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Requirements Engineering for an Industrial Symbiosis Tool for Industrial Parks Covering System Analysis, Transformation Simulation and Goal Setting

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Abstract: Industrial Symbiosis (IS) is a collaborative cross-sectoral approach to connect the resource supply and demand of various industries in order to optimize the resource use through exchange of materials, energy, water and human resources across different companies, while generating ecological, technical, social and economic benefits. One of the main goals of IS is the set-up of advanced circular/cascading systems, in which the energy and material flows are prolonged for multiple utilization within industrial systems in order to increase resource productivity and efficiency, while reducing the environmental load. Many Information Communication Technology (ICT) tools have been developed to facilitate IS, but they predominantly focus on the as-is analysis of the IS system, and do not consider the development of a common desired target vision or corresponding possible future scenarios as well as conceivable transformation paths from the actual to the defined (sustainability) target state. This gap shall be addressed in this paper, presenting the software requirements engineering results for a holistic IT-supported IS tool covering system analysis, transformation simulation and goal-setting. This new approach goes beyond system analysis and includes the use of expert systems, system dynamics and Artificial Intelligence (AI) techniques, which turn the IT-supported IS tool to be developed into a comprehensive and holistic instrument with which future scenarios and transformation paths can be simulated.

Keywords: Industrial Symbiosis; Industrial Ecology; expert system; Artificial Intelligence; Machine Learning; Agent-Based Modelling; system dynamics; resource efficiency; resource productivity

1. Introduction

Current global challenges such as climate change, increasing freshwater consumption, chemical pollution (Rockström et al. 2009) and limited resource availability have triggered social, governmental and economic activities to reduce the burden to ecosystem functioning and services to human societies. One of the application concepts in industrial contexts is Industrial Symbiosis (IS), which takes an emerging priority on the European Union (EU) policy agenda (EEA 2016) and is considered to be a key enabling factor for resource efficiency and circularity.

IS is a collaborative cross-sectoral approach to connect the resource supply and demand of various industries in order to optimize the resource use through exchange of materials, energy, water and human resources across different companies, while generating ecological, technical, social and economic benefits (Ehrenfeld and Gertler 1997; Chertow 2004; Van Berkel et al. 2009; Sokka et al. 2010;

Herczeg et al. 2016; Ruiz-Puente and Bayona 2017; Chertow et al. 2019; Doménech et al. 2019). One of the main goals of IS is the set-up of advanced circular/cascading systems, in which the energy and material flows are prolonged for multiple utilization within industrial systems in order to increase resource productivity and efficiency, while reducing the environmental load.

The holistic view along the entire life cycle opens up various points of contact and leverage points for resource circularity opportunities and to improve the overall sustainability impact. Figure 1 shows four mechanisms as Life Cycle Material Reflows:

(a) recycling reflow from the end of life phase back to the (raw) material processing stage,
(b) remanufacturing reflow either from the end of life phase or from the consumption/usage step back to the manufacturing phase,
(c) reusing reflow from the end of life stage back to the usage phase,
(d) and the extended/internal cascading loops in IS systems in the manufacturing phase in form of water, material and energy networks, networks of shared utilities and infrastructure (incl. storage capacity and logistics) and networks of joint disposal and procurement processes. This is a further point of contact for increasing resource productivity/efficiency and reducing consumption of primary resources, while mitigating/reducing negative environmental burden and economic costs.

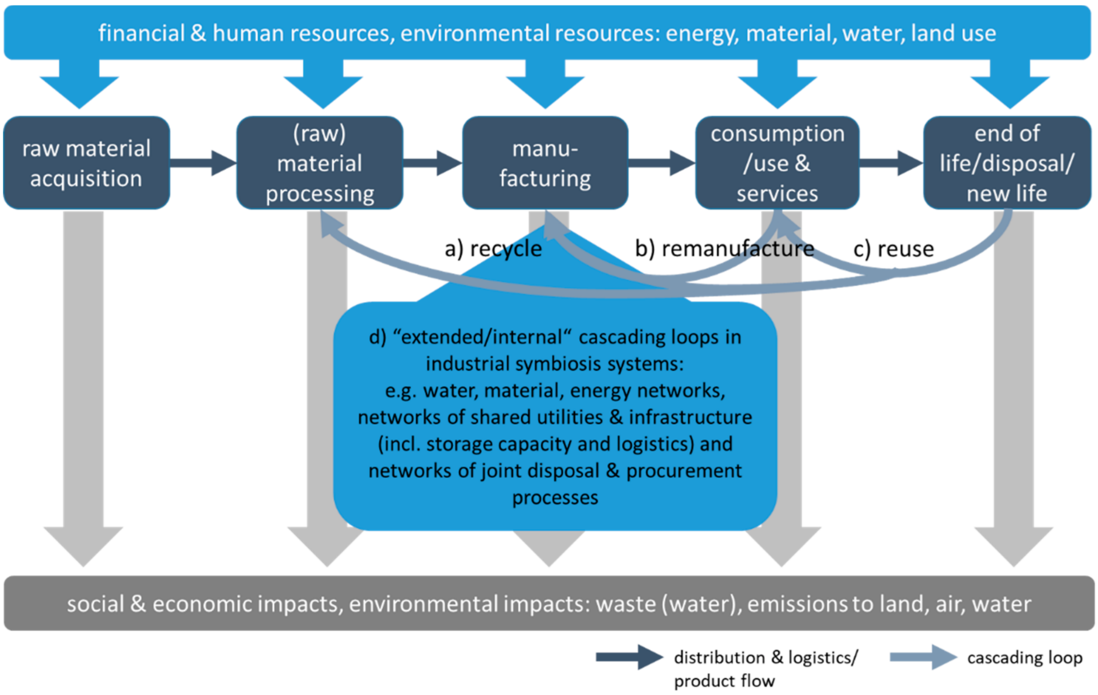

Figure 1. Life Cycle Material Reflows with Industrial Symbiosis as extended/internal cascading loop in the manufacturing phase.

Close geographic proximity is considered to be a facilitating factor for IS systems (Wallner 1999; Chertow 2004; Sterr and Ott 2004; Hewes and Lyons 2008; UNIDO 2016), that is why this work focuses on industrial agglomerations and industrial parks (IPs) as a starting context/geographical system boundary for IS. IPs could or should be seen as entire eco(sub-)systems (Côté and Hall 1995), which are embedded in the overarching natural ecosystem (Chertow 2008). According to Erkman (2001), ecologically oriented IPs consider technologies, process economics, the inter-relationships of businesses, financing, overall governmental policy, and the entire spectrum of issues that are involved in the management of commercial enterprises as equally important as environmental protection and optimizing the use of resources. According to Frosch and Gallopoulos (1989), they have three main principles: (1) the minimization of consumed energy, (2) the (re-)use of industrial waste, (3) the development of a resilient system.

Especially environmental regulations and laws are considered to be triggering and pushing forces for companies to engage in an IS system (Bacudio et al. 2016; Ji et al. 2020), beside the motivation of economic advantages. Among others, hindering factors are the lack of awareness of IS concepts (Sakr et al. 2011; Bacudio et al. 2016; Ji et al. 2020), lack of local IS possibilities, lack of information sharing among locators (Sakr et al. 2011; Bacudio et al. 2016), lack of an institutional support for integration, coordination and communication, lack of technology and infrastructure readiness (Bacudio et al. 2016) and difficulties in reaching agreements (Ji et al. 2020). The identified barriers of IS implementation has driven the current research work, which aims to tackle these aspects and facilitate the exploitation of IS to be used as a lever for a sustainable industrial development. Therefore, information exchange is crucial to identify IS business matches and potentials (Heeres et al. 2004; Ismail 2014). So, the inter- and cross-company information flows can be enabled by an information platform (Sakr et al. 2011; Isenmann 2013; Song et al. 2018). One of the essential technology-enabled factors is the establishment of an information platform, which provides an integrated analysis tool for the IP itself in order to add the functions of performance monitoring, social modules supporting trust and community building, and systematic approaches to identify possible IS activities and to evaluate them from an economic, social and ecological perspective (Lütje et al. 2018; Lütje et al. 2019a). Many Information Communication Technology (ICT) tools have been developed to facilitate IS, but they predominantly focus on the as-is analysis of the IS system (Grant et al. 2010; Maqbool et al. 2019). The main focus is on the identification of possible IS measures and (the management of) material and energy exchanges by output-input matching of various resource flows among companies, functionality and technical opportunities (Grant et al. 2010). Furthermore, decision support such as advanced analysis regarding economic viability of different IS activities (Raabea et al. 2017) and ecological impacts (reduction) are not provided. Additionally, the development of a common desired target vision for an IP or corresponding possible future scenarios as well as conceivable transformation paths from the actual state to the desired target vision are not taken into account. This gap shall be addressed in this paper, presenting the requirements engineering results for a conceptual IT-supported IS tool. This new approach goes beyond as-is and system analysis and includes the use of system dynamics and Artificial Intelligence (AI) techniques, which turn the IT-supported IS tool to be developed into a comprehensive and holistic instrument with which future scenarios and transformation paths can be simulated.

The following exemplary tools approach the dynamic effects and impacts of possible IS activities. Raabea et al. (2017) developed an IS collaboration platform, using a by-product exchange network (BEN) model based on an agent-based modelling approach (ABM). Applying the model to a case study of food waste in Singapore, it provided decision support for companies to evaluate the economic viability of IS (Raabea et al. 2017). Companies in the IS network are embodied by virtual agents. Each agent is programmed based on rules to actively consume and/or produce resources, while resources are represented by agents that passively change their states such as quantities and locations (Raabea et al. 2017). Yazdanpanah et al. (2018) studied IS networks with coordinated game theory and normative multi-agent systems in order to investigate fair and stable benefit allocation among IS entities. Yazan and Fraccascia (2019) proposed an IS model, enabling the exploration of “the space of cooperation, defined as the operationally favourable conditions to operate IS in an economically win-win manner”. Therefore, they developed an IS decision-support tool which is based on an enterprise input-output model and provides a cost-benefit analysis (Yazan and Fraccascia 2019). An agent-based simulation was incorporated to present the share allocation of the total economic benefits resulting from IS activities (Yazan and Fraccascia 2019). Lütje et al. (2019b) proposed a first framework concept for a combinatorial approach of Agent-Based Modelling (ABM) and the Artificial Intelligence (AI) technique of Reinforcement Learning (which belongs to the sub-field of Machine Learning (ML)) for exploring the system dynamics of IS. So, the agents can take note of rewards received by specific actions and record it, in order to adapt the model and accelerate the learning phase for better solution finding.

This hybrid-approach opens up the simulation of scenarios with optimally utilized IS systems in terms of system adaptability and resilience (Lütje et al. 2019b).

However, the evaluation, simulation, planning, implementation and operation of IS activities need to be carefully considered beforehand, as the (long-term) functioning/success of IS is highly context-depend (e.g., local circumstances of resource availability/scarcity, political, technological, socio-cultural and organizational aspects). In some contextual constellations IS may not be the only or optimal approach to solve resource efficiency and productivity problems (Holgado et al. 2016), as it may shift the issue out of the IS scope, and then may occur elsewhere. Blinkered thinking should therefore be avoided and socio-ecological-economic effects of IS measures should also be taken into account beyond the IS scope in order to assess the overall sustainability effectiveness.

2. Results

2.1. Applied Methods in Industrial Symbiosis Systems

Traditionally, IS networks have been divided up into three main categories of exchange types: water, power (including heat) and materials (Kastner et al. 2015). The process of identifying IS opportunities can be conducted by various quantitative methods. Table 1 shows the methods applied to IS systems and their application context of the investigated case studies (see full list in Appendix A). It is noteworthy that there are various more methods applicable to IS systems; the ones listed here capture exclusively the results of the conducted cross-case analysis. Particular attention was paid to ensure that the methods selected were suitable for the application context of the IT tool to be developed and the usability of companies. In this study, the methods of Material Flow Analysis (MFA), Life Cycle Assessment (LCA) and Social Network Analysis (SNA) were detected as the most applied methods in the IS context to reveal IS opportunities and analyze the actual state of an IS system. Other researchers confirm these findings very close to congruent (Li et al. 2017; Kastner et al. 2015; Huang et al. 2019): the most widely applications are MFA (Geng et al. 2012; Sendra et al. 2007; Yong et al. 2009), LCA (Sokka et al. 2010; Sokka et al. 2011), and environmental indicators (Kurup and Stehlik 2009; Pakarinen et al. 2010; Zhu et al. 2010). Which methods are considered for which purpose and for which context? This needs to be differentiated when applying various methods for the IS identification, IS performance measurement and the investigation of existing IS systems concerning inter alia the structure and morphology, etc.

In the following, a selection of diverse case studies is described to briefly demonstrate the various application possibilities and contexts of the presented methods. For instance, Bain et al. (2010) conducted a case study on an industrial site in South India, using MFA to analyze the recovery, reuse and recycling of industrial residuals and to match potential IS connections among companies. Chertow et al. (2008) applied MFA in a multiyear investigation (2001-2007) of industrial areas in Puerto Rico, in order to develop IS scenarios dedicated to utility sharing, joint service provision and by-product exchanges, which were evaluated by technical, economic and environmental criteria afterwards. LCA was used by Sokka et al. (2010) who investigated a Finnish Forest Industry Complex around a pulp and paper mill, in order to identify inter alia potential IS connections. Martin (2013) explored IS in the biofuel industry in Sweden to identify IS potentials and quantify the environmental impacts of the IS network with LCA. This method also revealed an approach to allocate impacts and credits for IS exchanges among the occupants and to assess the environmental benefits of the IS network (Martin 2013). Ulhasanah and Goto (2012) applied MFA, LCA and MFCA in a cement production case study in Indonesia, in order to identify IS opportunities and evaluate them from physical, environmental and economic perspectives.

So, in the IS context, MFA, MFCA and LCA are mainly based on the principles of Output-Input and Supply-Demand Matchings of the entities involved. By analyzing and matching each supply-demand and output-input (e.g., human and material resources, utilities and (infra-)structure) of each company, possible IS connections can be revealed. From the methodological perspective, MFA is the first basis to map physical resource flows (material, water, energy) and respective processes. LCA and MFCA can then be set up on this foundation to illuminate the environmental impacts/performance (LCA) and/or the economic performance of, particularly, processes, resource and waste flows (MFCA).

Table 1. Overview of methods for the identification and investigation of IS systems and their application context.

Method	Description	Application Context	References
Material Flow Analysis (MFA)	Quantifies the flows and stocks of materials and energy of the system under consideration in physical units (e.g., kg), distinguishing between input and output streams of the respective processes	Applicable to material and energy flows, crossing exchange type boundaries (water, power, materials), first starting point to visualize the (production) system with its respective input and output flows and screen first possible IS matchings	(Chertow et al. 2008; Park et al. 2008; Yang and Feng 2008; Zhu et al. 2008; Van Berkel et al. 2009; Yuan and Shi 2009; Bain et al. 2010; Ulhasanah and Goto 2012; Sun et al. 2016; Li et al. 2017; Taddeo et al. 2017; Mauthoor 2017; Morales et al. 2019)
Substance Flow Analysis (SFA)	Quantifies and traces the flows and stocks of one specific substance/chemical or a group of substances within the system under consideration	Detailed investigation to determine the flows and stocks of one specific substance, suitable, if further clues have already been identified in the system/context, for disclosing IS possibilities for a particular substance.	(Zhang et al. 2013a; Wen and Meng 2015)
Material Flow Cost Accounting (MFCA)	Traces and quantifies the flows and stocks of materials and energy of the system under consideration in physical and monetary units, especially the material losses, non-/by-products and waste flows are evaluated (standardized to ISO 4051)	MFCA is based on the method of MFA, additionally all input and output flows are attributed an economic value, especially the material losses/waste flows, which incentivizes the optimization of processes as well as the use of resources and provides a better decision-making basis regarding economic viability and prioritization of IS measures	(Viere et al. 2011; Ulhasanah and Goto 2012; Lütje et al. 2018; Lütje et al. 2019a, 2019b)
Life Cycle Assessment (LCA)	Quantifies the flows and stocks of materials and energy of the system under consideration and assesses the associated environmental impacts, such as global warming and eutrophication potential (standardized to ISO 14040)	LCA is based on the method of MFA, applicable to material, water and energy flows, considers all exchange type boundaries throughout an entire product life cycle (from raw material extraction, production, distribution/retail, to usage and disposal), assesses the environmental impacts of products and services.	(Sokka et al. 2010; Ulhasanah and Goto 2012; Marinos-Kouris and Mourtsiadis 2013; Sacchi and Ramsheva 2017; Marconi et al. 2018; Martin and Harris 2018; Chertow et al. 2019)
Emergy Analysis	Emergy is an expression of all the energy consumed in direct and indirect transformations in the processes to generate a product or service. Therefore, emergy analysis converts the thermodynamic basis of all forms of energy, resources and human services into equivalents of a single form of energy(usually solar emjoules).	Emergy is a more comprehensive and adequate way to value ecosystem goods and services, as they convey the past work performed by the environment, economy and society and does not consider only the amount of available energy that is used in the present to produce a good or service.	(Geng et al. 2014; Sun et al. 2016; Liu et al. 2018)

Table 1. *Cont.*

Method	Description	Application Context	References
Social Network Analysis (SNA)	Investigates social structures of networks and characterizes elements within the network in terms of nodes (e.g., individual actors, companies, people) and the connecting tie or links (relationships or interactions).	SNA analyzes the characteristics, power quantification and structure of the IS network and can provide insights for understanding the social aspects of an IS system and how (social) business relationships drive the exchanges of materials, energy and information	(Ashton 2008; Doménech and Davies 2009; Doménech and Davies 2011; Zhang et al. 2013a; Chopra and Khanna 2014; Song et al. 2018)
Agent-Based Modelling (ABM)	ABM is a class of computational models for simulating various scenarios of the outcome of the actions and interactions of autonomous agents within a system (both individual or collective (both individual or collective entities such as originations or groups)	In an ABM model, entities such as plants or facilities in the IS network are represented by agents that are programmed based on rules to actively consume and/or produce resources, while resources are represented by agents that passively change their states such as quantities and locations, suitable for simulating and modelling various IS scenarios and considering potential effects regarding vulnerability and resilience of the IS system.	(Axtell et al. 2001; Raabea et al. 2017; Yazdanpanah et al. 2018; Yazan and Fraccascia 2019)

The research methods on IS have expanded from focusing on material flows, environmental and economic benefits to broadening it to social aspects as collaboration and the relationships among the IS entities can profoundly determine the effectiveness and efficiency of the entire IS system. With the method of SNA, the structure of IS systems and the (power) relationships of the entities involved can be investigated. For instance, Song et al. (2018) analyzed the Gujiao eco-industrial park in China and found out that SNA reveals IS potentials to develop more synergy linkages, identifying key/anchor actors in the network and their relation/context to exchanges of material, energy and (waste) water. Ashton (2008) addressed interpersonal and organizational relationships, trust and the associated relationships within the IS network in an IP in Puerto Rico with SNA. Chopra and Khanna (2014) used SNA to study the Kalundborg Industrial Symbiosis in Denmark regarding the resilience of an IS network, suggesting design strategies for resilient and sustainable IS systems such as increased diversity, redundancy, and multi-functionality to ensure flexibility and plasticity.

All investigated case studies have in common, that they were used to analyze and describe the actual state of the IS system and to derive various IS measures, but no one mentioned that it was done in a targeted manner, so no explicit goals were defined when identifying and implementing IS opportunities.

2.2. Industrial Symbiosis Material Exchanges and Activities

The conducted cross-case analysis revealed several points of contact for a company to investigate systematically potential IS activities. In the following, a systematized overview was abstracted and exemplary cases are shown:

1. **Non-material exchanges**: sharing of knowledge/expertise, utilities/infrastructure, management of joint procurement and disposal/recycling processes. Mirata and Emtairah (2005) studied the Landskrona industrial symbiosis programme (LISP) in Sweden and found out that inter-organizational collaboration was not only important in implementing identified IS solutions, but also contributed to mutual learning in various forms. LISP actors were engaged not only in material exchanges, as this is more common in IS networks, but rather in cooperation on non-material synergies such as management routines, new business arrangements, collective bargaining, and envisioning joint goals towards sustainable development (Mirata and Emtairah 2005).

Beside non-material exchanges, there are physical exchanges of water, energy and materials.

2. **Input-related material and energy resources:**

    2.1. **Secondary raw/substitute materials:** Liwarska-Bizukojc et al. (2009) presented an Austrian IS example, in which the manufacturer of cellulose insulation collected wastepaper from onsite companies to re-process and re-utilized it as secondary raw material.

    2.2. **Energy**

        2.2.1. **(process) heat/cold (process):** Martin and Eklund (2011) studied the Händelö IS in Sweden, where the municipal wastes, process waste and biomass from local forestry industries feed a combined heat and power unit (CHP). Heat is injected in the district heating network, electricity to the grid, and steam to the nearby ethanol production plant, which also produces by-products that are forwarded to the biogas plant (Martin and Eklund 2011).

        2.2.2. **electricity:** Jyrki (2009) investigated an IS system of copper and nickel flash smelters, a nickel chemical producer, an energy producer, a hydrogen plant, a sulphuric acid plant and the town of Harjavalta in Finland, which have established symbiotic exchanges of energy cascading and material flows.

    2.3. **(process) water:** Shi et al. (2010) showed the water and energy cascading system of an IS network in China, which included additional waste and wastewater recovery and by-product exchanges.

3. **Output-related emissions:**

    3.1. **Waste heat/steam:** can be forwarded to other companies (Mirata 2004; Pakarinen et al. 2010; Yu et al. 2015; Earley 2015). Li (2011) presented an IS complex in China, comprising power generation, desalinization, sea salt production, brick production and a chemical plant. The IS network predominantly covers waste heat recovery and by-product exchanges such as the material utilization of coal ashes for brick production (Li 2011).

    3.2. **Gaseous waste/aerosols:** Melanen et al. (2008) studied an IS network in Finland, which has been established around a large pulp and paper mill. Among other things, the CO2 emissions are passed on to a calcium carbonate plant as a secondary raw material. Aerosol waste streams such as fly ash can be used as cement additive (Dong et al. 2013; Golev et al. 2014; Cui et al. 2018) or soil additive (Korhonen and Snäkin 2005; Notarnicola et al. 2016; Bain et al. 2010).

4. **Output-related waste:**

    4.1. **Solid waste/residuals:** Costa and Ferrão (2010) explored an IS system in Portugal, which is mainly characterized by the economic sectors of waste management and recovering industry (inter alia aluminium slag, plastic, battery recycler). Organic residual (solid) waste can be converted to animal/fish feeding (material utilization) (Chertow 2007; Alkaya et al. 2014), or where health and hygiene reasons need to be considered, can be processed into biogas and biofuel (energetic utilization) (Alkaya et al. 2014). The digestate of a biogas plant can be reused as fertilizer (Martin 2013; Alkaya et al. 2014).

    4.2. **Liquid waste:**

        4.2.1. **(waste/process) water:** Wastewater from a company that processes food such as olives, cereals, fruit and vegetables can be further used for the fertilized irrigation of agricultural land (Chertow et al. 2008; Notarnicola et al. 2016) or further processed into a fertilizer product.

4.2.2. **Sludge/mud:** the Guitang Group in China solved a disposal problem by using their sludge as the calcium carbonate feedstock to a new cement plant, while reducing residual and waste flows (Zhu et al. 2008).

In order to provide better knowledge diffusion and experience transfer, practical cases of IS and concrete material and energy exchange measures found in literature should be gathered in an IS (relational) database, creating a catalogue of IS material and energy exchanges and IS activities. The development of such a database should contain information of concrete IS measures and experiences, broken down by industrial sector, which company type/branch cooperates with which company type/branch and recording each input flows by type of energy and materials (raw materials, consumables and supplies) and output flows by product, by-product, residual and waste flows, on the one hand, and their corresponding application context and processing possibilities for output flows, on the other hand, in order to facilitate the identification of (further) IS opportunities. The existing (scientific) literature and the corresponding knowledge about IS systems already provides a sufficient basis for the development of extended IS cascade systems as generalizable templates/basic blueprints, which can be deposited in data/knowledge bases in order to facilitate and outline further IS exchanges and connections. With such a knowledge/insight base, concrete recommendations for action can be derived for specific IS activities and mapped/applied to the existing area under consideration. For example, there are concrete recommendations for utilization in which it is specified which output stream can be used as which input stream of another company, facilitating input-output/supply-demand matchings and suggestions. This can then be used in recommendation components of the presented concept for an IT-supported IS tools.

2.3. Requirements Engineering Results for the IT-supported Industrial Symbiosis Tool

All the collected information based on the conducted cross-case analysis were incorporated into a systematized Requirements Engineering (RE) scheme (see Figure 2) in order to envision a concept for a holistic IT-supported IS tool for the evolution of Industrial Symbiosis (IS) in Industrial Parks (IPs). For this purpose, modular solution approaches were designed that address all three types of knowledge (system, transformative and normative). The concept includes elements of system analysis, information and collaboration platform, goal setting, the IS identification and assessment as well as the simulation of transformation pathways, which are combined into an overall web-based platform.

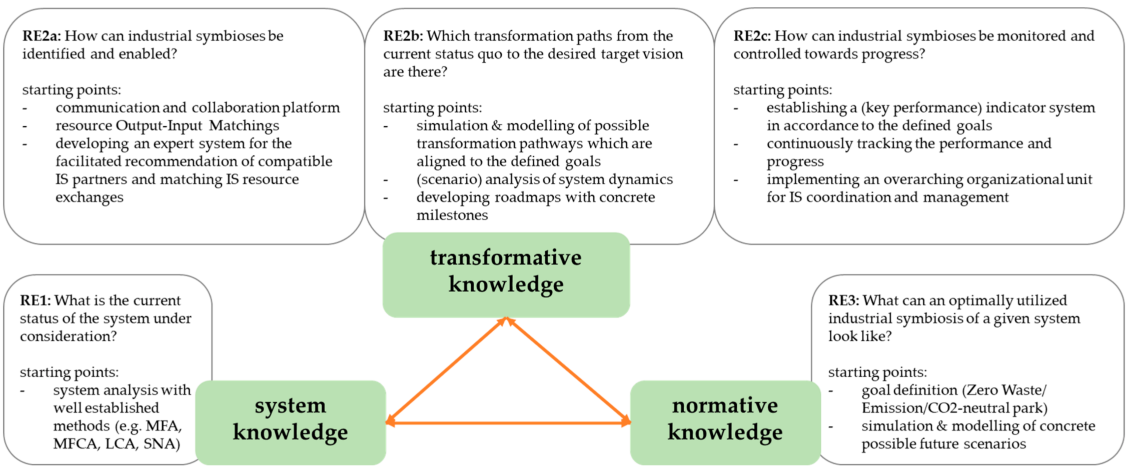

Figure 2. Systematized Requirements Engineering (RE) scheme.

The web application to be developed is based on the analysis toolbox (see Table 2, SK1.0), in which every company can store its information and data with specific access rights. The introduced methods in this paper such as MFA, SNA, LCA and MFCA are means to describe the actual state of the system under consideration, which already can reveal IS opportunities. The visualization of the results is carried out by means of input-output balance sheets, statistical graphs, indicators, Sankey diagrams[1], material flow cost matrices[2] and sociograms[3]. From a business perspective, a successive and gradual approach is suggested to reduce the starting barrier by placing MFA and SNA at the starting point for exploring potential IS connections among the entities, then the scope of the investigation can be narrowed and specifically targeted towards a more detailed level. Additionally, to the Input-Output and Supply-Demand Matchings, with the method of SNA, same suppliers and recycling/disposal companies can be detected, so that the IS network can be intensified (Lütje et al. 2019a). Depending on what objectives have been defined, appropriate methods can then be applied showing the ecological and/or economic perspective in more detail in order to assess and prioritize IS opportunities. So, the basis of analysis can be expanded inter alia with the method of MFCA (economic focus) or LCA (environmental focus) and, hence, increasing the complexity and scope gradually.

Table 2. Detailed Requirements Engineering Overview.

Nr.	System Knowledge (SK)	Remarks
SK1.0	**Analysis Toolbox**	
SK1.1	Energy and Material Flow Analysis (MFA)	System analysis of physical input-output resource flows in order to identify compatible IS resource exchanges and increase resource productivity and efficiency by reducing primary resource consumption.
SK1.2	Material Flow Cost Accounting (MFCA)	Economic evaluation of resource flows, especially waste flows, in order to generate cost savings and incentivize/prioritize IS measures.
SK1.3	Life Cycle Assessment (LCA)	Environmental evaluation (e.g., global warming potential, eutrophication potential, ozone depletion potential) in order to reduce environmental impacts and drive/prioritize IS measures.
SK1.4	Social Network Analysis (SNA)	Investigation of the as-is structure/composition of participating companies and their (power) relationships in order to intensify network connections, identify same suppliers and disposal companies and to evaluate the system resilience of IS activities.
	Transformative Knowledge (TK)	
TK1.0	**Information exchange**	
TK1.1	Integrated social network platform with social add-ons	Inter-company communication, nurturing social relationships, trust and community building shall be supported.
TK1.2	Knowledge exchange	Enabling knowledge transfer between participating companies (e.g., experienced companies in auditing/certification processes can share their knowledge with unexperienced companies which plan certain audits and certifications).
TK1.3	Cross-company IS management	Enabling joint management of e.g., storage and logistics capacities, joint procurement and recycling/disposal processes.

[1] A Sankey diagram is a graphic representation of physical quantity flows of the respective resources with arrows proportional to the quantity.

[2] A material flow cost matrix shows the process-specific material flow cost allocation of a company in accordance to the four major cost items: material, energy, system and waste management costs.

[3] A sociogram is a graphic representation of the connections and relationships among group members.

Table 2. *Cont.*

Nr.	System Knowledge (SK)	Remarks
TK2.0	**Facilitated Synergy Identification**	
TK2.1	Resource Output-Input Matchings	Matching of actively supplied and demanded resource output-input flows of participating companies.
TK2.2	Supply-Demand Matchings	Referring to actively supplied and demanded technologies, human resources, expertise, storage and logistics capacities.
TK2.3	Integrated expert system	For the facilitated recommendation of compatible IS partners, matching IS resource exchanges and additional IS activities in order to exhaust further IS potentials.
TK3.0	**Simulation and Modelling**	
TK3.1	simulation and modelling of possible transformation pathways	which are aligned to defined goals (e.g., via Agent-Based Modelling and/or other methods of (scenario) analysis of system dynamics).
TK3.2	roadmaps	Developing roadmaps with concrete milestones and measures.
TK3.3	(key performance) indicator system	Continuously tracking the performance and progress towards the defined goals.
TK4.0	**IS administration and management**	
TK4.1	overarching organizational unit	For IS coordination and management with administrator function of the IT-supported IS tool.
	Normative Knowledge (NK)	
NK1.0	**Desired future visions**	
NK1.1	Goal setting	Participating companies are encouraged to collaboratively define quantifiable (sustainability) goals for the IS network (e.g., zero waste park, zero emission park, CO2-neutral park).
NK1.2	Possible future scenarios	Simulation and modelling of concrete possible future scenarios that allow the full range of IS potential to be exploited.

As Boons and Baas (1997) pointed out "coordination does not automatically mean cooperation"; the second component of the IS tool addresses social aspects (Table 2, TK1.1) in order to foster good personal and business relationships and the cultivation of cooperation (Sakr et al. 2011). The communication and collaboration platform comprises an integrated social network platform, enabling social relations, intensifying networking and trust building among the entities. Social add-ons for the industrial area shall support the inter-company communication and trust building, for example, by organizing cross-company sports, benefit and other cultural events via an integrated "Social Media" area or by creating other interest groups such as a carpool exchange for the local employees. Especially the exchange of information shall be promoted, so that knowledge and experience transfer and diffusion is facilitated (Table 2, TK1.2). Furthermore, the information exchange addresses cross-company management, so potential capacities of storage and logistics shall be identified in order to utilize free capacities optimally (Table 2, TK1.3). The procurement, recycling and disposal processes shall be managed efficiently by merging external services and (infra-) structure for joint usage and better purchasing and payment conditions, resulting in mutual cost reduction and higher revenues due to increased capacity utilization.

Another component is the facilitated synergy identification of IS opportunities, which covers match-making algorithms including output-input as well as supply-demand resources such as technologies, human resources, expertise, storage and logistics in order to enable the identification of potential cooperation partners in a defined geographical radius, for example, to identify same suppliers and disposal companies or to match input-output flows (Table 2, TK2.0). The integration of expert systems can round off a concept for an IT-supported IS tool and advance the functional spectrum of an IS web application (Table 2, TK2.3). A first preliminary concept for an expert system is divided into three functionality components:

(1) **Knowledge acquisition component** (creating and improving the knowledge base): Therefore, several IS activity patterns based on real concrete case studies and IS measures need to be gathered and stored, so that the IS tool can access the information and provide concrete recommendations. This requires the setup of (relational) databases, which comprises data and information of inter alia IS activities/measures, structural IS classification, and sector and material specific information. So, a comprehensive knowledge of the material and energy flows, their type, quantity and composition are essential (Li 2018). With such a knowledge/data base, concrete recommendations for IS action and connections can be suggested for the existing area under consideration.

(2) **Problem solving component** (to process the knowledge base provided and find appropriate solutions): Very different models can be used both to represent knowledge and to draw conclusions. The following two models should be taken into account in the concept for an IT-supported IS tool, since the most suitable one should be selected automatically depending on the application context:

- In *case-based systems* there is a case database, which contains concrete problems in their context including a description of the solution (IS activity/measurement catalogue). The system tries to find a comparable case for a given case in its database and to transfer its solution to the current case (so in this application context of IS systems, real concrete case studies).
- *Rule-based systems* or Business Rule Management Systems (BRMS) are based on rules of the type "If A, then B". The rules therefore tend to follow general laws from which conclusions are to be drawn for concrete situations. (Business) Rules must usually be defined beforehand by human experts and entered into the system manually. For example, "if there is a company with an output flow of coal fly ash, then this material can be further utilized as fertilizer". The rules can be derived from a knowledge base to be developed (IS resource catalogue of compatible material exchanges) that needs to cover sector-specific resource data allowing compatible cross-sectoral resource output-input match-makings.

Typical task classes for expert systems that are to be used in particular in the application context of the IT-supported IS tools are:

- *Planning:* Generation and evaluation of action sequences to achieve target states
- *Design:* Description of structures that meet given requirements
- *Prognosis:* Prediction and evaluation of achievable states of time-varying systems

(3) **Explanation component** (making the results/solutions understandable to the user): The IT-supported IS tool shall provide various visualization formats to present the results and recommendations for action (e.g., interactive Sankey diagrams, social networks, tables, input-output balances, statistics, written text).

The innovative part of the web application is the module of simulation and modelling (Table 2, TK3.0) which shall use methods of system dynamics and artificial intelligence (AI) algorithms such as Artificial Neural Networks (ANN) and/or hybrid-approaches of ABM and Reinforcement Learning (a machine learning technique, sub-field of AI) (Lütje et al. 2019b). So, the web application should be able to simulate and model various transformation pathways with two anchor points: from the actual state to the desired future scenario which is aligned to the defined goals of, for example, "zero waste", "zero emission" or "CO2-neutral" park, or the IP pursues to align its business performance to the science based targets (SBT) (SBTi 2019)[4]. Therefore, the underlying AI algorithms need to "learn" from several IS activity patterns and data based on real concrete case studies and stored IS measures. This requires the setup of a (relational) database, which contains all the required sector and material specific information. Of particular importance are the databases of IS material exchanges, IS activities/measures and structural IS formations for creating templates/blueprints and IS actions with their respective numeric data which the AI algorithms can use for the training and testing phase (learning process). With the help of iterative and combinatorial application of the individually deposited IS measures/templates, appropriate transformation pathways and concrete recommendations for IS actions can be simulated and modelled. Additionally, the phase of IS identification can be tremendously accelerated, once the (relational) databases are developed. In order to track the performance and progress towards set (sustainability) goals, a performance indicator system should be defined by the IS entities (Table 2, TK3.3).

It is recommended to establish an overarching organizational unit (Li et al. 2017) for IS administration and management (Table 2, TK4.0), that can additionally serve as an administrator of the IT-supported IS tool (Lütje et al. 2019a).

In order to align the approach in a targeted manner, quantifiable goals must be defined (Table 2, NK1.1), which is crucial for the arrangement of suitable IS measures, guiding the IS trajectory in the context of sustainable development. What is the purpose of the intended IS activities? Regarding sustainability development, it is certainly advantageous to envision a desired future scenario of, for example, a "zero waste park", "zero emission park", "CO2-neutral park" in a co-creational manner. If even enough information about concrete IS activities is stored in the tool or in a linked database, scenarios of optimally used IS systems can be simulated and modelled with the help of system dynamics and/or AI methods (Table 2, NK1.2).

3. Discussion and Concluding Impulses for Future Research

IS can occur spontaneously due to economic motivation, but just up to a certain point, then it needs to be further driven to exhaust its full potential (Mirata 2004). Each IS system is embedded in geographical, structural, economic, cognitive, cultural, political, temporal and spatial environments, which determine and guide the development of IS systems and their potentially optimal activities. The success of the IS evolution is highly dependent on the level of trust, motivation/interests, willingness, readiness and openness of the entities involved, so beside the most known primary economic motivation (Heeres et al. 2004; Jackson and Clift 1998; Şenlier and Albayrak 2011; Sakr et al. 2011), the social, ethical, organizational and technological factors are the crucial driving forces to exploit the full range of IS.

This work focuses the technology-enabled environment for IS system analysis, transformation simulation and goal-setting in order to enable and facilitate IS in IPs. Therefore, a first prototype has been already conceptualized (Lütje et al. 2019a) and implemented (the manuscript of the prototype is currently under review), covering the first component of multi-methods system analysis, and the framework for a (key performance) indicator system has been developed (Lütje and Wohlgemuth 2020), which is to be incorporated into the web tool.

The proposed concept for a holistic IT-supported IS tool goes beyond the previous approaches of system analysis and IS identification as well as information and collaboration platform. The innovative elements in this approach are, on the one hand, the extension of perspective to future visions/scenarios and goal setting for elaborating target-oriented transformation pathways and, on the other hand, the inclusion of supporting simulation and modelling techniques. As Lütje et al. (2019b) proposed,

[4] Science based targets (SBT) were established by the Science Based Targets initiative to drive corporate climate action that is aligned to meet the goals of the Paris agreement in 2015—to limit global warming to well below 2 °C above pre-industrial levels.

hybrid approaches of ABM and Reinforcement Learning enable the investigation of system dynamics of IS and therefore open up the exploration of various transformation pathways from the actual state of an IP to the desired goal state of an IS system. Detailed research is needed to conceptualize and implement such approaches. So, topics of system analysis and IS identification are well recorded in the scientific and non-scientific literature, but there are still profound research gaps in the fields of normative and transformative knowledge, which should be prioritized in future research activities. Especially the elaboration of quantifiable goals (which can be in line with the Sustainable Development Goals (SDGs) of the United Nations (UN) and/or Science Based Targets (SBT)), their respective (key performance) indicators and the development of a corresponding roadmap with concrete IS measures should be addressed intensively in this research field.

The concept for a web application to be developed, presented in this paper, is an innovative and promising approach to enable the evolution of IS systems and requires further research especially in the field of building up respective databases in order to exhaust the full potential of the presented IT-supported IS tool. The buildup of such an (international) IS database should be part of future research and forms a cornerstone for the inclusion of system dynamics and AI methods as well as supporting expert systems, which accelerate IS identification. Information and data on IS structure and morphology as well as material exchanges can be basic properties that an ANN can use to characterize and classify IS network types. The prerequisite for the use of expert systems and AI techniques is essentially the development of (relational) databases that can be compiled from previous (non-)scientific literature.

However, still further research is suggested for the development of IT-supported IS information and integrated analysis tools. The existing literature should be analyzed in-depth in order to extract valuable IS knowledge (addressing system, transformative and normative knowledge) and to crystallize out general IS patterns, activities and core elements for the development of an expert system. The identification of common (key) patterns of IS systems are required relating to detailed IS structures, characteristics, attributes and causations. Future research could address for example:

- the detection of IS key entities in order to ensure resilient IS systems,
- the investigation of recurring composition patterns in IS systems (repetitious cooperating IS industries) in order to facilitate the recommendation of potential IS partners,
- the mapping of common resource exchange flows in IS systems (which output flows can function as which input flows?) in order to create an IS resource catalog for the facilitated recommendation of concrete IS resource flow connections.

This, in turn, can be used as a knowledge base for the transformation simulation to derive application rules, insights and to develop optimally utilized IS scenarios.

We need to keep in mind, that planet earth and its embedded ecosystems are not static states, but dynamic ones, which are connected and interfere with each other, so each subsystem cannot be considered separately. It is like a dynamic system that continuously tends to oscillate to a new equilibrium. The socio-economic-technological sphere is embedded in the global ecosystem; hence it is constrained by it regarding ecosystem functioning and ecosystem services to humankind. So, there are environmental impacts while the resources move within the socio-economic-technological sphere. For every step of recycling or processing of secondary raw materials, additional energy and resources are required. There is no "perpetuum mobile". We know, that if we continue the pathway of business as usual, we would gradually deprive ourselves of our own livelihood. We need to pose the crucial question: "How to shape and create safe operating activities within the planetary boundaries?" Moreover, as every human activity generates environmental impacts, we need to consider the "safe operating range" of human activities as well as in terms of compensation and balance. We need to find a sustainable pathway gradually and successively. From an anthropocentric point of view, global society needs to steadily converge to a consensus of what is bearable and proportionate for present and future generations concerning inter-, intra- and transgenerational justice.

4. Materials and Methods

This study aims to present the results for the software/system development process phase of Requirements Engineering (RE), also called requirements analysis, to elaborate an initial basic framework for a holistic IT-supported IS tool covering system analysis, transformation simulation and goal-setting. The first steps of RE focus on identifying software requirements, then detailing and refining them. By the first conception of a holistic IT-supported IS tool fundamentally crucial and trend-setting requirements are formulated here. The IS tool has been designed based on an extensive cross-case analysis. An extensive literature review, employing bibliometric analysis and snowballing techniques, was conducted to select a total of 105 freely accessible papers, including 75 case studies (see full list in Appendix A), to synthesize and abstract knowledge of Industrial Symbiosis (IS) in order to converge to possible answers of the research questions, displayed in Figure 3. The design of the research scheme is oriented to the three types of knowledge, which have its origins in the fields of transdisciplinarity and sustainability sciences (Lang et al. 2012), showing the iterative and recursive processes of gaining insights for system, transformative and normative knowledge.

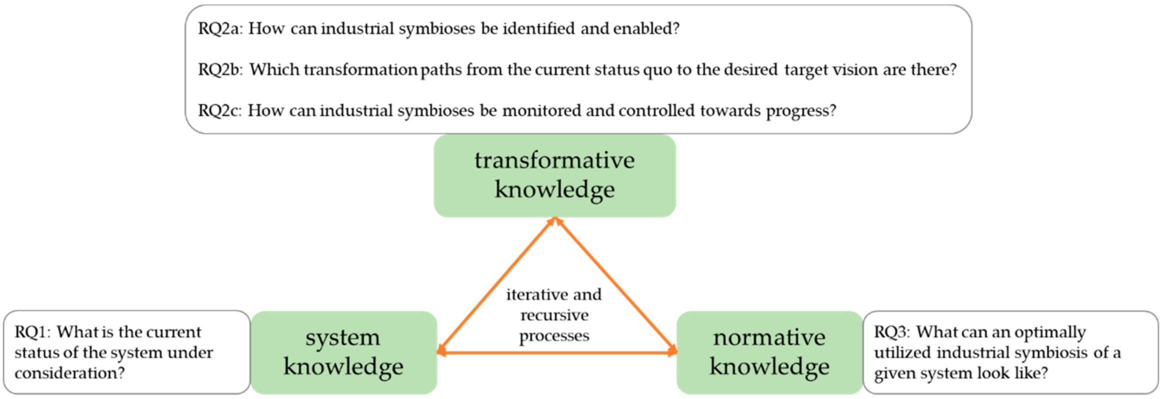

Figure 3. Research scheme and questions for the development of a systematic approach for IS Figure 75. Case studies were chosen with the non-probability sampling technique of purposive sampling. The initial sample size of 75 case studies was predetermined by the authors. The processes of qualitative data collection and analysis were conducted simultaneously. As a purposive sampling technique, the maximum variation sampling was applied in order to cover a wide range of perspectives and IS case studies, enabling the examination of software requirements and IS patterns across the sample case. When selecting the case studies, consideration was given to addressing a diverse set of different IS systems. Additionally, it was ensured to collect case studies from different periods, authors and geographical regions. Once a paper addressed the topics of: (1) (IT-supported) IS tool, (2) the application of a method in IS context, (3) representing IS case studies with mentioned concrete material exchanges and IS activities as well as (4) case studies addressing IS structures/morphologies, they were chosen for this paper. Only publications in English and German were included in the study due to reasons of language comprehension.

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Appendix A

List of analyzed case studies.

Nr.	Main author (Publication year)	Publication Title	Region of IS system
1	Alkaya et al. (2014)	Industrial Symbiosis in Iskenderun Bay: A journey from Pilot Applications to a National Program in Turkey.	Turkey
2	Ashton (2008)	Understanding the organisation of Industrial Ecosystems - A social network approach.	Puerto Rico
3	Bain et al. (2010)	Industrial Symbiosis and waste recovery in an Indian industrial area.	India
4	Behera et al. (2012)	Evolution of 'designed' industrial symbiosis networks in the Ulsan Eco-industrial Park: 'research and development into business' as the enabling framework.	South Korea
5	Chertow et al. (2008)	Industrial Symbiosis in Puerto Rico: Environmentally Related Agglomeration Economies.	Puerto Rico
6	Chertow and Ashton (2009)	The social embeddedness of Industrial Symbiosis linkages in Puerto Rican industrial regions.	Puerto Rico
7	Park (2010)	Industrial symbiosis potential and urban infrastructure capacity in Mysuru, India.	India
8	Park (2010)	Understanding resilience in industrial symbiosis networks: Insights from network analysis.	Denmark
9	Park (2010)	A case study of Industrial Symbiosis development using a middle-out approach.	Portugal
10	Cui et al. (2018)	Understanding the Evolution of Industrial Symbiosis with a System Dynamics Model: A Case Study of Hai Hua Industrial Symbiosis, China.	China
11	Dai (2010)	Two quantitative indices for the planning and evaluation of eco-industrial parks.	China
12	Park (2010)	Structure and morphology of industrial symbiosis networks: the case of Kalundborg.	Denmark
13	Dong et al. (2013)	Promoting low-carbon city through industrial symbiosis: A case in China by applying HPIMO model.	China
14	Park (2010)	Towards preventative eco-industrial development: an industrial and urban symbiosis case in one typical industrial city in China.	China
15	Francis (2003)	The chemical industry from an industrial ecology perspective.	United States of America
16	Geng et al. (2014)	Emergy-based assessment on industrial symbiosis: a case of Shenyang Economic and Technological Development Zone.	China
17	Golev et al. (2014)	Industrial symbiosis in Gladstone: a decade of progress and future development.	Australia
18	Hatefipour et al. (2011)	The Händelö area in Norrköping, Sweden - Does it fit for Industrial Symbiosis development?	Sweden

19	Heeres et al. (2004)	Eco-industrial park initiatives in the USA and the Netherlands: first lessons.	United States of America and Netherlands
20	Jacobsen (2006)	Industrial Symbiosis in Kalundborg, Denmark: a quantitative assessment of economic and environmental aspects.	Denmark
21	Jyrki (2009)	Harjavalta industrial eco park—A success story of the industrial ecology in the area of metallurgical industry to increase regional sustainability.	Finland
22	Korhonen and Snäkin (2005)	Analysing the evolution of industrial ecosystems: concepts and application.	Finland
23	Park (2010)	Opportunities through Industrial Symbiosis: UK NISP and Global Experience.	United Kingdom
24	Li (2011)	A case study of Industrial Symbiosis: the Beijiang power plant complex in Tianjing, China.	China
25	Park (2010)	Industrial symbiosis as a countermeasure for resource dependent city: a case study of Guyang, China.	China
26	Li et al. (2017)	The vulnerability of industrial symbiosis: a case study of Qijiang Industrial Park, China.	China
27	Liu et al. (2018)	Co-benefits accounting for the implementation of eco-industrial development strategies in the scale of industrial park based on emergy analysis.	China
28	Liwarska-Bizukojc et al. (2009)	The conceptual model of an eco-industrial park based upon ecological relationships.	Austria
29	Park (2010)	Ecological Network Analysis for Carbon Metabolism of Eco-industrial Parks: A Case Study of a Typical Eco-industrial Park in Beijing.	China
30	Marconi et al. (2018)	An approach to favor industrial symbiosis: the case of waste electrical and electronic equipment.	Italy
31	Park (2010)	Environmental limits of industrial symbiosis: the case of aluminium eco-industrial network.	Greece
32	Park (2010)	Quantifying the environmental performance of an industrial symbiosis network of biofuel producers.	Sweden
33	Park (2010)	Improving the environmental performance of biofuels with industrial symbiosis.	Sweden
34	Park (2010)	Prospecting the sustainability implications of an emerging industrial symbiosis network.	Sweden
35	Mathews and Tan (2011)	Progress toward a circular economy in China.	China
36	Mauthoor (2017)	Uncovering industrial symbiosis potentials in a small island developing state: The case study of Mauritius.	Mauritius
37	Melanen et al. (2008)	Industrial Symbiosis for global climate change mitigation.	Finland
38	Mirata (2004)	Experiences from early stages of a national industrial symbiosis programme in the UK: determinants and coordination challenges.	United Kingdom

39	Park (2010)	Industrial Symbiosis networks and the contribution to environmental innovation: the case of the Landskrona Industrial Symbiosis programme.	Sweden
40	Morales et al. (2019)	"By-product synergy" changes in the industrial symbiosis dynamics at the Altamira-Tampico industrial corridor: 20 years of industrial ecology in Mexico.	Mexico
41	Notarnicola et al. (2016)	Industrial Symbiosis in the Taranto industrial district: current level, constraints and potential new synergies.	Italy
42	Pakarinen et al. (2010)	Sustainability and industrial symbiosis - The evolution of a Finnish forest industry complex.	Finland
43	Park (2010)	Eco-industrial development in South Korea and its future	South Korea
44	Park et al. (2008)	Strategies for sustainable development of industrial park in Ulsan, South Korea—From spontaneous evolution to systematic expansion of industrial symbiosis.	South Korea
45	Park (2010)	Industrial symbiosis of very large-scale photovoltaic manufacturing.	United States of America
46	Raabea et al. (2017)	Collaboration platform for enabling industrial symbiosis: Application of the by-product exchange network model.	Model
47	Roberts (2004)	The application of industrial ecology principles and planning guidelines for the development of eco-industrial parks: an Australian case study.	Australia
48	Park (2010)	The effect of price regulation on the performances of industrial symbiosis: a case study on district heating.	Denmark
49	Saikku (2006)	Eco-industrial parks: a background report for the eco-industrial park project at Rantasalmi.	Finland
50	Sakr et al. (2011)	Critical success and limiting factors for eco-industrial parks: global trends and Egyptian context.	Egypt
51	Sendra et al. (2007)	Material flow analysis adapted to an industrial area.	Spain
52	Park (2010)	Opportunities for sustainable industrial development in turkey: Eco-industrial parks.	Turkey
53	Shi et al. (2010)	Developing country experience with eco-industrial parks: a case study of the Tianjin Economic Technological Development Area in China.	China
54	Park (2010)	From Refining Sugar to Growing Tomatoes: Industrial Ecology and Business Model Evolution.	United Kingdom
55	Park (2010)	Analysing the development of Industrial Symbiosis in a motorcycle local industrial network: the role of contextual factors.	Italy
56	Sokka et al. (2010)	Analyzing the Environmental Benefits of Industrial Symbiosis - Life Cycle Assessment Applied to a Finnish Forest Industry Complex.	Finland

57	Song et al. (2018)	Social network analysis on industrial symbiosis: A case of Gujiao eco-industrial park.	China
58	Sun et al. (2016)	Eco-benefits assessment on urban industrial symbiosis based on material flow analysis and emergy evaluation approach: a case of Liuzhou City, China.	China
59	Taddeo et al. (2017)	The development of Industrial Symbiosis in Existing Contexts. Experiences from three Italian clusters.	Italy
60	Park (2010)	Preliminary Design of Eco-City by Using Industrial Symbiosis and Waste Co-Processing Based on MFA, LCA, and MFCA of Cement Industry in Indonesia.	Indonesia
61	UNIDO (2016)	Eco-industrial parks in emerging and developing countries: Achievements, good practices and lessons learned, a comparative assessment of 33 cases in 12 emerging and developing countries.	various countries
62	Van Beers et al. (2007)	Industrial Symbiosis in the Australian minerals industry: the cases of Kwinana and Gladstone.	Australia
63	Van Berkel et al. (2009)	Quantitative assessment of Urban and Industrial Symbiosis in Kawasaki, Japan.	Japan
64	Park (2010)	Promoting industrial symbiosis: empirical observations of low-carbon innovations in the Humber region, UK.	United Kingdom
65	Wen and Meng (2015)	Quantitative assessment of industrial symbiosis for the promotion of circular economy: a case study of the printed circuit boards industry in China´s Suzhou New District.	China
66	Park (2010)	A case study of industrial symbiosis: Nanning Sugar Co., Ltd. in China.	China
67	Park (2010)	Sustainable operations of industrial symbiosis: an enterprise input-output model integrated by agent-based simulation.	Numeric example model
68	Park (2010)	Industrial Symbiotic Networks as Coordinated Games.	Model
69	Yu et al. (2015)	Evolution of industrial symbiosis in an eco-industrial park in China.	China
70	Park (2010)	Improving enterprise competitive advantage with industrial symbiosis: case study of a smeltery in China.	China
71	Park (2010)	Boosting circular economy and closing the loop in agriculture: Case study of a small-scale pyrolysis-biochar based system integrated in an olive farm in symbiosis with an olive mill.	Italy
72	Zhang et al. (2013a)	Social network analysis and network connectedness analysis for industrial symbiotic systems: model development and case study.	China
73	Zhang et al. (2013b)	Analysis of low-carbon industrial symbiosis technology for carbon mitigation in a Chinese iron/steel industrial park: A case study with carbon flow analysis.	China

74	Zhang et al. (2015)	Ecological network analysis of an industrial symbiosis system: A case study of the Shandong Lubei eco-industrial park.	China
75	Park (2010)	Industrial Symbiosis in China. A Case Study of the Guitang Group.	China

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