Austrian one – 11 companies (nodes) that exchange 33 waste materials (links) among them (Table 2), the latter also comparable to the Austrian one. Yet the constellation is very diverse, with a public utility playing a central role and with several two-sided flows (like the Slovenian one).

Lastly, the industrial symbiosis network for Finland includes the utility companies from the Finish region of Tavastia Proper. The network operates on a local and regional level, with no apparent links outside the Tavastia Proper region. The network includes 9 companies (nodes) that exchange 22 waste materials (links) among them (Table 2).

4.2. Analysing the maturity of the IS networks supporting circularity

Next, we turn our attention on analysing and comparing the structures of the focal networks. One of the goals of our analysis is to recognize the network features resembling a cyclical structure, which would indicate the circulation of waste materials in a region or in a country. In contrast to this, our networks can also exhibit what we could moniker as 'linear network features' or a limited complexity.

Table 3
Node flow statistics in the industrial symbiosis networks.

	Case 1 (CRO)	Case 2 (SI)	Case 3 (A)	Case 4 (DK)	Case 5 (FI)
flow= 0	13	14	7	3	3
flow= 1	8	0	2	0	1
flow= 2	2	0	1	1	3
flow= 3	0	0	0	0	1
flow= 4	0	1	0	2	0
flow= 6	0	0	1	1	0
flow= 7	0	0	0	0	1
flow= 8	0	2	0	2	0
flow= 14	0	1	0	0	0
flow= 15	0	0	0	1	0
flow= 28	0	0	0	1	0
Total number of nodes with node flow > 0	10	4	4	8	6

Note: We do not display flows with intensity 5, 9–13 and 16–27 as we have no such cases in our sample.

To do so, we rely on the measure we constructed, i.e., the node flow. As defined above, we are here focusing on the nodes' in-degrees and out-degrees, that is the number of different waste materials 'imported' and 'exported' by the given node. Strong presence of nodes with node flow value equal to zero and one (importing or/and exporting only one material) is indicative of more linear network structures. In contrast, higher node flows are associated with the companies that import and/or export several waste materials, and which are concerned with both the resources that can use gained from other organisations, as well as pay attention internally as to which residuals (byproducts etc.) they have that can be used by some other organisation. In sum, that reflects more complex networks based on included organisations' higher opportunity recognition regarding waste resources exchange. In Table 3, we report the statistics of node flow values for nodes in all networks.

As seen from Table 3, the network for Croatia has a strong presence of nodes with node flow 0 or a low node flow (1 or 2), which clearly indicates that there is a lack of presence of structures indicative of actors engaging in more complex opportunities of waste and products as a business case, both focusing on inflow and outflow. In other networks the presence of non-zero flow nodes is less prominent, even involving nodes with flow as high as 28 (case of Denmark), which suggests that structures of such networks are more complex. Actually, the network for Denmark appears to be structurally the most elaborate, i.e. complex, one, followed by the Finish one.

We are also interested in the circular (closed) flow of waste materials, i.e. in the cyclical features of our networks. Therefore, we explore the subgraphs we have determined above as cyclical subgraphs, hence in our case groups of size 2 nodes (i.e. companies) that mutually exchange waste materials, or those that are larger than 2 nodes, but there is a cyclical path of the waste exchange (e.g. from company 1 to company 2 and then company 3, and then back to company 1). The results are reported in the first part of Table 4, where we show the attributes of all the cyclical subgraphs of size 2–5 nodes in our networks. The networks for Croatia, Austria and Finland have no cyclical subgraphs of any size. In contrast the Danish and the Slovenian do. While the Slovenian network has two 2-cycles, the Danish one is the most advanced in this regard, exhibiting cycles of all sizes, including two 5-cycles. This is again clearly indicative of the Danish network being the most structurally elaborate one, as it also showcases the most cyclicality.

Finally, to quantify the redundancies in our networks, as a proxy for network resilience, we resort to counting single and double redundancy graphlets, introduced in the Methods section. Presence of these two graphlets indicate characteristic synergies and resilience among stakeholders in our symbiosis networks. The lower part of Table 4 summarises these results as well. The Croatian network has the strongest presence of these two types of graphlets, indicating that despite its apparent linearity, this network does have a potential for complex exchange of waste materials. The Danish network is again rich with both graphlets, suggesting that this network is indeed the most evolved industrial symbiosis network among the studied ones. In contrast, Slovenian, Austrian and Finnish networks have a weak presence of simple redundancies only, indicating weak resilience of these networks.

5. Discussion

5.1. General features of the focal IS networks supporting circularity: Locality and actors diversity as industrial convergence potential

We first focus on some general features of these networks, which were also already mentioned within the circular economy literature. Our analysis has focused both on loops that are shorter, i.e., the actors involved all being embedded in the same region (or even locality), as well as those that involve actors beyond the core region and even those that involve organisations outside the core country (i.e. international level), such as Slovenia and Croatia. In both of these, there are also Austrian organisations included. The need for these longer loops can be typically related to the lack of the appropriate organisations in their own regions, as well as the lack of proper bulks of waste materials, or is a reflection of more general collaborative activities (both related to circular economy activities and beyond).

In terms of the diverse actors involved in these IS networks supporting circularity, similarly to e.g., Köhler et al. (2022), Berardi and de Brito (2021), Christensen et al. (2022) we also discover quite a diversity of actors. Nonetheless, some are commonly present, such as public utility companies and recycling centres (beside waste management companies). This aligns with ideas of these types acting as facilitators of these networks (Bröring et al., 2006). Also very common are heating plants and production of energy organisations, the first appearing at the end of loops, but the second appearing not only at the beginning, but also seeing them as those nodes with node flow of 1, indicating they can appear as organisations that take in external resources in terms of waste, but also provide resources to others. Next, in terms of different industries taking part in these loops, we can see a big diversity of these: e.g., glass, construction, furniture, rubber, equipment, wood, metallurgy and chemical, plastics, and paper industry. We can thus see that these networks cover several industries that have been seen with high potential for circularity and as problematic in terms of negative environmental

Table 4
Structural characteristics of the industrial symbiosis networks (cyclicality and resilience).

	Case 1 (CRO)	Case 2 (SI)	Case 3 (A)	Case 4 (DK)	Case 5 (FI)
Number of 2-cycles	0	2	0	3	0
Number of 3-cycles	0	0	0	2	0
Number of 4-cycles	0	0	0	1	0
Number of 5-cycles	0	0	0	2	0
Number of single redundancy graphlets	3	1	2	4	2
Number of double redundancy graphlets	5	0	0	1	0

consequences. Furthermore, having stakeholders from diverse industries in these networks increases the potential for industrial convergence (reference from above) – potentially producing new types of industries at the cross-section. Hence, we have potential here not only for what we call within-industry convergence – where convergence occurs among sub-industries within a specific industry sector (Kim et al., 2015) – but also for so-called inter-industry convergence, in which two distinct industries overlap (Schmenner, 2009). This is also aligned with the policy-driven environmental enhancer type of industry convergence, which we would also expect in this type of networks (Geum et al., 2016). We can also see that the transitions are creating opportunities for specialisation – which we can already see integrated into our networks, such as, for example, detecting more general paper industry and recycling industries – but also specific paper recycling facilities.

5.2. The taxonomy of IS networks supporting circularity: Addressing the complexity, cyclicality and resilience

We have observed in our networks also the issues of complexity (showcasing advanced circular economy thinking and integrating opportunities from waste resource exchanges in (circular) business models. Whereas the two Scandinavian examples (regional in nature) showcase relatively high percentages of nodes with higher node flows (see Table 3), thus showcasing more advanced circular thinking in terms of the opportunities related to the exchange of waste materials, the rest of the focal networks seem to be less complex in this sense.

Next, in terms of cyclicality, the Danish network showcases the most closed loops, followed by the Slovenian case, where the first is an inter-regional IS network only; the other one, however, also includes stakeholders beyond Slovenia. Furthermore, combined with the resilience scoring (presence of redundancies in the system), we can distinguish the Danish network as the most evolved one.

Based on the above from literature derived elements of complexity, cyclicality and resilience we distinguish three evolutionary types of IS networks supporting circularity, whilst adhering to the Nickerson et al. (2013) criteria of building 'good' taxonomies. First are *mature IS networks,* such as the Danish one, which are complex cyclical resilient networks (cf. Fig. 2 in the above right quadrant), i.e. networks that are characterised by all three above elements. Next are the *evolving IS networks* supporting circularity, in which at least one of the elements is advanced, but the others remain underdeveloped; meaning they can come in a variety of subtypes such as complex non-cyclical non-resilient networks (Finland), or non-complex cyclical and non-resilient networks (Slovenia) or non-complex non-cyclical, but resilient networks (Croatia). Lastly, *emerging IS networks* (Austria) are already more than what Chertow (2007) would call a simple "resource exchange" but remain non-evolved (i.e., non-complex, non-cyclical, and non-resilient networks).

5.3. Network analysis as a diagnostic tool of industrial symbiosis networks

Our data on industrial symbiosis were represented as networks (graphs) and examined via social network analysis as our main methodological framework. Rather than using standard methods such as measures of network centrality, we opted for designing our own methods, such as node flow. In addition, we relied on counting the presence of specific subgraphs (graphlets) to create ways for measuring circularity, complexity, and robustness in our networks. Albeit simple, these custom methods are specifically tailored to our data and to our purposes and are easily interpretable in the context of this work. Speaking more broadly, such custom methods lend themselves as diagnostic tools of the industrial symbiosis networks. As we discussed above, they can be employed also to quantify each network's maturity and evolution. In fact, further development of such methods could lead to a specialised toolkit for research and policymaking on industrial symbiosis and circular economy. Moreover, richer data (that also include, for example, temporal dynamics of waste transfers between nodes) will require more sophisticated methods of this kind but will yield more precise and reliable information on the status of industrial symbiosis from the available data.

5.4. Limitations of the approach

Our research is not without limitations. Other research could focus both on additional European localities as well as going beyond the European milieu, which has been monikered as a CE policy front-runner (Modic et al., 2021; Kalmykova et al., 2018). Secondly, we propose both a widening and a deepening strategy in terms of future research. In regards to widening, our detected three-type taxonomy of IS is not necessarily exhaustive – indeed, in the evolving group, we already point out several potential subtypes. This is

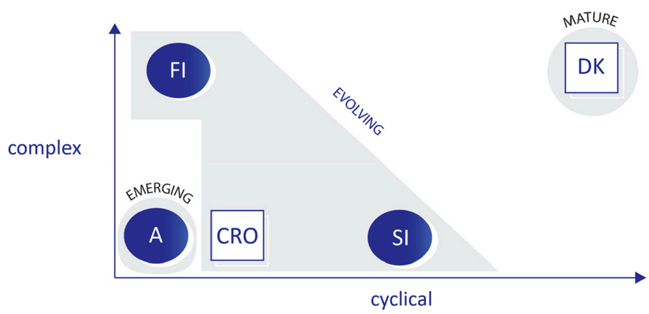

Fig. 2. Taxonomy of IS networks supporting circularity. Note: in boxes = resilient networks, in circles = non-resilient networks.

important as the strategies addressing them could be influenced by differences between them. On the other hand, in terms of deepening the research, one should also focus on particular types of waste streams – where several factors could influence the complexity, cyclicality as well as robustness of these IS networks. Another issue relates to the diversity of actors in these networks and their potential to produce industry convergence – also considering all three measures (complexity, cyclicality, and robustness). Lastly, the understanding on both antecedents of these resilient and circular networks potentially also via using other approaches such as a configurational approach, e.g. using a qualitative comparative analysis (QCA), which can provide an understanding of various pathways and diverse constellations of elements needed to be in place for nurturing more advanced IS networks supporting circularity as well as understanding how these then contribute to the sustainability. Subsequently the process of creation of such networks and their impacts could be better understood and instigated.

Next, our approach, while benefiting from being focused, cannot take into account other factors, such as individual cognitive frames, manifesting themselves through personal preferences and inclinations, which have proven as relevant (Di et al., 2024) and can impact both micro level – through decisions of decision-makers within specific network nodes – and on macro level – through inclinations of policy-makers shaping emergent circumstances within which networks develop. Policies in particular can indeed have a major impact on the transformation of the economy to circular (Di et al., 2023; Džajić Uršič et al., 2024). Our approach also cannot take into account the combined impact of strategies, economic structure and other factors such as social ones (Di et al., 2024a). This limitation can be compensated by including results of proposed network analysis in analysis that take into account these combined aspects, for example by building a qualitative multi-criteria decision model for evaluation of the development of IS network model (Mileva-Boshkoska et al., 2018).

Lastly, there are limitations that regard the data and its analyses. First, our symbiosis networks might include links that we failed to detect. Their presence could impact the number of cycles and redundancies. In fact, the number of cycles and redundancies we found is to be understood as the minimum such number, since additional cycles and redundancies could be hidden in missing links. Second, we have not considered the flow of materials that nodes in a network receive from outside the network. It is clear that at least some of the nodes (stakeholders) work with materials that they obtain from somewhere else, rather than as waste products of other nodes. Third, node flows could be studied better if we had the data on how much material is transmitted via each link and how often that exchange occurs. Obviously, some nodes could be exporting their waste materials every day, while other nodes could be doing it on a monthly basis. In terms of data analysis, we stress that we considered only two types of redundancy graphlets and four types of cycles. More complicated graph structures could be hiding additional complexity, cyclicality, or robustness. However, it can be shown that many of such complicated graph structures are combinations of the basic ones that we did consider. Plus, classical social networks teach us that, in reality, supplementation is usually limited only to organisations that are very few network steps away.

5.5. Implications of research

The taxonomy provides several implications due to its nuanced understanding of IS network evolution, enabling policymakers to design targeted interventions that support the development of complex, cyclical, and resilient IS networks, i.e., mature networks. In particular, special attention should be given to emerging IS networks, providing them with the necessary support and incentives to evolve the missing features while nurturing already developed ones. Similar insights are relevant for IS managers (for example at industry parks). as for e.g., emerging networks might benefit from initial guidance and support to establish foundational connections, while mature networks may require a stronger focus on optimising resource exchanges and enhancing resilience.

This study also spotlights the need for policies supporting collaborations that facilitate cyclical closure of material loops, ensuring that waste resources are effectively reused within the network, whilst making sure those are also resilient to foster regional development. IS managers as well as those individuals concerned with regional development and managers of individual companies, should consider identifying (and incorporating) redundancies in IS networks to mitigate the impact of potential disruptions, ensuring the operations remain robust. This involves creating and actively engaging in backup options for resource exchanges and having contingency plans in place. This can also help finding a new stable constellation, which can bring even increased circularity results, as solutions can often also be locked-in by legacy relationships. This can be done by collecting and analysing data on waste material flows and exchange frequencies allowing the companies to optimise their participation in IS networks focused on waste materials exchanges, and subsequently, to enhance their contributions to network complexity, cyclicality and resilience. Lastly, the article illustrates that mature networks also need more holistic and complex thinking about the circular opportunities. In this line, managers should explore both the provision and acquisition of resources within their network, i.e. the evolution of IS networks goes hand in hand with the evolution of more complex circular economy business models of individual actors in the network.

6. Conclusions

This study examines IS networks supporting circularity by conceptualising them as complex adaptive systems. By applying social network approaches, we theoretically underpin the elements of complexity, cyclicality, and resilience, and develop new measures thereof. We find that these networks exhibit these traits to varying degrees. We propose a taxonomy of IS supporting CE from an evolutionary perspective: i) mature IS networks exhibiting complexity, cyclicality, and resilience; ii) evolving networks with at least one of these traits; and iii) emerging networks that, while more than simple waste exchanges, are still un-evolved. In practical sense, the study points out we want to nurture complex IS networks where actors adopt a holistic view of circular opportunities, considering both their waste and byproducts both as inputs to own activities as well as their possible value to others, and being cognizant of the potential for building redundancies, which can be activated if a disturbance occurs.

CRediT authorship contribution statement

Borut Rončević: Writing – review & editing, Supervision, Methodology, Conceptualization. **Dolores Modic:** Writing – review & editing, Writing – original draft, Visualization, Investigation. **Zoran Levnajić:** Writing – review & editing, Writing – original draft, Software, Formal analysis. **Urška Fric:** Writing – review & editing, Software, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The research was co-funded and supported by the Slovenian Research and Innovation Agency (ARIS) through the annual work program of Rudolfovo – Science and Technology Centre, and the Slovenian Research and Innovation Agency Programs P1-0383 and P5-0445. The authors also acknowledge that the research was financially supported by the Slovenian Research and Innovation Agency through the project Encouraging the Development of Industrial Symbiosis Networks in Slovenia – transition to the Circular Economy, and the European Education and Culture Executive Agency through the Jean Monnet Centre of Excellence Technology and Innovations for Agenda 2030 – EU Global Leadership ERASMUS-JMO-2023-COE-101127584. The work was supported also by the Ministry of Education, Science, and Sport of the Republic of Slovenia via ERA-MIN financing framework, project AI-COSTQO, and the Developing Skills in Intellectual Property Rights Open Data for Sustainability and Circularity (IPR4SC), Erasmus+ Programme, Key Action - Alliances for Education and Enterprises proj. no. 101056129.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eti.2025.104026.

Data Availability

Raw dataset is available in the supplementary material.

References

Albizua, A., Bennett, E.M., Larocque, G., Krause, R.W., Pascual, U., 2021. Social networks influence farming practices and agrarian sustainability. PLOS One 16 (1), e0244619.

Annarelli, A., Nonino, F., 2016. Strategic and operational management of organizational resilience: current state of research and future directions. Omega 62, 1–18.

Ashton, W.S., 2009. The structure, function, and evolution of a regional industrial ecosystem. J. Ind. Ecol. 13 (2), 228–246.

Aspelund, A., Olsen, M.F., Michelsen, O., 2021. Simultaneous adoption of circular innovations: a challenge for rapid growth of the circular economy. In: Siri, J., Thomas, L., Francesco, Q., Einar, R., Marianne, S. (Eds.), Research Handbook of Innovation for a Circular Economy. Edward Elgar Publishing, Cheltenham, pp. 160–173.

Atanasovska, I., Choudhary, S., Koh, L., Ketikidis, P.H., Solomon, A., 2022. Research gaps and future directions on social value stemming from circular economy practices in agri-food industrial parks: insights from a systematic literature review. J. Clean. Prod. 354, 131753.

Baars, J., Domenech, T., Bleischwitz, R., Melin, H.E., Heidrich, O., 2021. Circular economy strategies for electric vehicle batteries reduce reliance on raw materials. Nat. Sustain. 4 (1), 71–79.

Bag, S., Gupta, S., Foropon, C., 2019. Examining the role of dynamic remanufacturing capability on supply chain resilience in circular economy. Manag. Decis. 57 (4), 863–885.

Bailey, K.D., 1994. Typologies and Taxonomies: an Introduction to Classification Techniques. Sage, New York.

Baldassarre, B., Calabretta, G., Bocken, N., Diehl, J.-C., & Duygu, K., 2019. The evolution of the Strategic role of Designers for Sustainable Development. In: Erik B., Gerda G., Cees de B., Nuša F., & Rita A.A. (Eds.), Academy for Design Innovation Management Conference 2019: Research Perspectives in the era of Transformations, pp. 1–15.

Barabási, A.-L., 2016. Network Science. Cambridge University Press. ⟨https://networksciencebook.com/⟩ (accessed 29 August 2024).

Barrau, E., Tanguy, A., Glaus, M., 2024. Closing the loop: structural, environmental and regional assessments of industrial symbiosis. Sustain. Prod. Consum. 50 (2024), 87–97.

Barros, M.V., Salvador, R., do Prado, G.F., de Francisco, A.C., Piekarski, C.M., 2021. Circular economy as a driver to sustainable businesses. Clean. Environ. Syst. 2, 100006.

Bartolacci, F., Del Gobbo, R., Paolini, A., Soverchia, M., 2017. Waste management companies towards circular economy: what impacts on production costs? Environ. Eng. Manag. J. (EEMJ) 16 (8), 1789–1796.

Bassi, A.M., Bianchi, M., Guzzetti, M., Pallaske, G., Tapia, C., 2021. Improving the understanding of circular economy potential at territorial level using systems thinking. Sustain. Prod. Consum. 27, 128–140.

Berardi, P.C., de Brito, R.P., 2021. Supply chain collaboration for a circular economy-from transition to continuous improvement. J. Clean. Prod. 328, 129511.

Besednjak Valič, T., Kolar, J., Lamut, U., 2022. Fighting the big bad wolf of global trends: technology transfer between HPC centres and SMEs. Digit. Policy, Regul. Gov. 24 (6), 498–512.

Besednjak Valič, T., Kolar, J., Lamut, U., Pandiloska Jurak, A., 2023. Key policy mechanisms supporting the University–Industry collaboration in the Danube region: case study of academic HPC centres and SMEs. Eur. J. Manag. Bus. Econ. 32 (5), 509–524.

Bocken, N.M.P., de Pauw, I., Bakker, C., van der Grinten, B., 2016. Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. 33 (5), 308–320.
Boons, F., Spekkink, W., Mouzakitis, Y., 2011. The dynamics of industrial symbiosis: a proposal for a conceptual framework. J. Clean. Prod. 19 (9), 905–911.
Borgatti, S.P., Everett, M.G., Johnson, J.C., 2013. Analyzing Social Networks, first ed. SAGE Publications Ltd, London.
Boulding, K., 1966. The Economics of the Coming Spaceship Earth, first ed. Routledge, New York, United States.
Bröring, S., Martin Cloutier, L., Leker, J., 2006. The front end of innovation in an era of industry convergence: evidence from nutraceuticals and functional foods. RD Manag. 36 (5), 487–498.
Chertow, M.R., 2000. Industrial symbiosis: literature and taxonomy. Annu. Rev. Energy Environ. 25 (1), 313–337.
Chertow, M.R., 2004. Industrial symbiosis. Encycl. Energy 3 (2004), 407–415.
Chertow, M.R., 2007. Uncovering industrial symbiosis. J. Ind. Ecol. 11 (1), 11–26.
Chopra, S., Khanna, V., 2014. Understanding resilience in industrial symbiosis networks: insights from network analysis. J. Environ. Manag. 141, 86–94.
Christensen, T.B., Johansen, M.R., Buchard, M.V., Glarborg, C.N., 2022. Closing the material loops for construction and demolition waste: the circular economy on the island Bornholm, Denmark. Resour., Conserv. Recycl. Adv. 15, 200104.
Christopher, M., Peck, H., 2004. Building the resilient supply chain. Int. J. Logist. Manag. 15 (2), 1–13.
Circle Economy, 2024. The circularity gap report 2024. ⟨https://www.circularity-gap.world/2024⟩ (accessed 3 September 2024).
Corvellec, H., Stowell, A.F., Johansson, N., 2022. Critiques of the circular economy. J. Ind. Ecol. 26 (2), 421–432.
Coscia, M. 2021. The Atlas for the Aspiring Network Scientist. ⟨https://www.networkatlas.eu/⟩ (accessed 7 September 2024).
Cristoni, N., Tonelli, M., 2018. Perceptions of firms participating in a circular economy. Eur. J. Sustain. Dev. 7 (4), 105–105.
De Nooy, W.D., Mrvar, A., Batagelj, V., 2011. Exploratory Social Network Analysis with Pajek, second ed. Cambridge University Press, Cambridge.
Deutz, P., 2014. Food for thought: seeking the essence of industrial symbiosis. In: Salomone, R., Saija, G. (Eds.), Pathways to Environmental Sustainability: Methodologies and Experiences. Springer International Publishing AG, Dordrecht, The Netherlands, pp. 3–11.
Di, K., Chen, W., Shi, Q., Cai, Q., Liu, S., 2024. Analysing the impact of coupled domestic demand dynamics of green and low-carbon consumption in the market based on SEM-ANN. J. Retail. Consum. Serv. 79, 103856.
Di, K., Chen, W., Shi, Q., Cai, Q., Zhang, B., 2024a. Digital empowerment and win-win co-operation for green and low-carbon industrial development: analysis of regional differences based on GMM-ANN intelligence models. J. Clean. Prod. 445, 141332.
Di, K., Chen, W., Zhang, X., Shi, Q., Cai, Q., Li, D., Di, Z., 2023. Regional unevenness and synergy of carbon emission reduction in China's green low-carbon circular economy. J. Clean. Prod. 420, 138436.
Domenech, T.A., 2010. *Social aspects of industrial symbiosis networks* (Doctoral dissertation). University College London.
Domenech, 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. Resour. Conserv. Recycl. 141, 76–98.
Doreian, P., Woodard, K.L., 1994. Defining and locating cores and boundaries of social networks. Soc. Netw. 16 (4), 267–293.
Džajić Uršič, E., 2020. Morphogenesis of Industrial Symbiotic Networks. Peter Lang, Berlin.
Džajić Uršič, E., Fric, U., Rončević, B., 2024. The circular economy: recent debates and research trends. J. Infrastruct., Policy Dev. 8 (3), 1–20.
Easley, D., Kleinberg, J., 2010. Networks, Crowds, and Markets: Reasoning about A Highly Connected World. Cambridge University Press, New York.
Ellen MacArthur Foundation and McKinsey. 2015. *Growth within: a circular economy vision for a competitive Europe*. Foundation for Environmental Economics and Sustainability, Dublin, Ireland.
Esposito, M., Tse, T., Soufani, K., 2018. Introducing a circular economy: new thinking with new managerial and policy implications. Calif. Manag. Rev. 60 (3), 5–19.
Estrada, E., 2012. The Structure of Complex Networks: Theory and Applications. Oxford University Press, Oxford.
European Commission. 2020. *A new Circular Economy Action Plan. For a cleaner and more competitive Europe. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions*. COM (2020) 98 final. ⟨https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A98%3AFIN⟩ (accessed 11 July 2024).
Fraccascia, L., Giannoccaro, I., Albino, V., 2021. Ecosystem indicators for measuring industrial symbiosis. Ecol. Econ. 183, 106944.
Fraccascia, L., Yazan, D.M., Albino, V., Zijm, H., 2020. The role of redundancy in industrial symbiotic business development: a theoretical framework explored by agent-based simulation. Int. J. Prod. Econ. 221, 107471.
Geisdorfer, M., Vladimirova, D., Evans, S., 2018. Sustainable business model innovation: a review. J. Clean. Prod. 198, 401–416. https://doi.org/10.1016/j.jclepro.2018.06.240.
Genovese, A., Acquaye, A.A., Figueroa, A., Koh, S.L., 2017. Sustainable supply chain management and the transition towards a circular economy: evidence and some applications. Omega 66, 344–357.
Geum, Y., Kim, M.S., Lee, S., 2016. How industrial convergence happens: a taxonomical approach based on empirical evidences. Technol. Forecast. Soc. Change 107, 112–120.
Goldstein, L.S., 1999. The relational zone: the role of caring relationships in the co-construction of mind. Am. Educ. Res. J. 36 (3), 647–673. https://doi.org/10.2307/1163553.
Gonzalez-Moreno, Á., Triguero, Á., Díaz-García, C., Sáez-Martínez, F.J., 2024. Circular economy and entrepreneurship in Europe: an analysis of the impact of cultural factors, regulatory framework and rate of entrepreneurship. Environ. Technol. Innov. 35, 103656.
Hina, M., Chauhan, C., Kaur, P., Kraus, S., Dhir, A., 2022. Drivers and barriers of circular economy business models: where we are now, and where we are heading. J. Clean. Prod. 333, 130049.
Holling, C.S., 1973. Resilience and stability of ecological systems. Annu. Rev. Ecol. Syst. 4, 1–23.
Holling, C., 2001. Understanding the complexity of economic, ecological, and social systems. Ecosystems 4, 390–405. https://doi.org/10.1007/s10021-001-0101-5.
Jakobsen, S., Lauvås, T., Quatraro, F., Rasmussen, E., Steinmo, M., 2021. Introduction to the research handbook of innovation for a circular economy. In: Siri, J., Thomas, L., Francesco, Q., Einar, R., Marianne, S. (Eds.), Research Handbook of Innovation for a Circular Economy. Edward Elgar Publishing, Cheltenham, pp. 2–11.
Kalmykova, Y., Sadagopan, M., Rosado, L., 2018. Circular economy–from review of theories and practices to development of implementation tools. Resour. Conserv. Recycl. 135, 190–201.
Kim, N., Lee, H., Kim, W., Lee, H., Suh, J.H., 2015. Dynamic patterns of industry convergence: evidence from a large amount of unstructured data. Res. Policy 44 (9), 1734–1748.
Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour., Conserv. Recycl. 127, 221–232.
Kirchherr, J., Yang, N.H.N., Schulze-Spüntrup, F., Heerink, M.J., Hartley, K., 2023. Conceptualizing the circular economy (revisited): an analysis of 221 definitions. Resour., Conserv. Recycl. 194, 107001.
Köhler, J., Sönnichsen, S.D., Beske-Jansen, P., 2022. Towards a collaboration framework for circular economy: The role of dynamic capabilities and open innovation. Bus. Strategy Environ. 31 (6), 2700–2713.
Konietzko, J., Bocken, N., Hultink, E.J., 2020. A tool to analyze, ideate and develop circular innovation ecosystems. Sustainability 12 (1), 417.
Korhonen, J., Snäkin, J.P., 2005. Analysing the evolution of industrial ecosystems: concepts and application. Ecol. Econ. 52 (2), 169–186.
Kumar Behera, S., Kim, J., Lee, S., Suh, S., Park, H., 2012. Evolution of 'designed' industrial symbiosis networks in the Ulsan Eco-industrial Park: 'research and development into business' as the enabling framework. J. Clean. Prod. 29–30, 103–112.
Lavtizar, V., Hjaltadottir, R.E., Modic, D. and Elder, M. 2023. Why we need a transformative circular economy. IISD: SDG Knowledge hub.
Levnajić, Z., Pikovsky, A., 2011. Network reconstruction from random phase resetting. Phys. Rev. Lett. 107 (3), 034101.
Lüdeke-Freund, F., Gold, S., Bocken, N., 2018. A review and typology of circular economy business model patterns. J. Ind. Ecol. 23, 36–61. https://doi.org/10.1111/jiec.12763.
Menczer, F., Fortunato, S., Davis, C.A., 2020. A First Course in Network Science. Cambridge University Press, Cambridge.

Mileva-Boshkoska, B., Rončević, B., Uršič, E.D., 2018. Modeling and evaluation of the possibilities of forming a regional industrial symbiosis networks. Soc. Sci. 7 (1), 13.
Modic, D., Johnson, A., Vuckovic, M., 2021. Towards measuring innovation for circular economy using patent data. In: Siri, J., Thomas, L., Francesco, Q., Einar, R., Marianne, S. (Eds.), Research Handbook of Innovation for a Circular Economy. Edward Elgar Publishing, Cheltenham, pp. 265–276.
Modic, D., Lužar, B., Yoshioka-Kobayashi, T., 2023. Structure of university licensing networks. Scientometrics 128 (2), 901–932.
Neves, A., Godina, R., Azevedo, G.S., Matias, J.C.O., 2020. A comprehensive review of industrial symbiosis. J. Clean. Prod. 247, 113–119.
Newman, M.E.J., 2018. Networks. An introduction, first ed. Oxford University Press, Oxford.
Nickerson, R.C., Varshney, U., Muntermann, J., 2013. A method for taxonomy development and its application in information systems. Eur. J. Inf. Syst. 22 (3), 336–359.
Onita, J. 2006. How does industrial symbiosis influence environmental performance? (MSc thesis, Sweden: Linköpings Universitet).
Ormazabal, M., Prieto-Sandoval, V., Puga-Leal, R., Jaca, C., 2018. Circular economy in Spanish SMEs: challenges and opportunities. J. Clean. Prod. 185, 157–167.
Parejo-Moruno, F.M., Linares-Luján, A.M., Faisca, C.M., Rangel Preciado, J.F., 2024. *forthcoming*. Industrial agglomeration and cooperation: evidence of circular bioeconomy from the Iberian cork industry. In: Lars, H., Dolores, M., Einar, R., Siri, J., Wim, V. (Eds.), Research Handbook of Innovation for a Circular Bioeconomy. Edward Elgar Publishing, Cheltenham.
Perey, R., Benn, S., Agarwal, R., Edwards, M., 2018. The place of waste: changing business value for the circular economy. Bus. Strategy Environ. 27, 631–642.
Pržulj, N., 2007. Biological network comparison using graphlet degree distribution. Bioinformatics 23 (2), e177–e183.
Puntillo, P., Gulluscio, C., Huisingh, D., Veltri, S., 2021. Reevaluating waste as a resource under a circular economy approach from a system perspective: findings from a case study. Bus. Strategy Environ. 30 (2), 968–984.
Reike, D., Vermeulen, W.J., Witjes, S., 2018. The circular economy: new or refurbished as CE 3.0? – exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. Resour. Conserv. Recycl. 135, 246–264.
Ricciotti, F., 2020. From value chain to value network: a systematic literature review. Manag. Rev. Q. 70 (2), 191–212.
Salmenperä, H., Pitkänen, K., Kautto, P., Saikku, L., 2021. Critical factors for enhancing the circular economy in waste management. J. Clean. Prod. 280, 124339.
Sarajlić, A., Malod-Dognin, N., Yaveroğlu, Ö., Pržulj, N., 2016. Graphlet-based characterization of directed networks. Sci. Rep. 6, 35098.
Saunders, M., Lewis, P., Thornhill, A., 2009. Research Methods for Business Students. Pearson, New York.
Schmenner, R.W., 2009. Manufacturing, service, and their integration: some history and theory. Int. J. Oper. Prod. Manag. 29 (5), 431–443.
Sokal, R.R., 1966. Numerical taxonomy. Sci. Am. 215 (6), 106–117.
Song, X., Geng, Y., Dong, H., Chen, W., 2018. Social network analysis on industrial symbiosis: a case of Gujiao eco-industrial park. J. Clean. Prod. 193, 414–423.
Sorkhoh, I., Mahdi, K. and Safar, M. 2012. *Cyclic Entropy of Complex Networks*. IEEE/ACM International Conference on Advances in Social Networks Analysis and Mining, Istanbul, Turkey.
Stahel, W.R., 1984. The product-life factor. In an inquiry into the natureof sustainable societies: the role of the private sector. In: Susan, G.O. (Ed.), The Woodlands, The Woodlands. Houston Advanced Research Center. Tex.
Stahel, W.R., 2016. The circular economy. Nature 531 (7595), 435–438.
Stahel, W.R., Reday-Mulvey, G., 1981. Jobs for Tomorrow: the Potential for Substituting Manpower for Energy, first ed. Vantage Press, New York.
Sudusinghe, J.I., Seuring, S., 2022. Supply chain collaboration and sustainability performance in circular economy: a systematic literature review. Int. J. Prod. Econ. 245, 108402.
The Circularity Gap Report. 2024. ⟨https://www.circularity-gap.world/2024⟩ (accessed 28 August 2024).
Tura, N., Hanski, J., Ahola, T., Ståhle, M., Piiparinen, S., Valkokari, P., 2019. Unlocking circular business: a framework of barriers and drivers. J. Clean. Prod. 212, 90–98.
Urbinati, A., Chiaroni, D., Chiesa, W., 2017. Towards a new taxonomy of circular economy business models. J. Clean. Prod. 168, 487–498. https://doi.org/10.1016/j.jclepro.2017.09.047.
Uvarova, I., Atstaja, D., Volkova, T., Grasis, J., Ozolina-Ozola, I., 2023. The typology of 60R circular economy principles and strategic orientation of their application in business. J. Clean. Prod. 409, 137189.
Vanhamäki, S., Virtanen, M., Luste, S., Manskinen, K., 2020. Transition towards a circular economy at a regional level: a case study on closing biological loops. Resour., Conserv. Recycl. 156, 104716.
Vranić, A., Tomašević, A., Alorić, A., Mitrović Dankulov, M., 2023. Sustainability of stack exchange Q&A communities: the role of trust. EPJ Data Sci. 12 (1), 4.
Wang, Z., Jiang, Y., Huang, Y., Jia, X., 2017. Complex network method towards evaluating industrial symbiosis. Chem. Eng. Trans. 61, 169–174.
Wen, Z., Meng, X., 2015. Quantitative assessment of industrial symbiosis for the promotion of circular economy: a case study of the printed circuit boards industry in China's Suzhou New District. J. Clean. Prod. 90, 211–219.
Yaveroğlu, Ö.N., Malod-Dognin, N., Davis, D., Levnajic, Z., Janjic, V., Karapandza, R., Pržulj, N., 2014. Revealing the hidden language of complex networks. Sci. Rep. 4 (1), 4547.
Yazan, D.M., Romano, V.A., Albino, V., 2016. The design of industrial symbiosis: an input–output approach. J. Clean. Prod. 129, 537–547.
Zeballos, L.J., Gomes, M.I., Barbosa-Povoa, A.P., Novais, A.Q., 2012. Optimum design and planning of resilient and uncertain closed-loop supply chains. Comput. Aided Chem. Eng. 30, 407–411.
Zhou, X., Liang, X., Zhao, J., Zhang, S., 2018. Cycle based network centrality. Sci. Rep. 8 (1), 11749.
Zweig, K.A., 2016. Network Analysis Literacy: A Practical Approach to the Analysis of Networks. Springer-Verlag, Kaiserslautern, Germany.