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CRITICAL REVIEW

Life cycle environmental and economic assessment of industrial symbiosis networks: a review of the past decade of models and computational methods through a multi-level analysis lens

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Abstract

Purpose Industrial symbiosis network (ISN) facilitation tools seek to holistically evaluate the environmental and economic performance of ISNs through life cycle assessment (LCA) and life cycle costing (LCC). ISNs have many stakeholders with diverse interests in the LCA and LCC results thus requiring multi-level analysis. The objective of this review was to examine the state-of-the-art methodologies used in LCAs and LCCs of ISNs and understand how multi-level analysis can be conducted.

Methods The systematic literature review methodology was applied to develop a corpus of peer-reviewed LCA and LCC studies of ISNs published between 2010 and 2019 without any geographic boundary. Abstracts were reviewed to shortlist studies that conducted an LCA or LCC of an ISN with numerical results. LCA and LCC methodologies used in the shortlisted studies were collected and categorized. Each methodology was examined to understand how the foreground and background systems are represented, how waste-to-resource exchanges are analyzed, and how the results can be computed at the network, entity, and flow levels.

Results and discussion The review yielded 42 LCA studies and 11 LCC studies of ISNs that used eight different methodologies. Process-based LCA was used in 71% of the LCA studies, whereas tiered hybrid LCA was used in 14% of the studies. Waste-to-resource exchanges in ISN scenarios were represented either through process analysis or as a black box. Fewer LCC studies that evaluate the economic performance of ISNs exist compared with LCA studies. Economic studies often evaluated financial feasibility, net present value, profitability, or payback period of specific waste-to-resource exchanges or the network overall.

Conclusions The insights derived from this review chart future areas of research in multi-level modeling and analysis of the life cycle environmental and economic performance of ISNs. To improve the model construction and analysis process, research should be explored in developing a methodology for constructing a single model that represents multiple entities linked together by waste-to-resource exchanges and can provide LCA and LCC results for different stakeholder perspectives. The lack of LCC studies of ISNs merits the need for more research in this area at both the network and entity levels to quantify potential economic trade-offs between stakeholders. Developing a methodology for unified LCA and LCC modeling and analysis of ISNs can help ISN facilitation tool developers conduct simultaneous life cycle environmental and economic analysis of the potential symbiosis connections identified and how they contribute to the overall network.

Keywords Industrial ecology · Circular economy · Environmental modeling · Recycling · Zero waste manufacturing

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1 Introduction

Life cycle thinking has become more important in validating the environmental, economic, and social benefits the circular economy concept aims to deliver. Benefits of the circular economy such as harnessing the maximum value of earth's resources, waste mitigation, product recovery and regeneration, and new jobs have attracted widespread attention from governments, businesses, aid and development agencies, non-profit organizations, and the public (Walls and Paquin 2015; Asian Development Bank 2019; Climate-KIC 2019;

Low and Ng 2018). A discipline that has successfully operationalized a component of the circular economy between multiple businesses and is scalable is industrial symbiosis. Recognized as a subfield of industrial ecology, industrial symbiosis builds interfirm symbiotic activities with the objective to encourage industries that are typically separated to cooperate and create a competitive advantage through the exchange of one company's waste and byproducts as another company's productive input (Chertow 2000, 2007; Chertow and Park 2016; Neves et al. 2020). The benefits of industrial symbiosis have motivated the creation of over 160 eco-industrial parks and mixed urban-industrial settings that have achieved both environmental and economic benefits (Switzerland Federal Office for the Environment 2014). To replicate and scale up industrial symbiosis globally, many different information and communication technology and network optimization tools have been developed that facilitate industrial symbiosis by identifying synergistic linkages among industrial processes and businesses (Grant et al. 2010; Boix et al. 2015; Kastner et al. 2015; Puchala et al. 2016; Raabe et al. 2017; Low et al. 2018; van Capelleveen et al. 2018; Kerdlap et al. 2019a; Yeo et al. 2019a, b). Many industrial symbiosis facilitation tools and national industry networking programs have advocated for quantifying the benefits gained from waste-to-resource exchanges through indicators such as life cycle environmental impacts (Laybourn and Lombardi 2007; Kerdlap et al. 2019b, 2020). Not all waste-to-resource exchanges are beneficial to the environment (Mohammed et al. 2018), and failure to quantify the environmental and economic performance of industrial symbiosis networks (ISNs) can lead to burden shifts such as a circular economy rebound effect (Zink and Geyer 2017).

Studies conducted to understand both the environmental and economic benefits of ISNs started as early as the mid-2000s when Chertow and Lombardi (2005) quantified how the collaborating entities in an ISN in Guayama, Puerto Rico, would benefit from the exchange of wastewater, steam, and ash between each other. Their study revealed that the benefits of ISNs may be distributed unevenly among participating organizations and that policy intervention can enable more resource exchanges among a group of companies. Since then, more studies have been conducted on measuring the environmental benefits of ISNs using the life cycle assessment (LCA) methodology to account for the full value chain inside the ISN and beyond its group of companies. LCAs of ISNs have analyzed the network impacts of waste-to-resource exchanges between different entities, defined as companies or other types of organizations. Studies have also analyzed the sharing of resources such as water and heat between co-located entities. Some studies conducted an LCA to quantify the environmental impacts of specific waste-to-resource exchange processes without quantifying how the companies producing or receiving the waste or byproduct would benefit from such an exchange. Reviews of LCA studies of ISNs and different methodologies have been conducted as well. In 2010, Mattila et al. (2010) compared the use of process-based LCA, input-output LCA, and tiered hybrid LCA to quantify the environmental impacts of a forest ISN in Kymenlaakso, Finland. Their assessment revealed that it was unclear whether or not the higher impacts calculated in certain categories were overestimated or if the process-based LCA results were underestimated. Thus, input-output LCA requires careful interpretation of the results to understand the effects of data aggregation. Two years later, Mattila et al. (2012) reviewed the methodological aspects of applying LCA to ISNs. The authors proposed a typology of research questions which include (1) analysis; (2) improvement; (3) expansion of existing systems; (4) design of new eco-industrial parks; and (5) restructuring of circular economies. The purpose of the typology was to frame the LCA question and select the suitable reference case for comparison which helps reduce the risk of overestimating the benefits of exchanging byproducts. In 2015, Martin et al. (2015) discussed the LCA methodological considerations for quantifying environmental impacts of ISNs which include the definition of the reference systems and selection of allocation methods, system boundaries, and the functional unit. The authors also proposed an approach for distributing credits of waste-to-resource exchanges among the entities in the ISN as the benefits have implications on taxes, subsidies, and relations for the participating entities. More recently, Aissani et al. (2019) reviewed 26 peer-reviewed LCA studies of ISNs to do a cross-analysis of the different types of reference scenarios defined in the studies and the use of sensitivity analysis. The review revealed that the reference scenario defined is dependent on the type of ISN considered such as an existing ISN at industrial scale or a prospective ISN and that studies use sensitivity analysis to address the problem of variability of reference scenarios.

Although much LCA research has been done in evaluating ISNs, multi-level analysis of the life cycle environmental and economic performance of ISNs has been under-explored. Many studies evaluate the environmental and economic performance of the overall ISN, but only a few analyze the performance of the individual entities and how the impacts of waste-to-resource exchanges are distributed between entities (Martin et al. 2015). In an ISN, there are many stakeholders involved in implementation and operations management such as policymakers, land-use planners, individual companies, economists, or resource managers (Switzerland Federal Office for the Environment 2014). Each type of stakeholder is interested in measuring the performance of a specific part of the ISN such as the overall network or an individual company. The different perspectives of environmental and economic performance of ISNs and examples of stakeholders with interest are:

1 Network-level: policymakers, urban planners, industrial park owner/manager

2 Entity-level: companies
3 Resource flow-level: resource managers and material scientists.

If the results of an LCA and LCC of an ISN are not able to be disaggregated to the different levels of interest, each stakeholder will not be able to acquire the information needed to benchmark their own environmental and economic performance and ultimately decide whether or not engaging in an ISN contributes to their business and organizational goals. Thus, LCAs and LCCs require multi-level analysis to address the needs of different stakeholders.

There are three key gaps that limit current comprehension of multi-level LCA and LCC of ISNs. First, previous reviews have not taken stock of the models and computational methods used for measuring the life cycle environmental impacts of ISNs. Second, previous reviews have not looked at studies that evaluate the economic performance of ISNs and its relationship with LCA. Several studies have already examined the integration of LCA and LCC for single-product systems (Heijungs et al. 2013; Moreau and Weidema 2015; Miah et al. 2017), but such studies have not been conducted for the case of ISNs which involve multiple product systems, joint production processes, and resource flows with multiple origins (sources) and destinations (sinks). In ISNs, specific resource flows may be physically identical, but need to be differentiated because they have different sources and sinks. For example, an ISN could produce two waste flows that are exactly the same physically, but one waste flow is consumed by a recycling process to produce a new resource and the other waste flow is sent for disposal. Third, studies have not explicitly looked at how LCA and LCC methodologies can isolate the environmental impacts and economic costs of specific waste-to-resource exchange processes in the ISN and analyze which entities are affected by those conversion processes. Therefore, the objective of this review is to examine:

1 The state-of-the-art of methodologies used in LCA and LCC studies of ISNs
2 How the existing methodologies are able to provide multi-level results from the perspectives of the whole network, individual entities, and resource flows
3 How waste-to-resource exchanges between entities in an ISN are modeled and analyzed in each LCA and LCC methodology

In this review, the term methodology refers to the method for constructing the model(s) and the steps in analyzing the models to conduct the LCA and LCC of an ISN. The term model refers to the quantitative system constructed to represent the life cycle inputs and outputs of an ISN. The term computational method refers to the method used to analyze the constructed model(s) and compute the desired LCA and LCC results.

In this review, the systematic literature review methodology is used to shortlist peer-reviewed studies that conduct an LCA or LCC of an ISN and then identify the unique methodologies used. For each unique LCA or LCC methodology, its method for constructing the model and the computational method for analysis is explained. This review then analyzes how the existing methodologies are able to conduct multi-level LCAs and LCCs of ISNs. Finally, based on the review of the methodologies and studies, future areas of research in multi-level LCA and LCC of ISNs are discussed. The issue of cut-off versus aggregation errors in LCAs of ISNs is not included in the scope of this review as the focus is not inventory data quality for LCAs and LCCs of ISNs. The findings from this review can be used to support life cycle practitioners and ISN facilitation tool developers in future research to improve methodologies used to quantify both the environmental and economic performance of all types of ISNs for a wide variety of stakeholders.

Throughout this review, many different terms are used in the classification and analysis of the LCA and LCC studies of ISNs and the methodologies employed. For the purpose of consistency and clarity, Table 1 lists the terms frequently used and their definitions in this review.

2 Methodology

The systematic literature review methodology was employed to conduct a review process that is replicable and transparent (Denyer and Tranfield 2009). The steps of the systematic literature review methodology that were carried out to identify and analyze methodologies for conducting LCAs and LCCs of ISNs are as follows:

1 Question formulation: define scope of literature review
2 Locate studies: establish keywords and search strings
3 Study selection: review abstracts to shortlist studies
4 Analysis and synthesis: identify and analyze LCA and LCC methodologies used in ISN studies
5 Report and use results: discuss methodologies and future areas of research

2.1 Question formulation

To translate the life cycle environmental and economic performance of an ISN to the specific needs of diverse stakeholders, methodologies for multi-level LCA and LCC are required. Therefore, the primary research question of this review was:

Table 1 Definition of terms

Term	Definition
Industrial symbiosis network	A collection of entities where byproducts and wastes produced in the network are converted into resources that are consumed by other entities.
Entity	A company or another type of organization that participates in an ISN.
Methodology	Method for constructing the model(s) and the steps to analyze the model(s) to conduct the LCA and LCC of an ISN.
Model	Quantitative system that is constructed to represent the life cycle inputs and outputs of an ISN.
Computational method	The method used to analyze the constructed model(s) and compute the desired LCA and LCC results.
Network-level perspective	The life cycle environmental and/or economic performance of an entire ISN overall.
Entity-level perspective	The life cycle environmental and/or economic performance of an entity that is participating in an ISN.
Flow-level perspective	The life cycle environmental and/or economic performance of a specific flow (e.g., product, intermediary resource, waste, resource converted from a waste flow) in an ISN. An example is quantifying the life cycle environmental and/or economic performance of a waste-to-resource conversion process that takes place in an ISN.
Foreground system	Activities that take place between entities within an ISN.
Background system	Activities that take place beyond the boundary of the ISN. This includes upstream processes that supply resources to the ISN and downstream processes that treat wastes generated by the ISN.
Waste-to-resource exchange system	The processes of a waste-to-resource exchange that takes place between two or more entities in the foreground system.
Process-based approach	Constructing the life cycle inventory by identifying all the different processes that take place in the supply chain. Process-specific data is used to represent either some stages of the life cycle or all stages of the life cycle.
Process analysis	The use of process-specific data to quantify the inputs and outputs of an activity in the LCA and/or LCC.
Environmentally extended input-output analysis	The use of aggregated economic sector input-output data to quantify the inputs and outputs of an activity in the LCA and/or LCC.
Black box model	The model represents the total inputs and outputs of the system, but does not disaggregate inputs and outputs to specific activities that exist in the system.
Multi-product entity	A single entity in the ISN that produces more than one product (joint production). This could be several products or a product and byproduct (e.g., waste flow that can be recycled).

How are existing methodologies able to conduct multi-level analysis of the life cycle environmental and/or economic performance of ISNs?

The supporting questions to guide the examination of the state-of-the-art of methodologies for LCA and LCC of ISNs were:

1 What type of models and computational methods are used to represent the foreground and background systems in an LCA and/or LCC of an ISN?
2 How do existing LCA and LCC methodologies analyze the life cycle environmental and/or economic performance of a waste-to-resource conversion process that takes place between two or more entities in an ISN?
3 Is the life cycle environmental and/or economic evaluation carried out at the network-level, entity-level, and/or resource flow-level?

The first supporting question looks at how the foreground and background systems of an ISN are modeled and analyzed by the state-of-the-art LCA and LCC methodologies. In this review, the foreground system refers to all the activities that take place between entities in an ISN. The background system refers to the activities that take place beyond the boundary of the ISN which includes upstream activities that supply resources to the ISN and downstream activities that treat wastes generated by the ISN. The second supporting question seeks to understand if existing methodologies can isolate the life cycle environmental and economic performance of waste-to-resource exchanges in the ISN to quantify how certain entities are affected by specific waste-to-resource exchanges. The methodology used to analyze the waste-to-resource exchanges is relevant because it determines whether a stakeholder has to use a separate model to analyze only the waste-to-resource exchange or if a single model can be used to analyze both the network-level performance as well as the performance of a specific waste-to-resource exchange. The third supporting question aims to determine which ISN stakeholder perspectives the life cycle environmental and/or economic evaluation focused on analyzing in the studies.

2.2 Locating studies

To identify the methodologies used for conducting LCAs and LCCs of ISNs, a corpus of scientific studies was first developed. The Scopus and Web of Science databases were used to locate the studies of interest. To enable a systematic search for scientific studies, keywords to be used in the search strings were first identified as shown in Table 2.

The keywords were then used to develop the search strings that were entered in both databases to acquire the studies of interest. Only studies published between 2010 and 2019 were included in the search. A total of 263 LCA studies and 52 LCC studies of ISNs were identified after removing duplicates between both database results.

2.3 Study selection and classification

To select the studies, the abstract of each article was reviewed. For a study to be included in the corpus, the abstract had to state that an LCA or LCC of an ISN was conducted with numerical results. Table 2 summarizes the search strings used in both databases, the results of the search, and the number of studies shortlisted in the corpus for a full text review. Studies included in the corpus were then reviewed to identify the specific methodology used to conduct the LCA or LCC of an ISN and analyze its modeling and computational methods. Each LCA study was classified based on two specific characteristics:

1. How the foreground, background, and waste-to-resource exchange system were modeled
2. If the study carried out the analysis at the network, entity, and/or flow-level perspective(s)

Table 3 explains how the different LCA studies were classified in the two different characteristics.

In the case of an ISN, a black box model represents the total inputs and outputs of the ISN, but it does not disaggregate all the inputs and outputs to specific activities or entities that exist in the ISN. Black box models are advantageous at the network level when the analysis is focused on the overall life cycle inputs and outputs of the ISN. Thus, it is not necessary to analyze the intermediary processes that take place within the ISN. Although the use of a black box model is useful for network-level analysis, it limits the user's ability to do entity-level and flow-level analysis where it is necessary to know how changes in specific processes within the ISN affect the environmental and economic performance of specific entities and the waste-to-resource exchanges between entities.

3 Results

3.1 Synopsis of methodologies and studies

3.1.1 Environmental evaluation

Through a full text review of 42 LCA studies and 11 LCC studies of ISNs, a total of eight unique methodologies for conducting an LCA and LCC were identified, which are listed in Table 4.

Among the 42 LCA studies, four were methodology and review studies and one study used three different LCA methodologies. Therefore, a total of 40 LCAs were conducted in the corpus. S1 in the electronic supplementary material lists the LCA studies shortlisted for a full text review and the methodologies used. Figure 1 illustrates the number of LCA studies of ISNs conducted based on the type of methodology used and the year the study was published.

The seven unique LCA methodologies used in the corpus of studies can be categorized along a similar spectrum introduced by Crawford et al. (2018) where process-based LCA and input-output LCA represent the two ends, and everything

Table 2 Keywords, search strings, and search results

Study type	Life cycle environmental evaluation of industrial symbiosis		Life cycle economic evaluation of industrial symbiosis	
Group	A	B	A	B
Main term	Life cycle assessment	Industrial symbiosis	Life cycle cost	Industrial symbiosis
Synonyms	LCA	Eco-industrial park	LCC	Eco-industrial park
	Environmental impact	Eco-industrial park	Cost analysis	Eco-industrial park
	Material flow analysis		Economic analysis	
	MFA			
Search string	["life cycle assessment" OR LCA OR "environmental impact" OR "material flow analysis" OR MFA) AND ("industrial symbiosis" OR "eco industrial park" OR "eco-industrial park"]		["life cycle cost" OR LCC OR "cost analysis" OR "economic analysis" OR "economic assessment") AND ("industrial symbiosis" OR "eco industrial park" OR "eco-industrial park"]	
Scopus database	200 studies		47 studies	
Web of Science database	156 studies		10 studies	
Final (duplicates removed)	263 studies		52 studies	
Full text review	42 studies		11 studies	

Table 3 Categories for classifying LCA of ISN studies

Characteristic	Category	Requirement
Type of analysis	Process analysis	Uses process-specific data to quantify the inputs and outputs of an activity in the LCA and/or LCC.
	Environmentally extended input-output analysis	Uses aggregated economic sector input-output data to quantify the inputs and outputs of an activity in the LCA and/or LCC.
	Black box	The model represents the total inputs and outputs of the system, but does not disaggregate inputs and outputs to specific activities or ISN entities that exist in the system.
Stakeholder perspective examined in study	Network-level perspective examined	1. The study's objective was to quantify the life cycle environmental and/or economic performance of the ISN overall. 2. Results at the network-level are presented or discussed in the study.
	Entity-level perspective examined	1. The study's objective was to quantify the life cycle environmental and/or economic performance of one or more entities in the ISN. 2. Results for specific entities in the ISN are presented or discussed in the study.
	Flow-level perspective examined	1. The study's objective was to quantify the life cycle environmental and/or economic performance of a waste-to-resource conversion in an ISN. 2. Results for specific flows or a waste-to-resource conversion are presented or discussed in the study.

in between represents different tiered hybrid LCA methodologies as shown in Fig. 2.

The spectrum in Fig. 2 shows that there were several overlaps between the seven LCA methodologies used in the ISN studies listed in S1 of the electronic supplementary material. A majority of the LCA studies (95%) used a process-based approach to conduct the LCA of the ISN. In a process-based approach, the life cycle inventory was constructed by identifying all the different processes that take place in the supply chain. Through the process-based approach, process-specific data is used to represent either some stages of the life cycle or all stages of the life cycle. However, the LCA methodology used in studies that took a process-based approach used different methods to represent the foreground and background systems. Figure 3 maps the number of LCA studies to the specific methodologies used.

The process-based LCA methodology was the most prominently used methodology as 31 out of 40 LCAs conducted (77.5%) used only process analysis to represent the foreground and background systems. In process analysis, process-specific data is used to quantify the inputs and outputs of an activity in the LCA. Tiered hybrid LCA methodologies were the second most prominently used for quantifying the life cycle environmental performance of ISNs. The (1) integrated material flow analysis, carbon footprint, and emergy analysis methodology and the (2) integrated material/energy flow analysis, process LCA, and hybrid input-output model were categorized as tiered hybrid LCA as shown in Figs. 2 and 3. This is because those two methodologies use process analysis to represent the foreground system and waste-to-resource exchange system and environmentally extended input-output analysis to represent the background system.

Table 4 Methodologies identified for conducting LCA and LCC of ISNs

Methodology name	Environment consideration	Economic consideration	Number of studies
Process-based LCA	Yes	No	31
Input-output LCA	Yes	No	1
Tiered hybrid LCA	Yes	No	4
Hybrid physical input and monetary output model	Yes	No	1
Integrated material flow analysis, carbon footprint, and emergy analysis	Yes	No	1
Integrated material/energy flow analysis, process LCA and a hybrid input-output model	Yes	No	1
Systematic methodology for the environomic design and synthesis of energy systems	Yes	Yes	1
Life cycle costing	(Yes, through externalized cost)	Yes	9

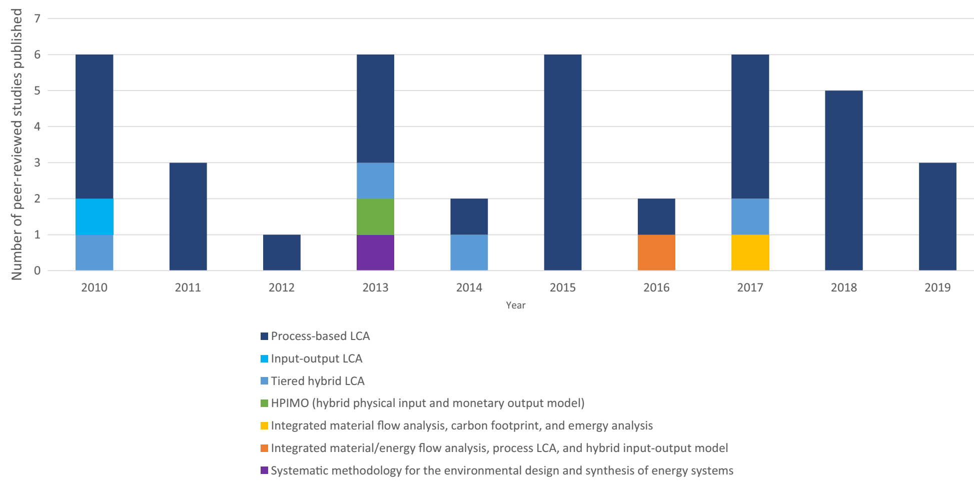

Fig. 1 Methodologies used in peer-reviewed LCA studies of ISNs published between 2010 and 2019

3.1.2 Economic evaluation

In economic evaluations, the review revealed that only two types of methodologies were used to measure the life cycle economic performance of ISNs. These were the LCC methodology (Swarr et al. 2011; Moreau and Weidema 2015; Reddy et al. 2015) and the systematic methodology for the environomic design and synthesis of energy systems. Fewer economic evaluations of ISNs have been conducted compared with environmental evaluations, especially economic analyses that conduct a comprehensive LCC. Compared with the 42 LCA studies shortlisted from the systematic search process, only 21 studies from the total 53 shortlisted included an economic analysis. Figure 4 illustrates the number of studies shortlisted that included an economic analysis of an ISN and the methodology used.

Only two studies explicitly stated the use of the LCC methodology for economic analysis of ISNs (Lim and Park 2010; Jung et al. 2012). Seven other studies applied the LCC methodology for economic analysis by including capital and operating expenses, but did not explicitly state the use of the LCC methodology. Only one study used the systematic methodology for the environomic design and synthesis of energy systems to conduct the LCC. There were 11 studies that used other methodologies for an economic analysis. There was a range of types of economic analyses of an ISN which included determining the financial feasibility, net present value (NPV), profitability, or payback period. The details regarding the type of economic analysis that each LCA and LCC study carried out can be found in S2 of the electronic supplementary material. The economic analyses varied in the types of costs accounted for due to differences in objectives. Some studies included only capital costs or only operation costs while others included both types of costs. Certain studies accounted for the time value of money through an NPV analysis, while other studies excluded this. Taxes, waste treatment, and recycling costs were included as operation costs in some studies and were not included in others.

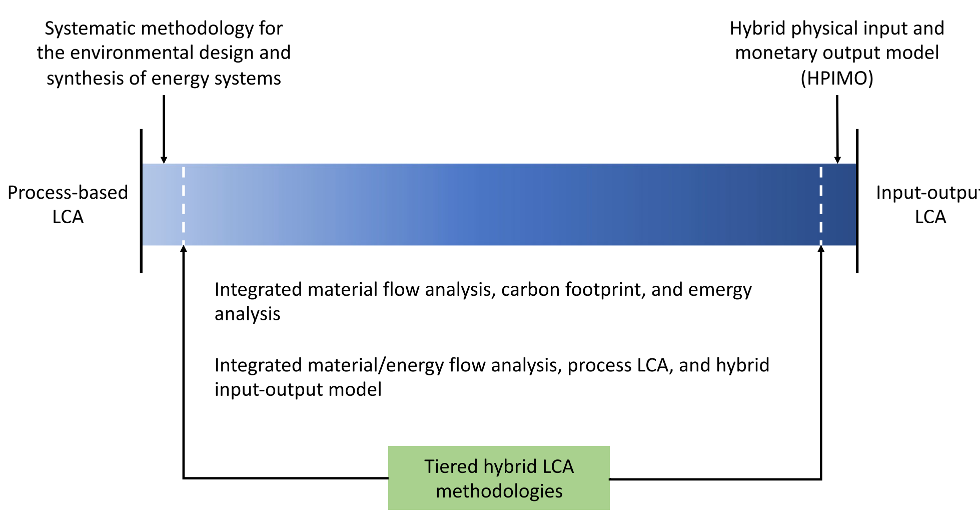

Fig. 2 Spectrum of LCA methodologies used in ISN studies

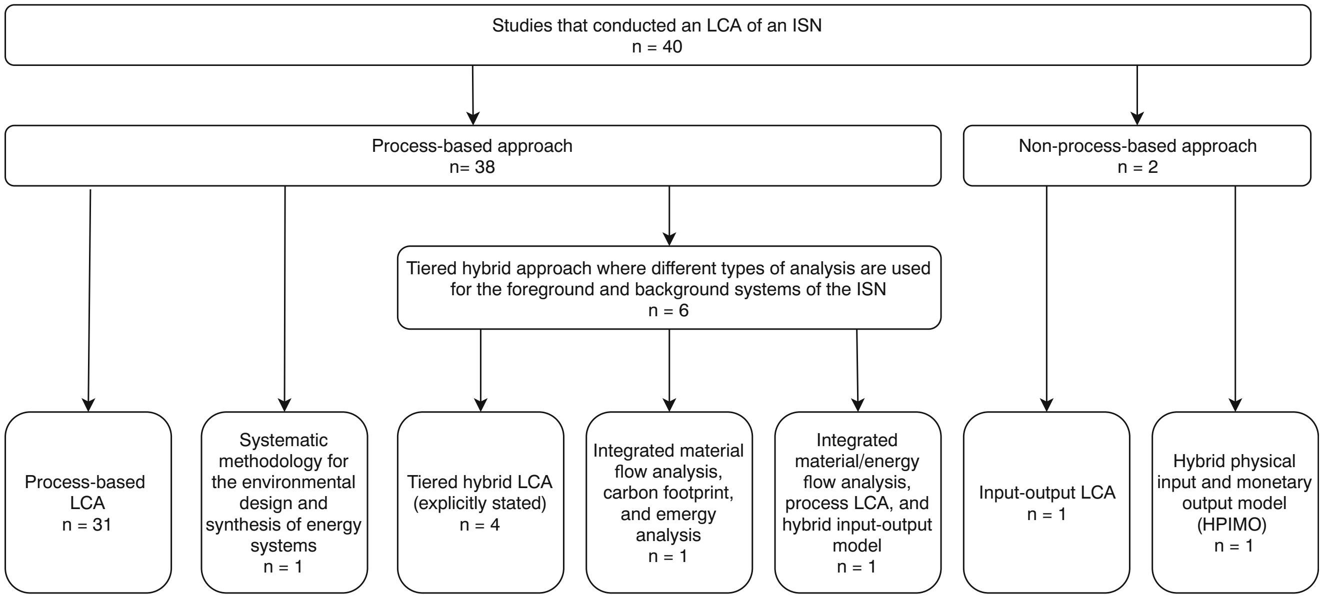

Fig. 3 Categorization of LCA methodologies used in studies reviewed

3.2 Analysis of LCA and LCC methodologies

This section provides an overview of the different methodologies listed in Table 2 that were used to conduct an LCA or LCC of ISNs. For each methodology, details are provided about how the LCA and LCC models are constructed and the computational method used to analyze the model and produce results at the network, entity, and resource flow levels. Details are also provided about how waste-to-resource exchanges are represented in each methodology. Although there are overlaps between some methodologies with regard to how the models are constructed and analyzed, each methodology is dedicated its own subsection because each one is unique overall. Some methodologies consider a

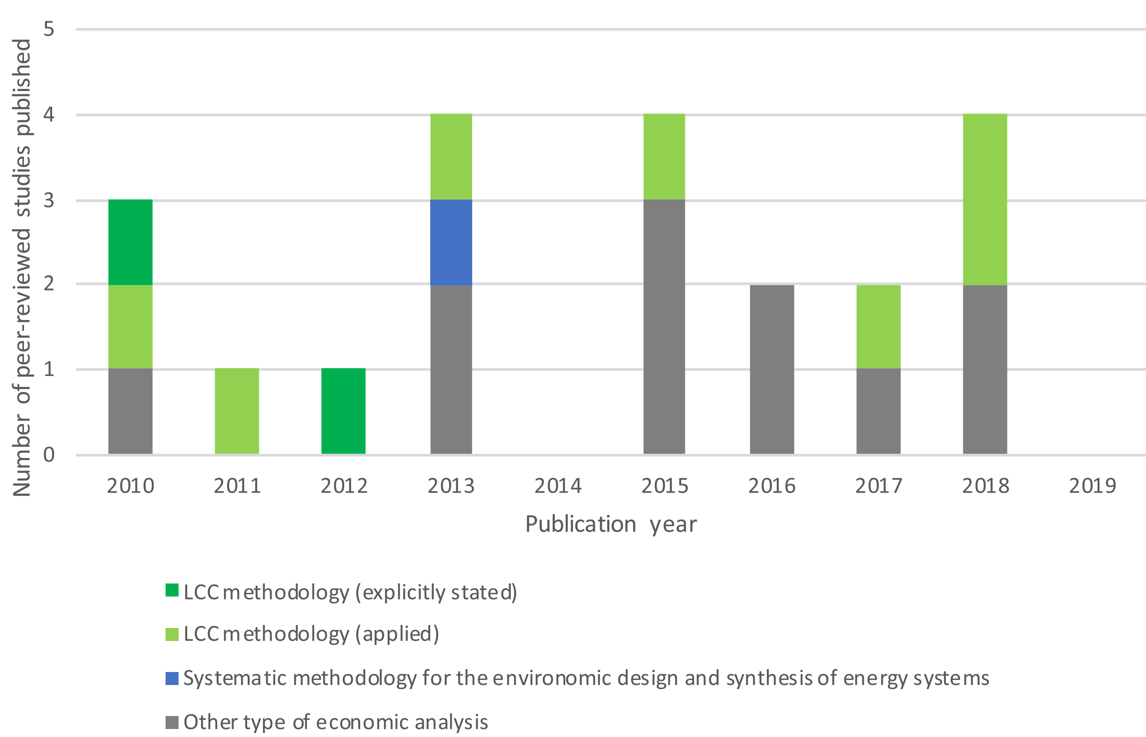

Fig. 4 Studies with an economic analysis of ISNs published between 2010 and 2019

specific number of impact categories while others do not state a limit. As shown in Table 4, certain methodologies consider only the environmental dimension or the economic dimension or both.

3.2.1 Process-based life cycle assessment

The process-based LCA methodology uses a bottom-up approach to compute the environmental impacts associated with the inputs and outputs of a product or service across all life cycle stages considered within the scope of the LCA study. To construct the model, a process flow diagram is first created to represent all unit processes of a product or service system thereby constructing a life cycle inventory (LCI). Each process is represented as a ratio between the number of inputs and outputs and all processes are interconnected by commodity flows. Through regular algebra, the amount of material, energy, water, and emission input and outputs of each unit process is multiplied by specific reference flows to meet a defined functional unit. The total emissions and resources consumed are then multiplied by characterization factors in different impact categories of interest to compute the total potential environmental impacts. Two modeling and analysis methods used in the process-based LCA methodology are the matrix-based model and sequential equations. In sequential equations, the computation of inputs and outputs are done in sequential order going from one unit process to the next, and each process is scaled according to its input to the overall product or service being modeled. The matrix-based model was introduced by Heijungs and Suh in *The Computational Structure of Life Cycle Assessment* (2002) and uses a system of linear equations to compute the LCI.

A total of 31 studies have used the process-based LCA methodology to quantify the life cycle environmental impacts of ISNs. In these studies, process analysis was used to represent all activities in the foreground and background system as well as all waste-to-resource exchanges in the ISN. There are two approaches to compute LCA results of an ISN at just the network level. The practitioner can either (1) construct multiple different models that represent each entity and waste-to-resource exchange process in the ISN or (2) construct a single matrix-based model that represents all entities and their intermediary life cycle processes. A few LCA studies have stated the use of multiple separate LCA models to represent each entity in the ISN (Martin et al. 2015; Kim et al. 2018; Hildebrandt et al. 2019). To generate the network-level life cycle environmental impacts, the studies take the total sum of each process-based LCA model's results for each entity in the ISN, per the defined functional unit. The purpose of this modeling approach is to not treat the network as a black box and instead gain process-specific detail. This is done so that the impacts of waste-to-resource exchange processes can be allocated, if necessary, to specific entities participating in the ISN. In a matrix-based model, the environmental impacts of a bundle of products can be calculated in one computation by specifying multiple values in the demand vector (Heijungs and Suh 2002). Results at the entity-level are computed by analyzing each process-based LCA model constructed for the specific entity if multiple separate models are constructed. In a matrix-based model representing multiple entities in the ISN, the environmental impacts of one entity in the ISN can be analyzed by specifying only the demand vector value for the product of interest. To obtain flow-level LCA results of one specific output from an entity with multiple products and byproducts, the entity-level LCA results would need to be disaggregated down to each product and byproduct from the entity. In a process-based LCA methodology, waste-to-resource exchanges between the entities can be computed separately by modeling the process for waste-to-resource exchange and having the process consume a waste flow generated by another entity in the ISN.

3.2.2 Input-output life cycle assessment

The input-output LCA methodology (IO-LCA) uses environmentally extended input-output analysis (EEIOA) to represent the foreground and background systems of the ISN as well as waste-to-resource exchanges that take place. Wassily Leontief developed input-output analysis to model the various inputs needed to produce a unit of output in each economic sector (Leontief 1970). By modeling all the sectors, input-output analysis can trace all direct and indirect inputs to produce outputs in each sector. IO-LCA assumes that industry sectors consume outputs from other sectors in fixed ratios and that monetary flows are a fair indication of the physical flows within an economy (Crawford et al. 2018). To construct the model, data from economic input-output tables are used to define input-output direct requirements matrix A, an nxn matrix where n represents the number of industry sectors within an economy. Each column of A represents the industry output in monetary values that is needed to produce one monetary output of another industry.

To compute the life cycle environmental impacts, a vector $\mathbf{x}$ is defined to represent the total required inputs from the economy in matrix A and $\mathbf{y}$ is the vector of total purchase of industry outputs, which represents the functional unit. The total domestic industry output x required to supply a total demand of vector $\mathbf{y}$ is computed by Equation 1

$$x = (\mathrm{I}-\mathrm{A})^{-1}\mathrm{y} \tag{1}$$

where I denotes an $n \times n$ identity matrix. To compute the environmental emissions, a $q \times n$ matrix B is defined to represent a q amount of different environmental pollutants for each industry sector n. The total direct and indirect pollution emissions and resources consumed are then calculated by Equation 2

$$M = Bx = B(I-A)^{-1}y \tag{2}$$

where **y** is an arbitrary vector that shows net industry output of the system. The direct and indirect pollution and resource consumption values in matrix M can then be multiplied by LCA characterization factors to compute the potential environmental impacts. Readers can refer to Hendrickson et al. (2006) and Mattila (2018) for further discussion regarding the mathematics of IO-LCA.

Only one study by Mattila et al. (2010) used the IO-LCA methodology to quantify the life cycle environmental impacts of ISNs. In this LCA study, EEIOA is used to represent the foreground and background systems, and the ISN is treated as a black box where the process-specific data of waste-to-resource exchange processes are not known. Thus, any changes between different ISN scenarios, such as avoided virgin resource requirements, would be attributed to the change in total inputs and outputs of the foreground system of the ISN. To compute the life cycle environmental impacts of an ISN through the IO-LCA methodology, the first step is to calculate the total inputs and outputs of the ISN that is treated as a black box for the scenarios before and after waste-to-resource exchanges. Then, the inputs and outputs of the ISN for each scenario are converted to monetary purchases from economic sectors and are then multiplied with the corresponding emission factors (Mattila et al. 2010). Price data, such as monetary use tables, is needed to convert the resource flows into the economic flows used in the IO-LCA.

To analyze the network-level LCA results of the ISN through the IO-LCA methodology, industry demand vector **y** would need to specify the monetary value of the products for all entities in the ISN. The IO-LCA methodology is able to conduct entity-level analysis by specifying the monetary value of the products from one specific entity in a particular industry sector. Analysis of the impacts of specific waste-to-resource exchange processes between specific entities in an ISN would require more disaggregated industry sector data. Input-output tables currently do not include information on waste flows. Flow-level analysis of joint production of products and recyclable waste flows at a single entity in the ISN could be done through the use of construct models (Majeau-Bettez et al. 2018).

3.2.3 Tiered hybrid life cycle assessment

The tiered hybrid LCA methodology uses process-based LCA and IO-LCA to combine the strengths both methodologies offer. To construct a tiered hybrid LCA model, process-based LCA is used to model the foreground system, and IO-LCA is used to model the background system and any remaining life cycle stages not covered by the process-based LCA. In the tiered hybrid LCA methodology, the process-based LCA and IO-LCA systems are treated separately and flexible interaction is not possible (Suh and Huppes 2005). Therefore, to compute the life cycle environmental impacts, process-based LCA is used to quantify the foreground system inputs and outputs for all entities in the ISN. The process-based LCA methodology is also used to quantify the inputs and outputs of the transportation and end-of-life processes for entities in the ISN. Then, the IO-LCA methodology is used to quantify the environmental impacts of the upstream production processes in the background system of the ISN. The LCIs developed from the process-based LCA and IO-LCA components of the tiered hybrid model are then combined to determine the total life cycle environmental impacts.

A total of four studies stated the use of the tiered hybrid LCA methodology to evaluate the environmental impacts of an ISN (Mattila et al. 2010; Dong et al. 2013a, 2014, 2017). Dong et al. (2013a, 2014) and Mattila et al. (2010) used the IO-LCA model only for the upstream processes in the background system of the ISN while process-based LCA was used to represent the foreground system and downstream processes of the ISN. Dong et al. (2017) specifically use the hybrid physical input and monetary output model, a type of IO-LCA methodology discussed later, to represent both upstream and downstream processes in the background system of the ISN. To conduct an LCA of an ISN at multiple levels through the tiered hybrid LCA methodology, the same steps explained for multi-level analysis using the process-based LCA methodology would be followed (section 3.2.1). However, the difference for the tiered hybrid LCA methodology is that upstream production processes in the background system of the ISN would be modeled using the IO-LCA methodology instead of the process-based LCA methodology. Since the process-based and IO-LCA components of the tiered hybrid LCA are not a single integrated model (Suh and Huppes 2005), the reviewed studies that use the tiered hybrid LCA methodology have reported that two separate computations would have to be done (Dong et al. 2017). The first computation for the foreground system would be done through either the matrix-based model or sequential equations. Then, the second computation for the background system would be done through EEIOA where aggregated industry sector data are used instead of process-based inventory data. It should be noted that other hybrid LCA methodologies such as the integrated hybrid LCA and the matrix augmentation methodology (also often referred to as input-output-based hybrid) would be able to carry out multi-level analysis in a single computation. However, none the studies examined in this reviewed reported the use of the integrated hybrid LCA or matrix augmentation methodology to carry out the LCA of an ISN.

3.2.4 Hybrid physical input and monetary output model

The hybrid physical input and monetary output model (HPIMO) methodology was developed by Dong et al. (2013b) to assess the environmental benefits of urban industrial symbiosis. The HPIMO methodology uses the same model construction process and computational method as the IO-LCA methodology. However, this methodology uses hybrid units that are both monetary and physical. This methodology was designed to quantitatively represent the correlations between economic sectors through monetary input-output tables and build the connections between environmental and economic systems. To construct the model, an $n \times n$ matrix M is defined that represents the monetary interactions among sectors, with n representing the number of sectors. Then, an $m \times n$ matrix E is used to represent physical energy resources (e.g., tons of raw coal, gasoline, liquid natural gas, fuel oil) consumed by the different sectors, with m representing the different types of physical energy resources. An $n \times 1$ column vectors $\mathbf{y}$ and $\mathbf{x}$ represent final demand and total output, respectively, of each sector in monetary units. An $n \times k$ matrix P indicates the pollution emissions of each sector, with k representing the number of pollutants being measured. Since the HPIMO methodology follows the same computational method of the IO-LCA methodology, the Leontif inverse is used to compute the life cycle environmental impacts of the ISN. The row balance equations are shown in Equation 3 and 4:

$$\mathrm{Ax} + \mathrm{y} = \mathrm{x} \tag{3}$$

$$\mathrm{x} = (\mathrm{I–A})^{-1}\mathrm{y} \tag{4}$$

The relationship between total energy consumption and final demand as well as the relationship between environmental emissions and final demand is represented through Equations 5 and 6 where D is the total energy consumption and W is the total environmental emissions.

$$\mathrm{D} = \mathrm{Ex} = \mathrm{E}(\mathrm{I–A})^{-1}\mathrm{y} \tag{5}$$

$$\mathrm{W} = \mathrm{Px} = \mathrm{P}(\mathrm{I–A})^{-1}\mathrm{Y} \tag{6}$$

Using the HPIMO methodology to compute the LCA results of the ISN at the network, entity, and flow levels, as well as specific waste-to-resource exchanges would follow the same procedure that was discussed previously for the IO-LCA methodology (section 3.2.2).

3.2.5 Integrated material flow analysis, carbon footprint, and emergy analysis

The integrated material flow analysis, carbon footprint, and emergy analysis (I-MFA-CF-EA) methodology was developed by Ohnishi et al. (2017) to evaluate the environmental benefits of industrial and urban symbiosis systems. As shown in Fig. 3, this methodology takes a process-based approach to LCA of an ISN except different methods are used to represent the foreground and background systems just like a tiered hybrid LCA. The I-MFA-CF-EA methodology first defines the entities in the foreground system of the ISN and the scenarios to be analyzed. What differentiates this methodology is that a material flow analysis (MFA) is conducted to quantify the input and output flows of the ISN's foreground system for each scenario. The MFA component treats each ISN scenario as a black box and quantifies all material, energy, water, and emissions that are inputs and outputs to the entire ISN within a defined time period. The results of the MFA are then used in two separate models to analyze the carbon footprint and emergy. To compute the life cycle carbon footprint, the tiered hybrid LCA methodology is used, specifically the methodology by Dong et al. (2013a). The life cycle stages covered by the carbon footprint are direct energy consumption, industrial processes, upstream material production emission, depreciation, electricity and heat production, and waste treatment. To conduct the emergy analysis, the energy and material inputs of the ISN quantified from the MFA are multiplied by transformity factors to convert all values to a single emergy unit of emjoules. The results from the MFA are then used to estimate the impacts to the environment through a carbon footprint and emergy analysis. Emergy analysis involves the transformation different kinds of energy, materials, and goods and services into the same unit through transformity factors (Odum 1988).

To use the I-MFA-CF-EA methodology to compute the LCA results of the ISN at the network, entity, and flow levels, the input values of the MFA have to be specified according to the level of interest. Therefore, to analyze the life cycle environmental impacts of the whole network, the scope of the MFA would have to include all entities in the ISN. To analyze a single entity or output flow in the ISN, the scope of the MFA would be limited to the entity or single output flow from the entity. Depending on whether the scope is defined as the whole network, entity, or an output flow, the results of the MFA would then be used as inputs to the carbon footprint and emergy analysis of the I-MFA-CF-EA methodology. Since the I-MFA-CF-EA methodology treats ISN scenarios as black boxes and does not use process analysis in the foreground system, waste-to-resource exchanges are represented as the net change in results of the different scenarios which are avoided or additional resource requirements and emissions in the foreground and background systems.

3.2.6 Integrated material/energy flow analysis, process LCA, and a hybrid input-output model

The integrated material/energy flow analysis, process LCA, and hybrid input-output model was developed by Dong et al. (2016) to quantify the life cycle environmental impacts of industrial and urban symbiosis. This methodology can be categorized under the process-based approach as shown in Fig. 3 and uses the tiered hybrid LCA methodology. Each entity is represented as a single process. To construct the model, material and energy flow analysis and process-based LCA models are developed to quantify the flows in the foreground system of the ISN. What differentiates this methodology is the use of an equation to represent the different flows between entities in an ISN. The relationship between the variables for the different flows is represented in Equation 7

$$A_M + Q_M + F_{M-1} = R_M + F_M + J_M + P_M + D_M \quad (7)$$

In the foreground system, each entity's input flows include:

- A_M, flows from the environment
- F_{M-1}, flows from upstream production processes
- Q_M, recycled material flows from other processes

Output flows include:

- F_M, a flow output from process M
- P_M, product flow
- R_{M-i}, recycled material flows reclaimed from a process M which is fed into an upstream process M_{-i},
- J_{M+j}, flow reclaimed from process M which goes to a downstream process M_{+j}
- D_M, the dissipative flows discharged to the environment

The IO-LCA methodology is then used to represent the environmental impacts of upstream and downstream processes in the background system of the ISN. The inputs to the IO-LCA model for the background system of the ISN are dependent on the material, energy, and water flows quantified in the foreground system which were determined by the material and energy flow analysis and process-based LCA.

Similar to the tiered hybrid LCA methodologies previously discussed, the material and energy flow analysis and process LCA model in the foreground system and the IO-LCA model in the background system are separated from each other. To analyze the environmental impacts of each individual entity and their respective products, the parameters for each model would need to be modified separately. Since this methodology relies on the results of the material and energy flow analysis to compute the life cycle environmental impacts, the LCA results for the network, entity, and flow levels are dependent on which processes the energy and material flow analysis includes. If the network-level results are of interest, every entity's processes would need to be included in the material and energy flow analysis. If the entity-level results are of interest, then only processes for the specific entity would be included in the material and energy flow analysis. Environmental impacts from upstream production processes, identified through the material and energy flow analysis, are then computed through EEIOA. Waste-to-resource exchanges are represented as avoided or increased use of resources depending on how the ISN scenario is defined through the material and energy flow analysis in the foreground system.

3.2.7 Systematic methodology for the environomic design and synthesis of energy systems

The systematic methodology for environomic design and synthesis of energy systems was developed by Gerber et al. (2013) to design eco-industrial parks or urban systems, identify the best conversion pathways of resources or waste, or to fix the optimal value of environmental taxes. This methodology considers both environmental and economic evaluation, unlike the previous methodologies that were discussed. It is a mixed integer non-linear programming multi-objective optimization model where the goal is to simultaneously minimize the economic costs and environmental impacts of the ISN. This methodology uses the process-based LCA methodology to compute the life cycle environmental impacts of an ISN. Unlike previous methodologies discussed, this one is focused on optimization of the environmental and economic impacts of an ISN as opposed to constructing analytical models. To construct the model, a superstructure is defined which includes all the different technology conversion processes that exist in the ISN. Each process in the superstructure is modeled using a flowsheeting software or average models that pull data from LCI databases such as Ecoinvent. Energy and mass flows for each process are then calculated based on a set of given operational conditions. Each process in the superstructure is scaled by a utilization factor.

A process-based LCA model is used to compute the environmental impacts and economic costs of different ISN scenarios that are determined by waste-to-resource exchanges set up by the optimization model. To build the waste-to-resource exchanges in the ISN, the model conducts supply chain synthesis by solving a mixed integer linear programming problem to determine the optimal values for utilization factors of each process. Through the optimization process, matches are made between sources and sinks with respect to the definition of the functional unit which determine the possibilities for recycling of wastes within the network. Once the potential recycling configurations are determined, the model then determines the minimum environmental impacts and economic costs and computes the results. To analyze the impacts at the network and entity levels, the user would need to turn on or off the existence of specific waste-to-resource exchange processes in the ISN superstructure through a decision variable and then analyze the overall change in the system's environmental impacts and economic costs. It should be noted that as an optimization model, only the minimal environmental impacts and economic costs would be determined, and so for the model to explore the case of the greatest impacts and costs, the objective of the optimization model would need to be modified.

3.2.8 Life cycle costing

The LCC methodology is used to assess all the costs associated with a product over its entire life cycle and can be used to economically evaluate a project or investment (Swarr et al. 2011; Reddy et al. 2015). Several different methods can be used to conduct an LCC. Heijungs et al. (2013) and Moreau and Weidema (2015) discuss a method for constructing a matrix-based model for conducting an LCC of single products. Moreau and Weidema (2015) define LCC as the sum of all value added (also referred to as profit margin) over the life cycle of a product or service. Reddy et al. (2015) define an equation with different cost variables which are listed in Table 5.

To compute the LCC using the method outlined by Reddy et al. (2015), each cost is annualized and then a summation is done as shown in Equation 8.

$$\mathrm{LCC}_{xt} = f\left\{\sum_{t=1}^{n}(\mathrm{CapExhw}_{xt};\mathrm{CapExsw}_{xt};\mathrm{CapManEx}_{xt};\mathrm{CoCap}_{xt};\mathrm{DsCost}_{xt};\mathrm{IDsCost}_{xt};\mathrm{OpEx}_{xt}) + \mathrm{CoEExt}_{xt}\right\} \tag{8}$$

To make both the present and future costs comparable and account for the time value of money, the present value of the costs is then computed through Equation 9 where pvf_{xt} = present value factor $(1 + \mathrm{r})^t$; r = interest rate or inflator; t = time period.

$$\mathrm{LCC}_{xt} = f\left\{\sum_{t=1}^{n} pvf_{xt}(\mathrm{CapExhw}_{xt};\mathrm{CapExsw}_{xt};\mathrm{CapManEx}_{xt};\mathrm{CoCap}_{xt};\mathrm{DsCost}_{xt};\mathrm{IDsCost}_{xt};\mathrm{OpEx}_{xt}) + \mathrm{CoEExt}_{xt}\right\} \tag{9}$$

The LCC model can be used to compute the NPV, internal rate of return, total cost of ownership, payback period, savings investment ratio, and conduct cost-benefit analysis. Each of the financial indicators is valuable to specific decision-makers for their project needs. The LCC methodology can account for impacts to the environment, but this is usually expressed in terms of the financial cost of environmental externalities.

Out of the 12 studies in the literature review that conducted an economic analysis of ISNs, only two studies (Lim and Park 2010; Jung et al. 2012) explicitly stated the use of the LCC methodology. The LCC studies shortlisted did not cite a specific methodology for conducting the LCC such as matrix-based modeling or a set of equations. Instead, they provide detailed explanations about the assumptions and cost variables used. To conduct multi-level economic analysis of ISNs, multiple LCC models need to be constructed for each entity to analyze the costs of the whole network, individual entities, and resource flows. The network-level results are computed by summing the results of the LCC models for each entity in the ISN. A single LCC is needed for each entity because, in the case of ISNs, there are waste-to-resource transactions between different entities, and a monetary value that is a cost for one entity could also be revenue for another. Thus, monetary data is collected for each process from the perspective of each entity. Furthermore, different businesses in an ISN have different types of operation and capital costs that are incurred in different years. Operation costs for businesses are usually incurred on an annual basis, but businesses may have a wide range of different types of operation costs that may be incurred every 2 or 3 years or more instead of annually. In terms of capital costs, equipment for certain entities may have a longer lifetime than equipment used by other entities in the ISN depending on the type of business they are. Therefore, the upfront equipment costs as well as equipment replacement, repair, and maintenance can all take place in different years of the life cycle. The costs of waste-to-resource exchanges are accounted for as an end-of-life cost or an operation cost, and

Table 5 Parameters of the LCC methodology (Reddy et al. 2015)

Parameter	Definition
$\mathrm{CapExhw}_{xt}$	Capital expenditure on hardware (initial construction cost)
$\mathrm{CapExsw}_{xt}$	Capital expenditure on software
$\mathrm{CapManEx}_{xt}$	Capital management expenditure (rehabilitation cost)
CoCap_{xt}	Cost of capital
DsCost_{xt}	Direct support costs
$\mathrm{IDsCost}_{xt}$	Indirect support costs
OpEx_{xt}	Annual operation and maintenance cost
CoEExt_{xt}	Cost of environmental externalities

x represents the product or service and t represents the year the financial value gained from selling a byproduct or waste as a resource is accounted for as revenue.

4 Discussion and outlook

In this review, the objective was to examine the state-of-the-art methodologies for conducting life cycle environmental and economic evaluations of ISNs and how these methodologies can be used to carry out multi-level analysis to meet the needs of different stakeholders participating in an ISN. The review of the LCA and LCC studies and methodologies that evaluate ISNs revealed several trends that provide answers to the supporting research questions.

4.1 Foreground and background systems of ISNs

The first supporting question of the review was “What type of models and computational methods are used to represent the foreground and background systems in LCA and LCC of ISNs?” Current methods used to represent either the foreground or background systems were process-based LCA, material and energy flow analysis, and EEIOA. For LCA studies of ISNs, the process-based LCA methodology was a prominent choice. A total of 30 out of 40 LCAs (75%) used only process-based analysis for the entire study covering the foreground, background, and waste-to-resource exchange system. Only two LCA studies used EEIOA to represent both the foreground and the background systems. Six studies used the tiered hybrid LCA approach where the process-based LCA methodology or an MFA was used for the foreground system, and EEIOA was used for the background system of the ISN. The rationale a few studies cited for using the tiered hybrid LCA methodology in their studies was the difficulty of accessing inventory data in their countries to represent upstream material supply and transport in the background system (Dong et al. 2013a, 2016, 2017). Thus, a pure process-based LCA model was not able to support their analysis. In these instances, the tiered hybrid LCA methodology was selected to address an LCA inventory data gap challenge as opposed to improving flexibility in modeling and analysis of the ISN.

In economic evaluation of ISNs, the studies did not explicitly state a specific model and computational method for conducting the LCC. Thus, specific methodologies for representing the foreground and background systems were not stated as well. Based on the information provided by the authors, nearly all the economic evaluation studies took a process-based approach to conducting the LCC. The direct costs for a single entity or the entire network were computed by accounting for capital costs, operation costs, revenue from the sale of valuable waste streams, and the time value of money. Only two studies took a macro-economic approach to evaluate the economic performance of ISNs through the use of an input-output analysis model (Ferrão et al. 2015) and an econometric model (Zhang et al. 2016).

4.2 Waste-to-resource exchanges in LCA and LCC

The second supporting question of the review was “How do existing LCA and LCC methodologies analyze the life cycle environmental and/or economic performance of a waste-to-resource conversion process that takes place between two or more entities in an ISN?” Through the review, it was revealed that the two ways waste-to-resource exchanges between entities in an ISN were analyzed was either through process-based analysis or a black box approach. Four studies used the black box approach to represent waste-to-resource exchanges in the foreground system by quantifying the total inputs and outputs of the ISN for each of scenario analyzed (Mattila et al. 2010; Sokka et al. 2011; Dong et al. 2013b; Ohnishi et al. 2017). Using the black box approach to model the environmental impacts of waste-to-resource exchange scenarios will provide the same or nearly the same results for the ISN overall compared with taking a process analysis approach. Treating the ISN as a black box is useful when a stakeholder is only interested in the network-level LCA results of an ISN. However, when a stakeholder is interested in the LCA results of how a specific waste-to-resource exchange affects an entity involved in the exchange, process analysis can provide that level of granularity. Using the process-based LCA methodology to represent waste-to-resource exchanges in the foreground system can disaggregate the network-level results to the specific entities of interest which can help identify trade-offs in environmental impacts between specific entities engaged in an ISN.

Modeling and analyzing the life cycle environmental performance of waste-to-resource exchanges in an ISN reveal not only trade-offs between the network and its entities but also trade-offs between different environmental impact categories. In S1 of the electronic supplementary material, there were 29 studies that included more than one impact category in the scope of the LCA. Among the 29 studies, 13 studies discussed in the interpretation stage of the LCA that after waste-to-resource exchanges, the environmental performance of the ISN improved in some categories and became worse in other categories.

In economic evaluations of ISNs, waste-to-resource exchanges have been represented as:

1. Capital costs such as technology and infrastructure to enable exchange of waste between entities
2. Change in operation costs such as energy, water, and materials before and after waste-to-resource exchanges
3. Selling price of waste converted into a valuable resource
4. Cost savings from avoided treatment of waste

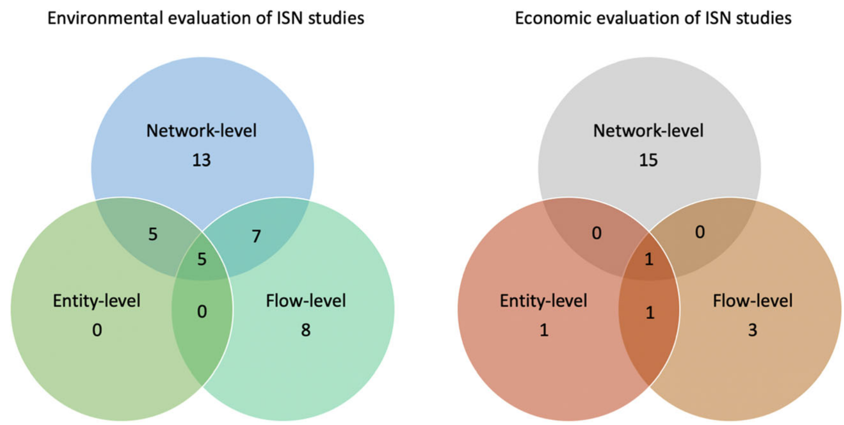

Fig. 5 Stakeholder perspectives analyzed in LCA and LCC studies of ISNs

4.3 Multi-level analysis

The third supporting question of the review was "Is the life cycle environmental and/or economic evaluation carried out at the network-level, entity-level, and/or resource flow-level?" Fig. 5 provides Venn diagrams that summarize the number of life cycle environmental and economic evaluation studies that analyzed the three different stakeholder perspectives.

In the LCA studies, 30 out of 38 studies analyzed the network-level perspective. More than half of the LCA studies analyzed the network-level perspective as well as the entity-level or flow-level perspective, or all three perspectives Among the five studies that analyzed all three perspectives, four of the studies used the process-based LCA methodology and one study used the tiered hybrid LCA methodology. Only a few studies analyzed only the flow-level perspective. Studies that focused on the flow-level perspective conducted an LCA of a waste-to-resource conversion process that could be applied in an ISN. Similar to the Venn diagram of LCA studies, a majority of the economic evaluation studies focused on analyzing the network-level perspective and only a few focused on analyzing the flow-level perspective. The classification of all the studies in this review can be found in S1 and S2 of the electronic supplementary material.

In environmental evaluation, the seven methodologies identified can provide results at each stakeholder level with different levels of granularity when analyzing specific waste-to-resource exchange processes between entities. Both the matrix-based model for process-based LCA and the IO-LCA methodology can use a single matrix to analyze the environmental performance of an ISN at both the network and entity levels. In the matrix-based model, the environmental impacts of a bundle of products can be calculated in one computation by specifying multiple values in the demand vector (Heijungs and Suh 2002). However, multiple separate technology matrices for each entity and several computations may be required if the user seeks to analyze how specific waste-to-resource exchanges in the ISN impact specific entities. Different types of allocation methodologies can be applied that determine which entities incur the environmental impacts of a waste conversion process and how much of the impacts should be allocated to the entity. Only by conducting separate LCAs for each product in the ISN will allow for the net impacts and benefits for each entity to become transparent (Martin et al. 2015). The IO-LCA methodology also allows for analysis at the network and entity levels through a single matrix, but through the use of aggregated data from input-output tables. A bundle of products from the network or a single product from an entity can be specified in the vector representing the net industry output of the system. However, if the foreground system of the ISN is treated as a black box without knowledge of processes for specific entities and waste-to-resource exchanges, limited insight can be derived regarding what environmental benefits specific entities are gaining from participating in an ISN. This is important if a decision has to be made about which entity is burdened with the impacts of a waste-to-resource exchange process and what allocation method is chosen (Martin et al. 2015).

Methodologies that conduct a tiered hybrid LCA, including the I-MFA-CF-EA and the integrated material/energy flow analysis, process LCA, and hybrid input-output model, are able to provide results at the network, entity, and resource flow levels. In the foreground system of the tiered hybrid LCA methodology, process-based LCA and MFA are used which provide detailed analysis of waste-to-resource exchange processes. However, in the tiered hybrid LCA methodologies there is a disconnection between the process-based LCA system and the EEIOA system. This prevents linking of process-based LCA model parameters to the relationships in the IO-LCA model for entity and flow-level analysis. Thus, two or more computations may be required to produce the results for each stakeholder perspective. One computation has to be done for the foreground system through process-based analysis and another computation has to be done for the background system through EEIOA.

In LCC, multi-level analysis still requires multiple separate LCC models to be constructed to represent the perspective of each stakeholder. Although matrix-based LCC methodologies have been researched (Heijungs et al. 2013; Moreau and Weidema 2015), such methods have only been tested at the scale of single-product systems. In the case of ISNs, certain monetary values can be a cost for one entity, but revenue for another, which has not yet been tested in matrix-based LCC modeling. The LCC studies that were reviewed conducted an analysis from the perspective of either the whole network or a single entity.

4.4 Future areas of research

This review provides an opportunity to identify several research opportunities in life cycle environmental and economic modeling and analysis of ISNs. Although existing LCA models of ISNs are strong in representing the foreground and background system and waste-to-resource exchanges down to the process level, further research can be done to develop a single model that can analyze the environmental impacts of the ISN from multiple perspectives at the network-level, individual entity-level, and the resource flow-level. Providing results for these different stakeholder perspectives is important because LCAs of only the total impacts of the ISN may fail to provide employable data for the entities involved in the ISN (Martin et al. 2015). Current process-based LCA approaches for evaluating ISNs require separate computations of each product system in the ISN to transparently allocate the impacts of waste-to-resource exchanges between the entities involved and avoid double counting. Being able to construct one LCA model for the entire ISN and then breaking down the results for each of the entities and valuable output flows can save time in the model construction and analysis processes. A single model could help provide results to multiple stakeholders through one computation as opposed to several computations in multiple separate models. Each business will prioritize its individualistic needs and will desire to see its own benefits of exchanging wastes in an ISN (Chertow 2000; Walls and Paquin 2015).

Similar research can also be done for LCC models of ISNs. The existing LCC methodology has proven to be successful in modeling all capital and operation costs, taxes, and waste treatment and recycling costs, as well as the time value of money to determine the feasibility, profitability, NPV, and other economic aspects of ISNs. However, many LCC studies of ISNs analyze either only the economics of the entire network, a waste-to-resource exchange process, or an individual entity within the network. An LCC methodology that can represent the network-level economic performance and then disaggregate the results down to the individual entities would be helpful in identifying potential financial benefits and trade-offs between companies engaged in partnerships within ISNs.

Research should be pursued in unifying LCA and LCC modeling and analysis of ISNs. Through unified modeling and analysis, the user would only need to construct a single model that could be used to analyze both the life cycle environmental impacts and economic costs at once instead of using separate models to conduct both types of analysis. Combining both types of analysis into a single model can help provide decision-makers in an ISN with a balanced set of information that considers both the environment and the economy (Miah et al. 2017). Research in this area has been under-explored overall as there are few methodologies and studies that comprehensively analyze the economics of ISNs from a life cycle perspective. In the studies reviewed, only two types of models were explicitly mentioned to conduct an economic evaluation of an ISN which were the LCC methodology and the systematic methodology for the environomic design and synthesis of energy systems. Out of the total 53 shortlisted studies in the systematic review, there were 21 studies that included an economic analysis. Figure 6 breaks down the type of analysis covered by studies in the corpus that included an economic analysis of an ISN.

There were 15 studies that did both an environmental and economic analysis of an ISN which included 11 studies from the LCA search results and four studies from the LCC search results. Among the 11 studies shortlisted through the LCA search, six studies did not complete a full LCC and only included one type of cost in their economic analysis, while the five remaining studies included capital, operation, and other types of costs. In the 11 studies shortlisted from the LCC search, four studies included an environmental analysis that was not based on the life cycle perspective and six studies did only an economic analysis of an ISN. A total of five studies incorporated the time value of money in their LCC or economic analysis usually by computing the NPV. Only two studies (Lim and Park 2010; Jung et al. 2012) explicitly stated the use of the LCC method to conduct an economic analysis of the ISN. There are very few studies that conduct both an environmental and economic analysis from a life cycle perspective. Only Lim and Park (2010) conducted a fully comprehensive LCA and LCC of an ISN. Seven out of the eight methodologies identified from the review were designed to conduct only either an LCA or an LCC. The only methodology that came closest to unifying the processes of LCA and LCC modeling and analysis of ISNs was the systematic methodology for the environomic design and synthesis of energy systems. However, the methodology was designed not as an analytical model but also as an optimization model to create matches based on the objective to minimize both the environmental impacts and economic costs.

These future areas of research in LCA and LCC models and computational methods can support existing industrial symbiosis facilitation tools in industry and provide environmental and economic insights to multiple stakeholders of an ISN from a life cycle perspective.

4.5 Limitations of study

This study applied the systematic review methodology to maintain a transparent, replicable, and thorough review of LCA and LCC methodologies for evaluating ISNs at multiple stakeholder levels. However, there are some limitations of this

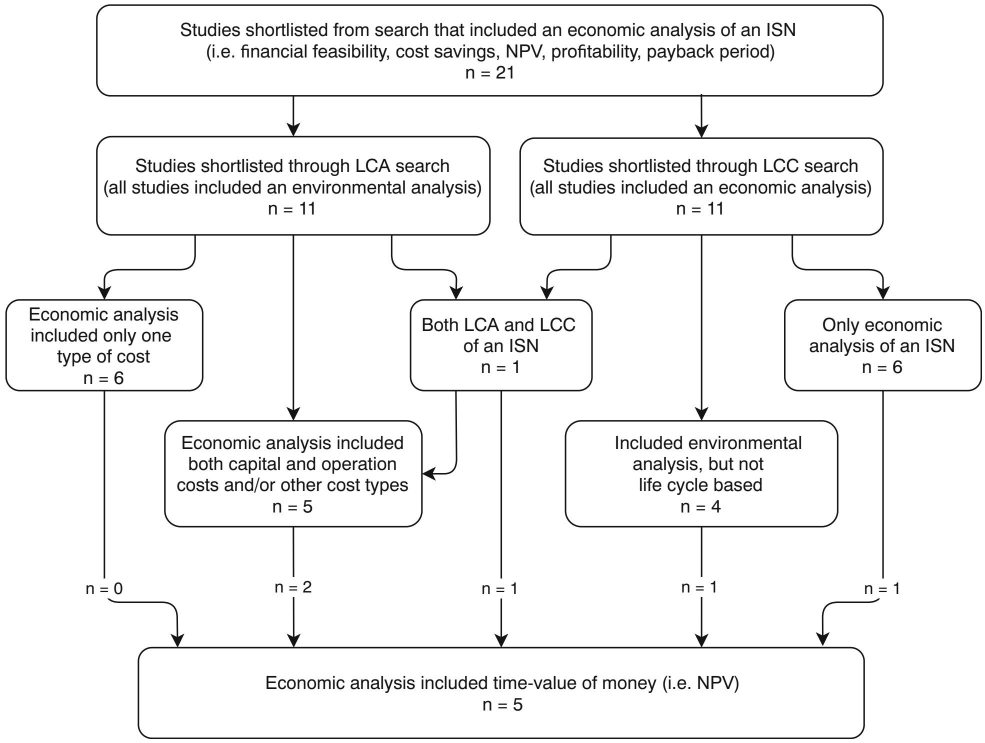

Fig. 6 Classification of studies that included an economic analysis of an ISN

review due to the niche research questions to be answered. The authors do not claim complete comprehensiveness in this review, but the results and findings provide a detailed representation of the research in methodologies for modeling and analyzing the life cycle environmental and economic performance of ISNs over the past decade.

One limitation of the review is the exclusion of other methodologies for environmental and economic analysis of ISNs. In the review of abstracts, there were studies that employed other analytical methods to evaluate the environmental and economic benefits of ISNs at a macro level. Although other methodologies besides LCA and LCC exist for environmental and economic analysis, those other methods were excluded from the full text review in order to focus on a detailed analysis on the state-of-the-art in life cycle–based modeling and analysis of ISNs. Another limitation is that single product and material recycling LCA studies were not included in the review. Such recycling processes can be applied in the industrial symbiosis context, but those studies were excluded as their scope did not state an application to industrial symbiosis.

Finally, this review does not rank each of the LCA and LCC methodologies used to evaluate ISNs to compare their performance with each other. Different modeling and analysis methodologies serve different purposes (Anex and Lifset 2014), and some methodologies may be ranked as better than others depending on the criteria specified by the intended audience of the methodology's objective. Instead, the findings from the review of the different methodologies aim at helping industrial symbiosis stakeholders gain a detailed understanding of the LCA and LCC methodologies that exist, how they can be used to provide results for multiple stakeholder perspectives, and support in deciding which methodologies are suitable for integrating with existing industrial symbiosis facilitation tools.

5 Conclusions

As industrial symbiosis practitioners continue to facilitate business-to-business waste-to-resource exchanges, methodologies will be needed that help communicate the life cycle environmental and economic performance of ISNs to a wide range of stakeholders with diverse interests. This review examined the literature of LCA and LCC studies of ISNs to examine the state-of-the-art of methodologies employed. A total of eight different LCA and LCC methodologies were identified from the corpus of studies shortlisted through the systematic literature review methodology. Each LCA and LCC methodology was analyzed in how the foreground and background systems of the ISN are modeled, how waste-to-resource exchanges between entities are analyzed, and how multi-level analysis can be done to provide results at the network, entity, and resource flow levels.

The review revealed that 95% of the LCA studies took a process-based approach in modeling and analyzing the ISN, but some studies used different methodologies to represent the foreground and background systems. Process-based LCA was used in both the foreground and background systems in 77.5% of the LCA studies, whereas a tiered hybrid LCA was used in

15% of the studies. A few authors that chose the tiered hybrid LCA methodology cited a lack of availability of process-based LCI data for the background system of the ISN and had to rely on the IO-LCA methodology to overcome this data gap. Waste-to-resource exchanges in the LCA studies were represented through process analysis or as a black box. Modeling an ISN as a black box can provide LCA and LCC results at the network level, but face limitations in analyzing the environmental and economic performance from the perspective of a specific entity. Each of the LCA and LCC methodologies identified through the review can be used to conduct multi-level analysis. Depending on the structure of the model and the number of models used to represent the foreground and background systems, either a single or multiple computations are required to produce the LCA and LCC results at the network, entity, and resource flow levels. A matrix-based model for the process-based LCA methodology and the IO-LCA methodology can analyze both a single or bundle of products in an ISN through construction of a single matrix. Tiered hybrid LCA methodologies require two or more computations to carry out multi-level LCAs because different LCA models and computational methods are used in the foreground and background system. Based on the LCC studies of ISNs reviewed, multiple separate LCC models need to be constructed to evaluate the economic performance from the perspectives of the different entities in the ISN. In LCCs of ISNs, a monetary value in a waste-to-resource exchange can either be a cost or a form of revenue depending on the perspective being analyzed.

Several future areas of research are recommended to advance multi-level LCA and LCC of ISNs. Developing a methodology for constructing a single model that can conduct an LCA and provide results to the different stakeholder perspectives through a single computation is needed. This would reduce the amount of work required by the LCA practitioner to conduct multi-level environmental performance evaluation. Such a methodology should be able to analyze how waste-to-resource exchanges impact certain entities and be flexible to different allocation methods chosen. Similar research should also be done for multi-level LCCs of ISNs as there are very few studies that conduct LCCs of ISNs which currently rely on multiple separate models to represent the perspective of each entity. Finally, research in developing a methodology for unified LCA and LCC modeling and analysis should be pursued to overcome the current approach of using separate models and computational methods for environmental and economic performance evaluation of ISNs. Through further research in unified LCA and LCC modeling and analysis of ISNs, developers of industrial symbiosis facilitation tools can benefit from simultaneous life cycle environmental and economic evaluation of the potential symbiosis connections identified, and determine how they contribute to the overall network.

References

Aissani L, Lacassagne A, Bahers J-B, Féon S Le (2019) Life cycle assessment of industrial symbiosis: a critical review of relevant reference scenarios. J Ind Ecol 23:972–985. https://doi.org/10.1111/jiec.12842

Anex R, Lifset R (2014) Life cycle assessment. J Ind Ecol 18:321–323. https://doi.org/10.1111/jiec.12157

Asian Development Bank (2019) Strengthening the environmental dimensions of the sustainable development goals in Asia and the Pacific: stocktake of national responses to sustainable development Goals 12, 14, and 15

Blengini GA, Busto M, Fantoni M, Fino D (2012) Eco-efficient waste glass recycling: integrated waste management and green product development through LCA. Waste Manag 32:1000–1008. https://doi.org/10.1016/j.wasman.2011.10.018

Boix M, Montastruc L, Azzaro-Pantel C, Domenech S (2015) Optimization methods applied to the design of eco-industrial parks: a literature review. J Clean Prod 87:303–317. https://doi.org/10.1016/j.jclepro.2014.09.032

Chertow MR (2000) Industrial Symbiosis: literature and taxonomy. Annu Rev Energy Environ 25:313–337. https://doi.org/10.1146/annurev.energy.25.1.313

Chertow MR (2007) Uncovering industrial symbiosis. J Ind Ecol 11:11–30. https://doi.org/10.1162/jiec.2007.1110

Chertow MR, Lombardi DR (2005) Quantifying economic and environmental benefits of co-located firms. Environ Sci Technol 39:6535–6541. https://doi.org/10.1021/es050050+

Chertow M, Park J (2016) Scholarship and practice in industrial symbiosis: 1989–2014 BT - taking stock of industrial ecology. In: Clift R, Druckman A (eds). Springer International Publishing, Cham, pp 87–116

Climate-KIC (2019) Municipality-led circular economy case studies

Crawford RH, Bontinck P-A, Stephan A, et al (2018) Hybrid life cycle inventory methods – A review. J Clean Prod 172:1273–1288. https://doi.org/10.1016/j.jclepro.2017.10.176

Denyer D, Tranfield D (2009) Producing a systematic review. In: The sage handbook of organizational research methods. Sage Publications Ltd, Thousand Oaks, pp 671–689

Dong H, Geng Y, Xi F, Fujita T (2013a) Carbon footprint evaluation at industrial park level: a hybrid life cycle assessment approach. Energy Policy 57:298–307. https://doi.org/10.1016/j.enpol.2013.01.057

Dong L, Fujita T, Zhang H et al (2013b) Promoting low-carbon city through industrial symbiosis: a case in China by applying HPIMO model. Energy Policy 61:864–873. https://doi.org/10.1016/j.enpol.2013.06.084

Dong H, Ohnishi S, Fujita T et al (2014) Achieving carbon emission reduction through industrial & urban symbiosis: a case of Kawasaki. Energy 64:277–286. https://doi.org/10.1016/j.energy.2013.11.005

Dong L, Fujita T, Dai M et al (2016) Towards preventative eco-industrial development: an industrial and urban symbiosis case in one typical industrial city in China. J Clean Prod 114:387–400. https://doi.org/10.1016/j.jclepro.2015.05.015

Dong L, Liang H, Zhang L et al (2017) Highlighting regional eco-industrial development: life cycle benefits of an urban industrial symbiosis and implications in China. Ecol Modell 361:164–176. https://doi.org/10.1016/j.ecolmodel.2017.07.032

Ferrão P, Lorena A, Ribeiro P (2015) Industrial ecology and portugal's national waste plans. In: Taking stock of industrial ecology. Springer

Gerber L, Fazlollahi S, Maréchal F (2013) A systematic methodology for the environomic design and synthesis of energy systems combining process integration, Life cycle Assessment and industrial ecology.

Comput Chem Eng 59:2–16. https://doi.org/10.1016/j.compchemeng.2013.05.025

Grant GB, Seager TP, Massard G, Nies L (2010) Information and communication technology for industrial symbiosis. J Ind Ecol 740–753

Heijungs R, Suh S (2002) The computational structure of life cycle assessment. Springer Netherlands

Heijungs R, Settanni E, Guinée J (2013) Toward a computational structure for life cycle sustainability analysis: unifying LCA and LCC. Int J Life Cycle Assess 1722–1733. https://doi.org/10.1007/s11367-012-0461-4

Hendrickson CT, Lave LB, Matthews HS (2006) Exploring environmental impacts and sustainability through life cycle assessment

Hildebrandt J, O'Keeffe S, Bezama A, Thrän D (2019) Revealing the environmental advantages of industrial symbiosis in wood-based bioeconomy networks: an assessment from a life cycle perspective. J Ind Ecol 23:808–822. https://doi.org/10.1111/jiec.12818

Jung S, Dodbiba G, Fujita T (2012) Economic evaluation of recycled waste acid and alkali solutions in the printed circuit board process of the eco-industrial park. Resour Process 59:9–16. https://doi.org/10.4144/rpsj.59.9

Kastner CA, Lau R, Kraft M (2015) Quantitative tools for cultivating symbiosis in industrial parks; a literature review. Appl Energy 155:599–612. https://doi.org/10.1016/j.apenergy.2015.05.037

Kim H-W, Ohnishi S, Fujii M et al (2018) Evaluation and allocation of greenhouse gas reductions in industrial symbiosis. J Ind Ecol 22:275–287. https://doi.org/10.1111/jiec.12539

Kerdlap P, Low JSC, Ramakrishna S (2019a) Zero waste manufacturing: A framework and review of technology, research, and implementation barriers for enabling a circular economy transition in Singapore. Resour Conserv Recycl 151:104438. https://doi.org/10.1016/j.resconrec.2019.104438

Kerdlap P, Low JSC, Steidle R et al (2019b) Collaboration platform for enabling industrial symbiosis: application of the industrial-symbiosis life cycle analysis engine. In: Procedia CIRP. Elsevier B.V., pp 655–660

Kerdlap P, Low JSC, Tan DZL et al (2020) M3-IS-LCA: A Methodology for multi-level life cycle environmental performance evaluation of industrial symbiosis networks. Resour Conserv Recycl 161:104963. https://doi.org/10.1016/j.resconrec.2020.104963

Laybourn P, Lombardi DR (2007) The role of audited benefits in industrial symbiosis: the U.K. National Industrial Symbiosis Programme. Meas Control 40:244–247. https://doi.org/10.1177/002029400704000809

Leontief W (1970) Environmental repercussions and the economic structure: an input-output approach. Rev Econ Stat 52:262–271. https://doi.org/10.2307/1926294

Lignos G, Stancari S, Bikos S, Kokossis A (2015) Structural and economic analysis of Industrial Symbiosis networks: a hybrid approach to assess investment opportunities. Elsevier Masson SAS

Lim S-R, Park JM (2010) Interfactory and intrafactory water network system to remodel a conventional industrial park to a green eco-industrial park. Ind Eng Chem Res 49:1351–1358. https://doi.org/10.1021/ie9014233

Low JSC, Ng YT (2018) Improving the economic performance of remanufacturing systems through flexible design strategies: a case study based on remanufacturing laptop computers for the cambodian market. Bus Strateg Environ. https://doi.org/10.1002/bse.2017

Low JSC, Tjandra TB, Yunus F et al (2018) A collaboration platform for enabling industrial symbiosis: application of the database engine for waste-to-resource matching. In: Procedia CIRP

Majeau-Bettez G, Dandres T, Pauliuk S et al (2018) Choice of allocations and constructs for attributional or consequential life cycle assessment and input-output analysis. J Ind Ecol 22:656–670. https://doi.org/10.1111/jiec.12604

Martin M (2015) Quantifying the environmental performance of an industrial symbiosis network of biofuel producers. J Clean Prod 102:202–212. https://doi.org/10.1016/j.jclepro.2015.04.063

Martin M, Svensson N, Eklund M (2015) Who gets the benefits? An approach for assessing the environmental performance of industrial symbiosis. J Clean Prod 98:263–271. https://doi.org/10.1016/j.jclepro.2013.06.024

Mattila T (2018) Use of input-output analysis in LCA. In: Hauschild MZ, Rosenbaum RK, Olsen SI (eds) life cycle assessment: theory and practice. Springer, pp 349–372

Mattila TJ, Pakarinen S, Sokka L (2010) Quantifying the total environmental impacts of an industrial symbiosis - a comparison of process-, hybrid and input−output life cycle assessment. Environ Sci Technol 44:4309–4314. https://doi.org/10.1021/es902673m

Mattila T, Lehtoranta S, Sokka L et al (2012) Methodological aspects of applying life cycle assessment to industrial symbioses. J Ind Ecol 16:51–60. https://doi.org/10.1111/j.1530-9290.2011.00443.x

Miah JH, Koh SCL, Stone D (2017) A hybridised framework combining integrated methods for environmental life cycle assessment and life cycle costing. J Clean Prod 168:846–866. https://doi.org/10.1016/j.jclepro.2017.08.187

Mohammed F, Biswas WK, Yao H, Tadé M (2018) Sustainability assessment of symbiotic processes for the reuse of phosphogypsum. J Clean Prod 188:497–507. https://doi.org/10.1016/j.jclepro.2018.03.309

Moreau V, Weidema BP (2015) The computational structure of environmental life cycle costing. Int J Life Cycle Assess 20:1359–1363. https://doi.org/10.1007/s11367-015-0952-1

Neves A, Godina R, Azevedo SG, Matias JCO (2020) A comprehensive review of industrial symbiosis. J Clean Prod 247:119113. https://doi.org/10.1016/j.jclepro.2019.119113

Odum HT (1988) Self-organization, transformity, and information. Science (80-) 242:1132–1139. https://doi.org/10.1126/science.242.4882.1132

Ohnishi S, Dong H, Geng Y et al (2017) A comprehensive evaluation on industrial & urban symbiosis by combining MFA, carbon footprint and emergy methods—Case of Kawasaki, Japan. Ecol Indic 73:513–524. https://doi.org/10.1016/j.ecolind.2016.10.016

Puchala B, Tarcea G, Marquis EA et al (2016) The materials commons: a collaboration platform and information repository for the global materials community. JOM 68:2035–2044. https://doi.org/10.1007/s11837-016-1998-7

Raabe B, Low JSC, Juraschek M et al (2017) Collaboration platform for enabling industrial symbiosis: application of the by-product exchange network model. In: Procedia CIRP. Elsevier B.V., pp 263–268

Reddy VR, Kurian M, Ardakanian R (2015) Life-cycle cost approach for management of environmental resources: A Primer. Springer

Schneider P, Folkens L, Meyer A, Tino F (2019) Sustainability and dimensions of a nexus approach in a sharing economy. Sustainability 11. https://doi.org/10.3390/su11030909

Sokka L, Lehtoranta S, Nissinen A, Melanen M (2011) Analyzing the environmental benefits of industrial symbiosis. J Ind Ecol 15:137–155. https://doi.org/10.1111/j.1530-9290.2010.00276.x

Suh S, Huppes G (2005) Methods for life cycle inventory of a product. 13. https://doi.org/10.1016/j.jclepro.2003.04.001

Swarr TE, Hunkeler D, Klöpffer W et al (2011) Environmental life-cycle costing: a code of practice. Int J Life Cycle Assess 16:389–391. https://doi.org/10.1007/s11367-011-0287-5

Switzerland Federal Office for the Environment (2014) International survey on eco-innovation parks: Learning from experiences on the spatial dimension of eco-innovation

van Capelleveen G, Amrit C, Yazan DM (2018) A literature survey of information systems facilitating the identification of industrial symbiosis BT - from science to society: new trends in environmental informatics. In: Otjacques B, Hitzelberger P, Naumann S,

Wohlgemuth V (eds). Springer International Publishing, Cham, pp 155–169
Walls JL, Paquin RL (2015) Organizational perspectives of industrial symbiosis: a review and synthesis. Organ Environ 28:32–53. https://doi.org/10.1177/1086026615575333
Yeo Z, Low JSC, Tan DZL et al (2019a) A collaboration platform for enabling industrial symbiosis: Towards creating a self-learning waste-to-resource database for recommending industrial symbiosis transactions using text analytics. Procedia CIRP 80:643–648. https://doi.org/10.1016/j.procir.2019.01.015
Yeo Z, Masi D, Low JSC et al (2019b) Tools for promoting industrial symbiosis: a systematic review. J Ind Ecol. https://doi.org/10.1111/jiec.12846
Zhang B, Wang Z, Lai K (2016) Does industrial waste reuse bring dual benefits of economic growth and carbon emission reduction? evidence of incorporating the indirect effect of economic growth in China. J Ind Ecol 20:1306–1319. https://doi.org/10.1111/jiec.12375
Zink T, Geyer R (2017) Circular economy rebound. J Ind Ecol 21:593–602. https://doi.org/10.1111/jiec.12545