Tools for promoting industrial symbiosis: A systematic review

Zhiquan Yeo[a,b], Donato Masi[c], Jonathan Sze Choong Low[b], Yen Ting Ng[b]
Puay Siew Tan[b] , Stuart Barnes[a]

Affiliations:

[a] *WMG, University of Warwick, Coventry, United Kingdom, CV4 7AL*

[b] *Singapore Institute of Manufacturing Technology, 2 Fusionopolis Way, #08-04, Innovis, Singapore 138634*

[c] *Aston Business School, Aston University, Birmingham, United Kingdom, B4 7ET*

Corresponding author: Zhiquan Yeo

Corresponding author's email: z.yeo@warwick.ac.uk

Address: WMG, International Manufacturing Centre, University of Warwick, Coventry,
CV4 7AL

Tools for promoting industrial symbiosis: A systematic review

Industrial Symbiosis (IS) employs a cross-organizational perspective to seek synergistic pairings of one company's waste output to another company's input, enabled by inter-firm cooperation through resource and information sharing. Orchestrating IS relationships among companies however, remains a complex process. In the literature, a wide range of qualitative and quantitative tools have emerged, tackling issues ranging from identifying IS creation opportunities to performance evaluation. Thus far, the available literature have focused on separate aspects and perspective of IS creation. Each individual work contributes, in part, to the overall process of IS creation. The disparate perspectives provided by the literature reflect the fragmented nature of available tools supporting IS, which operate in isolation of each other. An encompassing view of tools supporting the process of IS creation is missing to date. Therefore, to fill this gap, this study aims to develop a more comprehensive description of the landscape of IS tools by analyzing the associated approaches, roles and contribution of existing tools. Through this understanding, the insights gained can be utilized to aid future development and advancement of tools for IS practitioners.

Keywords: industrial symbiosis; industrial ecology; circular economy; recycling; sustainability; waste management

1 Introduction

Industrial Symbiosis (IS), widely recognized as a sub-field of Industrial Ecology (IE) (Albino *et al.*, 2015; Chertow, 2000; Lee, 2012; Yuan and Shi, 2009), aims to operationalize IE concepts at the inter-firm level (Chertow 2000). The concept of IS first gained popularity through the discussions by Frosch and Gallopoulos (1989), suggesting that one company's waste can be utilized by another company as productive input. Since then, discussions on IS in the literature centered around endeavors seeking opportunities for the synergistic inter-firm pairings focusing on physical materials and energy flows (Chertow 2007, 2000; Chertow and Park 2016). A very well-known example of IS is the Kalundborg eco-park (Ehrenfeld and Gertler 1997).

Previous studies focused for instance on the economic and environmental benefits of IS (Jacobsen 2006), the conditions for fostering eco-innovation (Valentine 2016), and the application of IS environments different from Kalundborg (Branson 2016). Examples of IS have also sprouted in various regions of the world, including the "by-product synergy" (BPS) referred by the United States Business Council for Sustainable Development (2017) and the National Industrial Symbiosis Programme (NISP) in the United Kingdom (Laybourn and Morrissey 2009; Mirata 2004). Modern IS practice has progressively expanded beyond the tenets of physical material and energy transactions, emphasizing on cooperation through resource, information, and knowledge sharing (Lombardi and Laybourn 2012). Through their experience in facilitating the creation of IS at the national-level in the UK and regional-level IS in nine other countries, Lombardi and Laybourn (2012) defined IS as follows:

> *"IS engages diverse organizations in a network to foster eco-innovation and long-term culture change. Creating and sharing knowledge through the network yields mutually profitable transactions for novel sourcing of required inputs, value-added destinations for non-product outputs, and improved business and technical processes."*

Orchestrating IS relationships and transactions among companies is a complex and dynamic process (Paquin and Howard-Grenville 2012; Boons *et al.* 2016, 2011) and supporting tools have emerged to facilitate the process. In the literature, there are at least four literature reviews discussing IS tools and methods. As shown in Table 1, current literature broadly presents tools aimed at identifying IS opportunities[i].

Table 1: List of existing literature reviews on IS tools

Author (Year)	**Research methodology**	**Focus**	**Main intent of tools**	**Application context**
Grant *et al.* (2010a)	Not specified; 17 pre-selected purpose-built IS tools	Information systems	Opportunity identification through identifying possible compatible flows and process matches; discovering IS possibilities (e.g. MatchMaker!, DIET)	Before IS creation (finding synergistic opportunities)
Boix *et al.* (2015)	Keyword-based search	Optimization	Opportunity identification through searching for an optimal solution among feasible solutions of source to sink matches (e.g. GAMS)	Before IS creation (eco-park network design and optimization)
Kastner *et al.*(2015)	Not specified	Optimization	Opportunity identification through searching for an optimal solution among feasible solutions of source to sink matches (e.g. Pinch analysis)	Before IS creation (eco-park network design and optimization)
Capelleveen *et al.* (2018)	Keyword-based search and snowballing	Information systems	Opportunity identification through identifying possible compatible flows and process matches; discovering IS possibilities (e.g. open online waste markets, facilitated synergy identification systems);	Before IS creation (finding synergistic opportunities)

1.1 Previous literature reviews on IS tools

Current literature reviews concentrate their discussion on identifying IS opportunities, which is the activity of identifying synergistic linkages among processes or businesses leading to the creation and development of IS.

Grant *et al.* (2010) performed a review on purpose-built information and communication tools (ICT) tools aimed at creating "IS, IE, by-product synergy and/or eco-industrial parks". Similarly, Capelleveen *et al.* (2018) focused their discussion on IS related information systems and proposed six concepts to characterize tools for facilitating IS identification. Collectively, the tools reviewed emphasized on discovering ***possibilities*** of IS opportunities.

Boix *et al.* (2015) and Kastner *et al.* (2015) focused on reviewing quantitative tools for network optimization. The tools discussed focus on ***optimality*** in the context of IS based water, energy and/or material streams with higher data precision requirements. Viewed holistically, opportunities identification act as the initiator for further development of IS.

1.2 Motivating factors for another literature review

While current reviews provide a very good initial overview of the tools, they have three key gaps that limit a comprehensive understanding of the interaction between tools and the IS creation process.

Firstly, in terms of literature review methodology, no prior reviews was found to have applied the *systematic review* methodology (Denyer and Tranfield 2009). Concomitantly, the *systematic review* methodology has been discussed as a highly reliable way for aggregating knowledge through well-defined processes and criteria

(Klewitz and Hansen 2014), guided by the scientific principles of replicability and transparency (Tranfield *et al.* 2003).

Secondly, existing literature reviews presupposes that opportunities for IS already exist but remain latent (Grant *et al.* 2010a; Capelleveen *et al.* 2018; Boix *et al.* 2015; Kastner *et al.* 2015) and attempts to inform decision makers of the missed opportunities to accelerate the “sprouting” process (Chertow and Ehrenfeld 2012) so that IS can be “uncovered” (Chertow 2007; Chertow and Ehrenfeld 2012). The tools reviewed serves to find previously latent IS opportunities and provides knowledge on sources and sinks of resource flows befitting the definition of IS. However, these reviews do not consider prior steps leading to the creation of these opportunities and the actual implementation after the optimal or possible flows have been identified.

Thirdly, current reviews focus on specific types of tools, like information systems (Grant *et al.* 2010a; Capelleveen *et al.* 2018) or optimization (Boix *et al.* 2015; Kastner *et al.* 2015), while there are other tools that include process simulation and design (Casavant and Côté 2004), green social networking (Ghali *et al.* 2016) and heuristic visualization (Aid *et al.* 2015).

1.3 Research Question

Thus far, the available reviews concentrate on tools for identifying IS opportunities with varying aims (i.e. possibilities and optimality). The disparate perspectives provided by the literature lends a glimpse of the fragmented nature of the tools supporting IS, which appear to operate in isolation of each other. In particular, there is a gap in understanding how IS tools and methods support the process of IS creation at their elemental stages.

A holistic view of the tools in relation to the process of creating IS is absent from current literature. Therefore, this review analyses a comprehensive set of IS related tools, contributing to the understanding of their roles towards IS creation.

The primary question that this study seeks to address is:

- What are the available tools [ii] employed to support the process of IS creation?

The supporting secondary questions are:

- What are the stages for the IS creation process?
- What is the role of these tools with respect to the IS creation processes?
- What are the contextual conditions enabling the use of a specific tool (e.g. availability of information, skills, etc.)
- Who are the target users of the tools?

The paper is structured as follows: Section 2 provides a description of the research methodology employed in this study. Section 3 presents the thematic results. Section 4 discusses the implication of these results on IS practices and future research. Section 5 concludes the paper.

2 Research Methodology

This study adapts the *systematic literature review* (SLR) methodology to provide an evidence-informed approach which is replicable, scientific and transparent, overcoming the apparent weaknesses by traditional narrative reviews (Denyer and Tranfield 2009). This section provides a description of the procedure.

2.1 Search process

The objective of the literature search process is to locate relevant studies that address the research questions. At this phase, the search engines and search strings are determined.

The search engines were identified based on their relevance to the field of inquiry, in particular the area of industrial symbiosis, industrial ecology, cleaner production and sustainability. As a result, the following search engines were selected: ScienceDirect, Scopus and Web of Science.

The process of determining the search string is performed in an iterative manner (Figure A-1, Appendix A). Firstly, the primary concept comprises the main field of this study – "industrial symbiosis". Next, related concepts were identified through preliminary literature search and screening to capture specific focus areas in the literature that address the research questions:

- Creation: discussions related to creating IS
- Business: current business practices related to IS
- Tools and methods: specific discussions on the artefacts created to aid IS
- Evaluation: discussions related to practical impact of IS (e.g. environmental, social, economic, etc.)

Following that, synonyms of these concepts were established. Finally, these four related concepts were combined with the primary concept to compose the search strings

(Table B-1 to B-4, Appendix B). This procedure yielded a total of 4,838 papers. The search result was further processed to remove duplicates and 1,390 papers were obtained.

2.2 Sample selection

The objective of sample selection is to select the most relevant articles for final analysis. Due to the large number of articles, this process is performed in two incremental steps to efficiently remove irrelevant articles, while maintaining sufficient article representativeness in addressing the research questions.

First, the titles and abstracts were screened to remove evident false positives derived from the automated search process. A set of criteria was developed and applied to ensure topic relevance. Thereafter, a set of criteria was developed and applied to the remaining articles through a full-text review to ensure subject matter relevance to the research question. (Table C-1 and Table C-2, Appendix C).

Finally, a snowballing technique is applied by analyzing first-degree cross-references[iii], combined with domain expert opinion to enrich and further substantiate the content of captured articles. A final sample of 180 articles is derived.

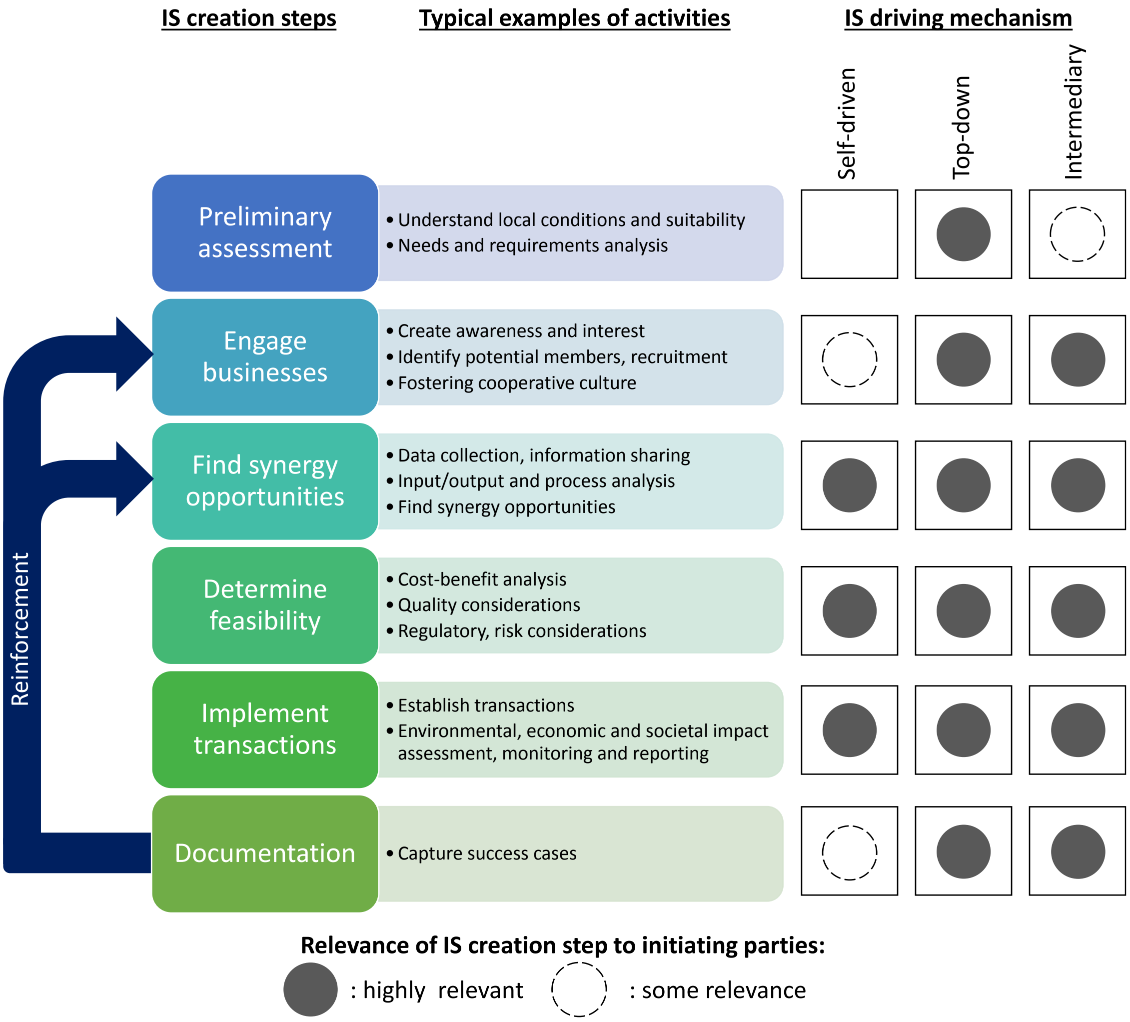
3 Thematic analysis

This section presents the thematic results of the SLR beginning with a framework for representing the IS creation process. Following the framework at every step, the respective tools are analyzed and evaluated.

3.1 Industrial Symbiosis creation process framework

Various authors have proposed models describing the process of IS creation. For instance, Massard and Erkman (2007) applied a methodology to systematically detect and implement by-product synergies. Grant *et al.* (2010) identified five developmental phases of IS by analyzing the usage context of 17 IS tools. Ghali *et al.* (2016) proposed a framework incorporating the phases of developing industrial synergy projects. In general, the three phases of IS creation – identification, assessment and implementation – have been frequently discussed (Capelleveen *et al.* 2018).

Based on the aggregated analysis of an additional 17 articles discussing the IS creation process (Table D-1, Appendix D) and generalizing the typologies of IS dynamics (Boons et al. 2016), a six-step IS creation process is synthesized to facilitate the analysis of tools supporting IS creation (Figure 1). The steps are subsequently described in their respective sections.



IS creation steps	Typical examples of activities	IS driving mechanism		
		Self-driven	Top-down	Intermediary
Preliminary assessment	• Understand local conditions and suitability • Needs and requirements analysis		●	○
Engage businesses	• Create awareness and interest • Identify potential members, recruitment • Fostering cooperative culture	○	●	●
Find synergy opportunities	• Data collection, information sharing • Input/output and process analysis • Find synergy opportunities	●	●	●
Determine feasibility	• Cost-benefit analysis • Quality considerations • Regulatory, risk considerations	●	●	●
Implement transactions	• Establish transactions • Environmental, economic and societal impact assessment, monitoring and reporting	●	●	●
Documentation	• Capture success cases	○	●	●

Relevance of IS creation step to initiating parties:

● : highly relevant ○ : some relevance

Figure 1: IS creation process framework proposed for this study, the grey dots indicate the relatedness of the steps to the three mechanisms driving IS creation for the parties initiating IS

3.2 Summary table

Table 2 summarizes the tools that will be discussed in subsequent sections of this review. The key characteristics of the tools are abstracted and grouped with respect to their use during the IS creation steps proposed in section 3.1. Particularly, the key functions of tools required by the individual steps are summarized. Following that, the instances of tools found within our sample articles are extracted and grouped into two categories – qualitative and quantitative tools. Qualitative tools are defined as tools that analyze non-numeric data (e.g. textual data) to fulfil functional requirements, while quantitative tools refer to tools that primarily process forms of numeric data to fulfil its key function. Based on the understanding derived from the tools reviewed, the tools' application context and target users are summarized. Finally, the general tool requirements for each category of tools are presented. The detailed review of the individual categories of tools is discussed in subsequent sections thereafter.

Table 2: Summary of IS tools

IS creation step	Key function required	Instances of IS tools reviewed	Application context and target users	Tool requirements
Preliminary assessment	Intelligence gathering to characterize regional attributes, pre-existing streams and determine the suitability and potential for creating IS	Qualitative Maturity grid Quantitative Sustainability suitability mapping Multi-criteria approach (Waste) streams assessment Geographic information system (GIS)	Application context Top-down and intermediary driven IS Target-users Eco-industrial estate/park planners (top-down driven) IS facilitator (intermediary driven)	Geo-spatial related data Process input-output data Statistical datasets Informational capturing historical cases

IS creation step	**Key function required**	**Instances of IS tools reviewed**	**Application context and target users**	**Tool requirements**
Engage businesses	Build and grow network of businesses. Creating awareness and interest. Build trust.	Note: No tools built specifically for IS was found, but general purpose tools are used in the context of fostering IS networks. <u>Qualitative</u> Cold-calling, mailings, emails and other business-to-business communications. Providing interaction spaces for businesses.	<u>Application context</u> All forms of IS creation driving mechanisms <u>Target users</u> Reported to be used by: The facilitation body in an intermediary driven IS. The authoritative body in a top-down driven IS. Could be used by: Individual businesses in a self-driven IS.	No specific requirements; general purpose tool. The desired effect of the tools could be enhanced with success cases illustrating the benefits of IS to prospective participants and business partners.

IS creation step	Key function required	Instances of IS tools reviewed	Application context and target users	Tool requirements
Find synergy opportunities	Determine the synergistic linkages among businesses	Qualitative Free-market mechanism based matching Process input-output stream based matching (name matching) Quantitative Process input-output stream based matching (stream attributes matching) Network design and optimization	Application context *Free-market mechanism based matching :* Top-down and intermediary driven IS *Process input-output stream based matching:* All forms of IS creation driving mechanisms *Network design and optimization:* Top-down driven IS Target users *Free-market mechanism based matching:* IS orchestrators (i.e. facilitators or eco-industrial estate/park planners) as hosts of platforms for matching, firms with interests in participating in IS exchanges as users of the platforms *Process input-output stream based matching:* IS orchestrators as hosts	*Free-market mechanism based matching:* Information such as company information, location, textual descriptions of waste at the supplier and buyer sides, availability/requirements in terms of quantity, time and price. Active user participation and critical mass required. *Process input-output stream based matching:* Firm-specific data on resource flows, "wants" and "haves" data *Network design and optimization:* Data required to describe the physical system, such as temperature, flow rate, pressure, enthalpy, concentration of chemical species of streams. Other parameters that relate to

IS creation step	Key function required	Instances of IS tools reviewed	Application context and target users	Tool requirements
			of platforms for matching, firms with interest in participating in IS exchanges as users of the platforms. Participating firms in self-driven IS as users of non-platform based stream matching techniques. *Network design and optimization:* Eco-industrial estate/park planners	case specific objective function.

IS creation step	Key function required	Instances of IS tools reviewed	Application context and target users	Tool requirements
Business feasibility	Provide decision support in planning and selecting among various IS-based options	Note: No dedicated purpose-built tool or process to appraise IS network financially was found. Generic tools were found to have been applied for IS. <u>Quantitative</u> Conventional financial appraisal techniques such as NPV, IRR, payback period, IIR and ROI. Cost savings.	<u>Application context</u> All forms of IS creation driving mechanisms <u>Target users</u> Participating firms in IS networks or IS exchanges	Data required by the financial computations, techniques are freely available to apply.
Implement transactions	Project management and tracking the progress of IS opportunities implementation, and performance evaluation	<u>Qualitative</u> CRISP (customized tool for IS project management) <u>Quantitative</u> Various performance metrics (e.g. eco-connectances), LCA technique	<u>Application context</u> All forms of IS creation driving mechanisms <u>Target users</u> IS orchestrators (i.e. facilitators or eco-industrial estate/park planners) seeking macro-level information on IS network	No specific requirement for CRISP, apart from data entry by IS practitioners. Input data requirements by each individual performance evaluation tool.

IS creation step	Key function required	Instances of IS tools reviewed	Application context and target users	Tool requirements
Document and reinforcement	General function of disseminating information of actual IS cases	<u>Qualitative</u> Enipedia ISDATA CRISP/NISP proprietary database	<u>Application context</u> All forms of IS creation driving mechanisms <u>Target users</u> IS orchestrators (i.e. facilitators or eco-industrial estate/park planners) for suggesting future IS exchanges to participating firms. Firms of self-driven IS utilizing existing documentations for IS idea generation.	Actual information describing the realization of IS instances and active documentation by tool maintainer.

3.3 Preliminary assessment

The preliminary assessment phase serves to provide a general initial understanding of the local conditions in which IS is intended to be implemented. This stage may be beneficial if gaining investor's confidence through demonstrating the prospects for IS is required (Laybourn 2017a). Generally, this stage could be viewed as intelligence gathering (Mattiussi *et al.* 2014) to analyze the current situation (Fichtner *et al.* 2004). Intelligence can be gathered at four levels:

(i) Identifying industries and firms in the region (Massard and Erkman 2007; Andiappan *et al.* 2016; Tan *et al.* 2016)

(ii) Identifying possible needs and requirements by industries and firms (Ghali *et al.* 2016; Sopha *et al.* 2010; Potts Carr 1998)

(iii) Identifying possible resource streams, processes and their utilization (van Beers *et al.* 2007a; Oh *et al.* 2005; Lowe 1997)

(iv) Understanding prevailing regional environmental policies (Massard and Erkman 2007)

3.3.1 Tools, techniques and functions

The tools and techniques applied at this stage focus on intelligence gathering to (1) characterize regional attributes, and/or (2) analyze existing streams within a region. In turn, they provide an indicative view on the prospects of finding synergistic opportunities within the targeted system boundary prior to any engagement activities with participants. These tools and techniques will be discussed in the following.

Tools and techniques which characterize regional attributes share the common feature of determining the suitability of a region for establishing IS. For instance, Fernández and Ruiz (2009) developed a multi-criteria approach to determine the most suitable EIP location. To identify areas conducive in fostering eco-industrial development, Jensen *et al.* (2012) developed a technique to construct a Sustainability Suitability Map derived from the Habitat Suitability Index. Adopting the notion of understanding regions' readiness for IS, Golev et al (2015) developed a Maturity Grid to evaluate regional actions and activities relevant to addressing barriers to IS.

Apart from characterizing regions, analyzing resource streams is another approach applied during preliminary assessment. The focus on resource streams relates back to the understanding of IS, rooted in the involvement of "physical exchange of materials, energy, water, and/or by-products" (Chertow 2000). To supporting the design of EIPs in maximizing resource utilization, Hardy and Graedel (2002) applied the theory of food-web to analyze the web of eco-industrial relationships and derive design insights. Highlighting the need to demonstrate IS prospects to attract initial participants while limited by the lack of detailed data at an early stage, Song *et al.* (2017) experimented with utilizing publicly available data to predict probable waste streams produced by facilities without the need of direct data collection. At the other end of the spectrum where waste input output statistics is available, Chen and Ma (2015) devised a technique to repurpose national level statistics to construct a waste input-output table for identifying synergistic opportunities at the industry level (as opposed to among companies). Geographic information system (GIS) technology has also been applied in conjunction with stream information to spatially characterize and visualize regions. Among the work that incorporates GIS, Togawa *et al.*, (2016) combined geographic data with city sensing technology to aid in the design of energy circulation systems.

Applying GIS system with material flow data, Massard and Erkman (2009) have developed a system that acts as decision support tool for engineers and territorial planners. The Looplocal tool utilizes industrial data with local digitized maps to visualize hotspots for potential synergies (Aid *et al.* 2015).

3.3.2 Tool requirements

While the individual tools and techniques possess their respective unique sets of data input requirements, emergent categories of data were observed in our sample.

Geo-spatial related data of the individual industrial entities was the most commonly reported type of data utilized (Togawa *et al.* 2016; Massard and Erkman 2009; Jensen *et al.* 2012; Hein *et al.* 2016; Song *et al.* 2017). The most basic form of data includes the location of the entities (i.e. latitude and longitude), alongside the other attributes characterizing individual entities such as entity type, industry classification and turnover (Aid *et al.* 2015; Jensen *et al.* 2012). These geo-spatial data are subsequently combined with visualization technologies to produce geographic and/or heat-maps that provide visual indications on the prospects of the area for IS development (Massard and Erkman 2009; Aid *et al.* 2015; Togawa *et al.* 2016; Jensen *et al.* 2012; Song *et al.* 2017).

Process input-output data is also utilized by various tools in order to estimate the flows of resources through the individual industrial entities (Song *et al.* 2017; Aid *et al.* 2015; Hein *et al.* 2016). Process input-output data could be derived from life cycle inventory (LCI) datasets that provides resource flow information associated to industrial process or products (Aid *et al.* 2015). Other approaches to obtaining process input-output data include plant meta-model and correlations (Hein *et al.* 2016) and publicly available technical references (Song *et al.* 2017).

Statistical datasets are also reported to be used for such assessment tools (Aid *et al.* 2015; Chen and Ma 2015). Instances of statistical datasets include international statistics (Aid *et al.* 2015), national statistics of physical input and output from facilities producing waste (Chen and Ma 2015), individual company reports and waste management company databases (Aid *et al.* 2015).

Information capturing historical cases of IS transactions or exchanges have been applied to enable predictive feature of some tools (Aid *et al.* 2015; Hein *et al.* 2016). Based on Aid *et al.* (2015) and Hein *et al.* (2016), the described tools demonstrated the feature of forecasting possible synergies within a bounded geographic region by incorporating historical data of IS.

3.3.3 Application context

Overall, preliminary assessment tools are reported to be applicable at various scales, including industrial park (Hein *et al.* 2016), city/region (Togawa *et al.* 2016; Song *et al.* 2017; Aid *et al.* 2015; Golev *et al.* 2015; Massard and Erkman 2009), national (Jensen *et al.* 2012; Chen and Ma 2015) levels. These tools have also been applicable for top-down driven (Jensen *et al.* 2012; Massard and Erkman 2009; Togawa *et al.* 2016) targeting eco-industrial park planners, as well as intermediary driven mechanisms (Aid *et al.* 2015; Golev *et al.* 2015; Hein *et al.* 2016; Chen and Ma 2015; Song *et al.* 2017) of IS creation targeting IS facilitating bodies.

3.4 Engage businesses

Business engagement is found to be one of the most critical IS creation activities in practice, without which subsequent steps is unable to proceed (Laybourn 2017a). One of the hallmark of IS is the cooperation that takes place within a network of industrial entities (Ashton 2008; Chertow and Ehrenfeld 2012). Therefore, engaging and recruiting members is critical to building up that prerequisite network (Paquin and Howard-Grenville 2013). Discussions in the literature have surfaced three key activities operating at this stage of IS creation:

(i) Establishing contact and communication with companies (Ghali *et al.* 2016; Massard and Erkman 2007)

(ii) Creating awareness (Nguyen and Matsuura 2016; van Beers *et al.* 2007a; Massard and Erkman 2007; Lowe 1997; Paquin and Howard-Grenville 2013)

(iii) Generate interest and positive culture (Geng *et al.* 2007b, 2007a; Oh *et al.* 2005)

3.4.1 Approaches and functions

While specific purpose-built tools and techniques currently has not been found for business engagement, examining current approaches applied in practice may still provide useful insights to guide efforts for future tool development.

During initial stage of business engagement, it is reported that cold-calling, mailings and emails were used as means to reach out to prospective companies (Paquin and Howard-Grenville 2012). Potential use of social media based platforms was also explored (Ghali *et al.* 2016). The use of these business-to-business communication tools can be coupled with the approach of leveraging other established organizations' pre-existing network to reach out to a wider audience for recruiting membership to IS network (Paquin and Howard-Grenville 2012). Other avenues include leveraging existing trade associations and networking events where businesses are already meeting as platforms to carry out information dissemination and engagement activities (Laybourn 2017a; Paquin and Howard-Grenville 2013). All these communication activities serve to establish the required initial contact time between the target audience and the organization responsible for initiating IS to create awareness.

Following the initial contact, facilitating “interaction spaces” helps further progress towards concrete IS connections formation (Paquin and Howard-Grenville 2012). The concept of interaction spaces are exemplified by the “Quick Wins Workshops” carried out by NISP, facilitating information exchange and capturing information companies’ resources “haves” and “wants” for serendipitous opportunities discovery (Laybourn and Morrissey 2009). Alternatively, a hypothetical Green Social Network with the functions of “exchange/sharing” and “discussion” mirrors such physical interaction spaces in the virtual world (Ghali *et al.* 2016). Follow-up site-visits and one-on-one meetings can also be arranged with the companies (Massard and Erkman 2007; Paquin and Howard-Grenville 2013). These activities allow IS facilitating organization to gain a deeper understanding on the participating company’s business as well as to instill their confidence (Paquin and Howard-Grenville 2013). Furthermore, trust can also be built through these close company interactions.

3.4.2 Application context

In general, business engagement tools have been discussed in the context of intermediary driven IS cases (Paquin and Howard-Grenville 2012; Laybourn and Morrissey 2009; Mirata 2004; Paquin and Howard-Grenville 2013; Massard and Erkman 2007). These IS cases typically occur at the scale of city to national levels (Paquin and Howard-Grenville 2012; Laybourn and Morrissey 2009; Mirata 2004; Paquin and Howard-Grenville 2013; Massard and Erkman 2007). This can be explained by the need to assemble a network at the beginning for facilitated IS programmes and to establish legitimacy, which is a precursor for subsequent information exchange activities (Paquin and Howard-Grenville 2013). Therefore, current practice relies on conventional communication and marketing tools which businesses are familiar with to help grow the IS network and to disseminate information. Moving forward, Ghali *et al.* (2016) suggest the use of social network based tool to replicate such aspects of conventional communication means in the virtual space. Therefore, the use of such tools are not limited to the usages reported in cases relating to facilitating or authoritative bodies, but self-driven businesses could in principle utilize them to promote IS.

3.5 Find synergy opportunities

Finding synergy opportunities receives the widest academic attention by far. Of the literature discussing the IS creation process, all have identified or implied the presence of opportunities identification stage (refer to Table D-1, Appendix D). Broadly, this stage encompasses finding the possible IS transactions that may occur among the group of businesses included in the analysis (Grant *et al.* 2010a; Massard and Erkman 2007; Ghali *et al.* 2016). While the previous stage is targeted at the company level, opportunities identification typically occurs at the companies' input-output streams and process level. It is at this stage that possible novel linkages among companies are surfaced for further analysis, planning and implementation.

3.5.1 Tools, techniques, approaches and functions

Based on analyzing existing tools supporting this stage, three types of tools are developed to identify possible linkages among companies, namely:

(i) Free-market mechanism based matching
(ii) Process input-output stream based matching
(iii) Network design and optimization

3.5.1.1 Free-market mechanism based matching

Free-market mechanism based matching applies the concept of free market mechanism as the basis of matching firms. In other words, firms are matched according to the demand and supply of their waste in the free market.

The function of a waste exchange was described as a means to enable the matching up of generators of waste with companies interested in recycling or reusing these materials (US EPA 1994). These waste exchanges may operate as information clearing houses to disseminate information of the availability of waste in terms of type, locality and period of availability to potential users, or, as brokers whereby the staff would provide active efforts to facilitate transactions among firms (US EPA 1994; Herndon and Purdum 1985).

The literature has identified online waste exchanges' role in catalyzing IS (Grant *et al.* 2010b) and several recent examples have been document in the literature (Fortuna and Diyamandoglu 2015; Dhanorkar *et al.* 2015; Geng *et al.* 2007b). As this category of tools is based on the Internet, a separate search[iv] is performed to gather current examples of such tools. Examples from the search include the United States Materials Market Place (BCSD-US 2016), WasteIsNotWaste (Green Future Solutions 2017), Resource Efficient Scotland (WRAP 2013), Minnesota Materials Exchange (iWasteNot Systems 2011), The Waste Exchange (Nothrow 2017), among others. A latest incarnation of such online materials exchange attempts to advance the free market mechanism through ontology engineering and semantic matching. The eSymbiosis platform demonstrated the use of an ontology to structure listing data, enabling automatic generation of suggestions of possible matches based on semantic similarity among its listings (Raafat *et al.* 2013; Trokanas *et al.* 2015; Cecelja *et al.* 2015b; Trokanas *et al.* 2014; Cecelja *et al.* 2015a).

3.5.1.2 Process input-output stream based matching

Process input-output stream based matching is the mechanism of finding possible IS matches through analyzing the characteristics of the streams that can be accepted by processes (i.e. process input requirements) and what is produced by processes (i.e. process outputs/by-products) (Song *et al.* 2015; Hein *et al.* 2016; Low *et al.* 2018). Unlike the concept of pure demand and supply matching through the market mechanism which focusses on waste streams voluntarily reported by suppliers and the explicit willingness of buyers to purchase, process input-output stream based matching attempts to find synergistic opportunities through technical knowledge of processes and their associated inputs/outputs (Low *et al.* 2018). This implies that, in principle, process input-output matching is not restricted by the case whereby not all process outputs/by-products are put up as listings for sale, or process inputs required by companies in waste exchanges listings. Furthermore, process input-output stream based matching may even suggest possible but yet to be implemented technologies capable of accepting available waste streams (Song *et al.* 2015; Brown *et al.* 1997; Low *et al.* 2018). Therefore, this class of tools is not bounded by the *willingness and knowledge* of sellers and buyers, but relies on *technical information* on stream characteristics and technological capabilities, and attempts to find the appropriate matches and recommendations.

Previously, most IS tools[v] reviewed by Grant *et al.* (2010a) fit the process input-output stream mechanism of matching to fulfil the function of opportunity identification. van Beers *et al.* (2007b) further revealed underlying elements of The *Regional Eco-Efficiency Opportunity Assessment Methodology*, that comprise the use of datasheets, templates and decision support tools for synergy opportunities. However, according to Grant *et al.* (2010a) most tools are no longer in use today.

In practice, utilizing this approach has seen success when coupled with a corresponding IS facilitation programme. It is reported that *Core Resource for IS*

Practitioners (CRISP) – a tool used internally by the NISP – possess the function of assisting practitioners in identifying current, as well as potential synergies (Laybourn and Morrissey 2009). The presence of an overarching IS programme may play a critical role for the continuity of such software as it is reported that face-to-face data collection mechanisms such as Quick Wins Workshop and site-visits carried out as part of NISP ensured the credibility and quality of the data that are subsequently input into CRISP by IS practitioners (Wang 2013). The successor of the CRISP tool – SYNERGie® – is also available to characterize, search, and match companies resources (International Synergies 2016). At the point of writing, the next generation of SYNERGie® – dubbed SYNERGie® 2.0 – will feature advanced recommendation system to support the role of IS practitioners in finding synergy opportunities (Laybourn 2017b) and is in the development stage under the SHAREBOX project (SHAREBOX 2017). This highlights the continuous usage and improvement efforts of the tool, indicating a successful case of such tool in practice.

In terms of technology, recent literature has pointed to the emergence of data analytics as an approach to uncover IS matches. Song *et al.* (2015) proposed a solution framework to utilize open-source data to visualize and detect eco-industrial networks. Similarly, Hein *et al.* (2016) proposed a methodology for identifying IS opportunities by utilizing a combination of pre-built plant meta-model, plant correlations and existing symbiosis data, prior to any extensive data collection from companies. Progress reports on SHAREBOX – a research in-progress – have also indicated the usage of “big data” as well as an ontological approach to augment IS tool with semantic and analytics capabilities (Laybourn 2017a; CORDIS 2017a, 2017b). Recommender algorithms have also been identified by Capelleveen *et al.* (2018) to be applicable to IS, which include techniques such as “rule mining, case-based reasoning, collaborative filtering, knowledge-based recommendation and rule-based recommendation”. One instance of such a knowledge-based recommendation system is a graph database developed by Low *et al.* (2018) that organizes knowledge of waste-to-resource matching to assist in the recommendation process.

3.5.1.3 Network design and optimization

Network design and optimization refers to the process of deriving sets of *optimal* matches among process output streams (source) to input streams (sinks). Supporting techniques operate under overarching sets of known physical constraints while attempting to maximize (or minimize) specific system-level variable(s). The notion of *best* is present as this design approach places optimizing predetermined system variable(s) at the focal point.

Formal mathematical optimization forms the core of network design and optimization techniques. This category of design techniques originated from the process industries (e.g. chemicals, refining, pharmaceuticals), also termed as process integration (PI) (collectively referring to heat integration, water and mass integration). First discussed by Linnhoff *et al.* (1982), it was a field developing in parallel to the fields of IE. These two distinct fields have since overlapped due to the similarity of concepts. It is noted that different terminologies are used for similar concepts (e.g. Total Site vis-à-vis EIP) and that PI literature may provide IE the quantitative basis for systematic planning of EIPs (Tan *et al.* 2016).

Among the literature, three dominant categories of optimization tools are present, segregated by their discussion on the type of resource flows optimized – water (see e.g. Ramos et al. 2016; Leong et al. 2016a; Lee et al. 2014), energy (see e.g. Liew et al. 2016; Hipólito-Valencia et al. 2014; Chae et al. 2010) and material (see e.g. Noureldin and El-Halwagi 2015; Cimren *et al.* 2011).

Individually, most articles' scope of discussion is limited to a single type of resource optimization, with the combined discussion of two or more resource optimization forming the exception rather than the norm. Of these combined resource optimization discussions, typically only two types of resources are optimized simultaneously. For instance, Boix *et al.* (2011) discussed the optimization of both water and energy consumption for EIPs, while other authors discussed the optimization of material and energy (Kantor *et al.* 2014; Mamoune and Yassine 2011; Kantor *et al.* 2012, 2015; Karlsson and Wolf 2008; Kuznetsova *et al.* 2016). As expressed by Boix *et al.* (2015), while it is important to simultaneously optimize the multiplicity of resource networks and account for their interactions, the literature have yet to discuss this aspect extensively.

Generally, optimization tools share similar mode of operation (Figure E1, Appendix E). The first step of the process involves the collection of data, also known as the data extraction step (Varbanov 2011). In this step, relevant data is collected in order to represent the system of interest to model. Additionally, associated economic and environmental data can be collected in relation to the input output streams depending on the goal of the optimization. Accordingly, the objective function of the optimization is defined, which can take the form of minimizing the resource consumption, costs and/or environmental impact. Following that, the mass and energy balances, representing fundamental scientific laws of conservation are solved and mathematical programming is employed to search for a feasible configuration (i.e. solution) that satisfies the objective function. The solution is further analyzed for implementation. Overall, this process may be iterative in order to achieve the satisfactory solution for implementation.

In terms of optimization technique, a mix of mathematical optimization programming has been utilized which include linear programing (LP) and non-linear programming (NLP), with the variables mainly taking the form of mixed-integers (i.e. mixed-integer linear and non-linear programming). To account for the satisfaction levels of the participants, fuzzy-based approaches has also been proposed to improve robustness in design (Aviso et al. 2010, 2011a, 2011b), perform targeting (Leong et al. 2016b), satisfying emergy goals (Taskhiri et al. 2011), accounting for investment returns (Ng et al. 2015) and tenant selection (Ubando et al. 2016).

3.5.2 Tool requirements

3.5.2.1 Free-market mechanism based matching

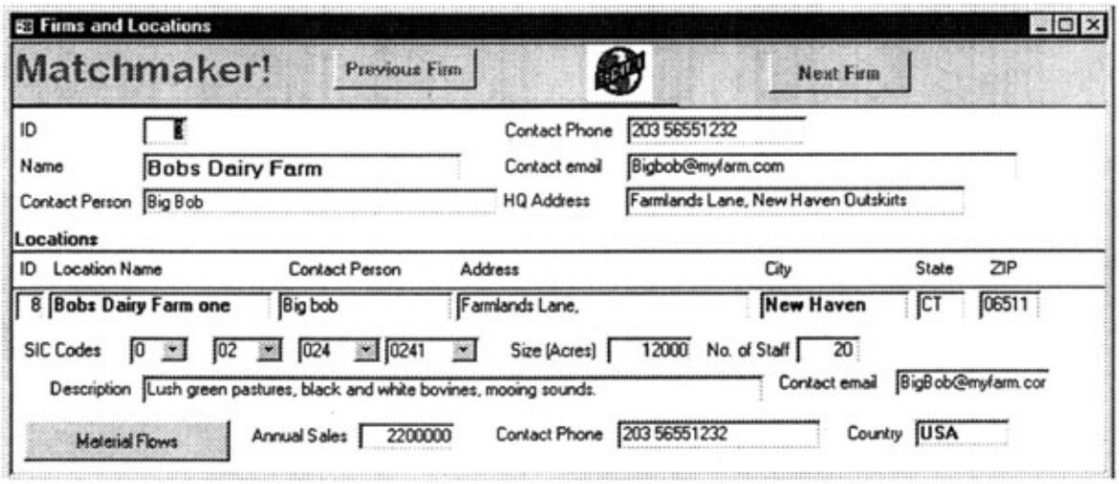
Collectively, such tools are avenues for waste sellers to list and advertise their waste, while the platforms act as a coordinating medium to match willing buyers for the waste. Among the sample of online waste exchanges examined (Nothrow 2017; iWasteNot Systems 2011; WRAP 2013; Green Future Solutions 2017), the typical data input requirements include company information, location, textual descriptions of waste at the supplier and buyer sides, availability/requirements in terms of quantity, time and price. The information transmitted via these voluntarily contributed electronic waste listings enables the free market forces to operate and match suppliers and buyers of these “wastes” autonomously.

To support the successful operations of these waste exchange platforms, active user participation is required. Just like any other user-generated content based web service, they stand to reap network effects if a sufficient pool of users participates on the platform (Evans and Schmalensee 2010). Although waste exchanges continue to be recognized as an approach towards achieving IS (Dhanorkar *et al.* 2015; Clayton *et al.* 2002), it has been shown through various cases that waste exchanges face challenges in sustaining operations financially, regulatory constraints and lack ability to engage the industry (Capelleveen *et al.* 2018). Furthermore, Ayres (1997) argues that decentralized pure market mechanism featuring competitive buying and selling is unlikely to optimize the use of by-products and secondary resources. Nevertheless, tighter regulations on waste may be a positive effector for the use of such tools as they serve to bridge the lack of information that may lead to inadequate and premature disposal of materials (Clayton *et al.* 2002; Fortuna and Diyamandoglu 2015).

3.5.2.2 Process input-output stream based matching

The requirements of process input-output stream based matching is derived based on the available information describing the tools' inner workings (e.g. MatchMaker! (Brown *et al.* 1997)). Therefore, it provides an indicative view on the tools' requirements rather than an extensive coverage of all the tools in this category.

Two main types of data are commonly stored in such tools – firm data and material flow data. In the instance of MatchMaker! tool (Brown *et al.* 1997), data describing firms and material flows are stored in a database. Firm data include address, contact information, description and associated Standard Industrial Classification (SIC) code. Material flows include the data describing materials and utilities. More specifically, materials are being classified by a customized taxonomy. Technically, these data are stored in a relational database so that data describing each firm is linked to the appropriate material flows accordingly. A sample screenshots of the software is shown in Figure 2 and Figure 3. Similarly, in the CRISP software (Wang 2013), firm information is also recorded and each firm is associated to "wants" and "haves" data. In this context, "wants" and "haves" pertain to the resources that each firm in the database requires or supplies, and the CRISP system is capable of assisting IS practitioners look for synergy opportunities through a manual search interface.



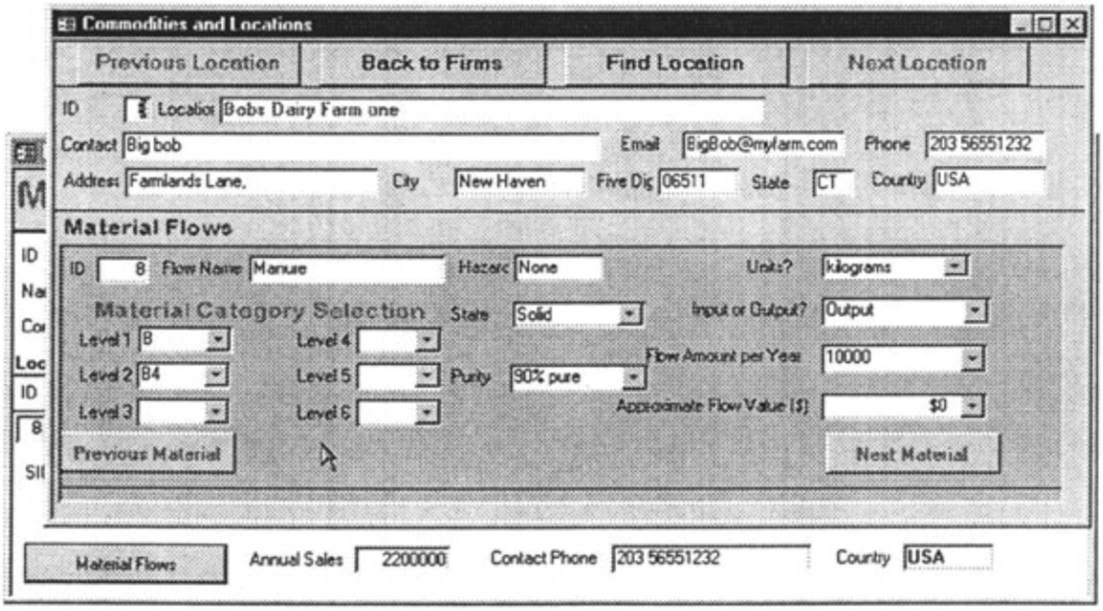
ID
Name Bobs Dairy Farm
Contact Person Big Bob
Contact Phone 203 56551232
Contact email Bigbob@myfarm.com
HQ Address Farmlands Lane, New Haven Outskirts

Locations

ID	Location Name	Contact Person	Address	City	State	ZIP
8	Bobs Dairy Farm one	Big bob	Farmlands Lane,	New Haven	CT	06511

SIC Codes 0 02 024 0241
Size (Acres) 12000
No. of Staff 20
Description Lush green pastures, black and white bovines, mooing sounds.
Contact email BigBob@myfarm.cor
Annual Sales 2200000
Contact Phone 203 56551232
Country USA

Figure 2: Screenshot of capturing firm data



ID Locatior Bobs Dairy Farm one
Contact Big bob
Email BigBob@myfarm.com
Phone 203 56551232
Address Farmlands Lane,
City New Haven
Five Dig 06511
State CT
Country USA

ID 8
Flow Name Manure
Hazarc None
Units? kilograms
State Solid
Input or Output? Output
Level 1 B
Level 2 B4
Level 3
Level 4
Level 5
Level 6
Purity 90% pure
Flow Amount per Year 10000
Approximate Flow Value ($) $0

Annual Sales 2200000
Contact Phone 203 56551232
Country USA

Figure 3: Screenshot of capturing material flow data linked to firm

It is reported that improving the usability and sociability of such tools may increase their uptake and ensuring continued use (Grant *et al.* 2010a). Conversely, an over-focus on connecting streams and the philosophy of merely encoding data in the database with little regard to the human-to-human connections underpinning the design of these tools will inhibit the use of such tools (*Ibid.*). In this vein, recent on-going efforts have been reported to develop the next-generation tools, improving upon previous generations, including the next-generation of IS matching applications

(International Synergies 2017) and platforms based on big data analytics (Song et al. 2017; Raabe et al. 2017; Song et al. 2015; Low et al. 2018), that are participation (LifeM3P 2017) and knowledge (MAESTRI 2017) driven.

3.5.2.3 Network design and optimization

In terms of data inputs, the requirements contingent upon the type of flow, as well as the objective of the network design and optimization.

In the case when the type of flow is heat (or energy), the typical data required to describe the physical system include the temperature, flow rate, pressure and enthalpy for all energy carrying streams (Hackl et al. 2011). In the case of water flows, the data required describing the physical system include flow rate and concentration of chemical species (Leong et al. 2016b; Aviso et al. 2010). In the case of material flows, the relevant physical data required are mass flow rates (Vadenbo et al. 2014; Cimren et al. 2011).

Additionally, if the objective function of the network design model considers financial cost, then data such as unit cost information (Kim et al. 2010) and interest rate (Chang et al. 2015) will be required; and if the objective function considers ecological costs, then environmental information such as emission factors will be required (Fichtner *et al.* 2004; Zhang *et al.* 2016).

3.5.3 Application context

The scale for free-market mechanism based matching has been observed to be applied at the industrial park level (Geng *et al.* 2007a), the city/region (iWasteNot Systems 2011; WRAP 2013; US EPA 1994) and the national (Green Future Solutions 2017; BCSD-US 2016; Nothrow 2017) levels. While most of these tools are applied in the self-driven context (e.g. iWasteNot Systems 2011; WRAP 2013; US EPA 1994;

Green Future Solutions 2017; Nothrow 2017), top-down driven (Geng *et al.* 2007a) and facilitated schemes (BCSD-US 2016) also utilize such material exchanges as information sharing platforms.

Similarly, process input-output based matching tools are observed to be applied at the scale of industrial park (Hein *et al.* 2016; Sterr and Ott 2004), city/region (Song *et al.* 2015; Raafat *et al.* 2013; Cecelja *et al.* 2015b; Trokanas *et al.* 2014; Cecelja *et al.* 2015a; Brown *et al.* 1997; Low *et al.* 2018) and the national level (Paquin and Howard-Grenville 2012; Grant *et al.* 2010a; Jensen *et al.* 2011; Wang 2013). This tool has also been applied in the self-driven (Cecelja et al. 2015b; Trokanas et al. 2015; Raafat et al. 2013; Cecelja et al. 2015a), top-down (Sterr and Ott 2004) and intermediary driven context (Paquin and Howard-Grenville 2012; Grant *et al.* 2010a; Jensen *et al.* 2011; Wang 2013).

3.6 Business feasibility

Traditionally, self-organized IS was mainly driven by economic benefits (Tudor *et al.* 2007; Velenturf 2016). While it is argued that IS driven by conventional business agendas predominantly leads to retrofitting and short term gains (Mirata 2004), Lombardi and Laybourn (2012) argued that "profitable" transactions has since been understood by the IS community to have a broader meaning that includes risk or reputation management, diversification and asset utilization, all of which contributes to businesses' bottom-line. Therefore, the authors posit that the presence of transactions that are aligned with business goals favor companies in bringing IS opportunities to fruition, particularly in the context of directed facilitation. Primarily, the main themes that emerged in literature discussions at this stage of IS creation are:

(i) Cost-benefit evaluation and allocation (Andiappan *et al.* 2016; Nguyen and Matsuura 2016; Tan *et al.* 2016; van Beers *et al.* 2009; Massard and Erkman 2007; Fichtner *et al.* 2004)

(ii) Validation and selection of opportunities (Ghali *et al.* 2016; Mattiussi *et al.* 2014; Grant *et al.* 2010a; Ardente *et al.* 2010)

Cost-benefit may connote direct financial cost and benefits (i.e. revenue), as well as, non-financial ones such as risks, reputation, resource security. Furthermore, as IS opportunities typically involve two or more organizations, fair allocation of the cost and benefits among the parties may need to be determined at this stage. With the prior knowledge of technical feasibility, costs and benefits of opportunities, validation and selection of those opportunities will have to be done. This step also encompasses prioritization and removal of any non-financial barriers such as regulations that may prevent opportunities from coming to fruition.

3.6.1 Tools, techniques and approaches

While economic (i.e. monetary, financial) considerations is primarily linked to the business feasibility of IS and reportedly a predominant factor for the success of IS networks (Mirata 2004; Tudor et al. 2007; Velenturf 2016; Côté and Cohen-Rosenthal 1998), literature discussions on financial tools applied in the context of IS remains scarce. Currently, there is no dedicated purpose-built tool or process to appraise IS network financially. However, the use of conventional financial appraisal tools on IS projects have been cited such as the net present value (NPV) (Li *et al.* 2015; Nair *et al.* 2016; Ubando *et al.* 2015), internal rate of return (IRR) (Li *et al.* 2015; Ubando *et al.* 2015), payback period (Li et al. 2015; Mirata 2004), incremental investment return (IIR) (Ng *et al.* 2015) and return on investment (ROI) (Theo et al. 2016; Jung et al. 2013; Mirata 2004). Cost savings is also a frequently used measure to exhibit the financial benefits of IS initiatives (Mirata 2004; Nair et al. 2016; Ubando et al. 2015; Raabe et al. 2017).

In practice, the mentioned financial tools are typically applied to provide decision support in planning and selecting among various IS-based options. For instance, the financial measures are incorporated in optimization models whereby the best network configuration can be determined which conforms to technical constraints while maximizing the financial performance of the IS network (Theo et al. 2016; Ng et al. 2015; Ubando et al. 2015; Nair et al. 2016; Raabe et al. 2017).

3.6.2 Application context

Fundamentally, IS networks comprise a collection of business entities linked by material and monetary flows and hence Mirata (2004) suggests that these business entities are inclined to align with conventional business agendas in the context of their involvement in IS activities. Moreover, these financial appraisal tools are embedded within optimal planning and design tools (Ng et al. 2015; Ubando et al. 2015) and collaborative based tool (Raabe et al. 2017). With the inherent conventional business tendencies, together with the observations of the context of the financial appraisal tools being applied provide a proxy to indicate that the financial appraisal tools are universally applicable in terms of scale of IS, regardless the type of driving mechanism which the IS is brought to fruition. The reviewed tools' unit of analysis is the firm level, therefore, these tools ostensibly target participating firms in IS networks.

3.7 Implement transactions

Implementation refers to the translation of IS opportunities into reality (Grant *et al.* 2010a; Sopha *et al.* 2010; Ghali *et al.* 2016). Oftentimes however, the actual details of the implementation of opportunities are not thoroughly discussed. Nevertheless, after the opportunities come to fruition, it is frequently coupled with efforts to monitor the impact realized by the opportunities as well as to make continuous improvement (Grant *et al.* 2010a; Massard and Erkman 2007; Sopha *et al.* 2010; Ardente *et al.* 2010).

3.7.1 Tools, techniques and approaches

In terms of tools supporting the implementation phase, CRISP was described to support this step in terms of project management and tracking the progress of IS opportunities implementation (Wang 2013; Grant *et al.* 2010a). Apart from this, the other tools applicable at this step function as performance measurement tools. Performance measurement tools are tools that yield metrics to quantitatively appraise the performance of IS exchange or EIPs. While this set of tools does not directly participate in the design of EIPs, it plays a supporting role in terms of providing feedback mechanism for the design process.

When performed during design time, the purpose of deriving performance metrics is to serve as a predictive feedback to act as a decision support tool for EIP designers on their design choices. Therefore, the appraisal is typically coupled with a model representation of the intended IS flows proposed. Among the work with themes covering EIP planning and performance metrics, Tiejun (2010) has proposed two quantitative indices – eco-connectances and the byproduct and waste recycling rates – to aid in the EIP planning, and have utilized existing EIP as illustrative case studies of the method. Extending the work by Tiejun (2010), Mantese and Amaral (2016) employed an agent-based model to simulate scenarios whereby IS relationships are being formed among the firms modelled. Following that, the computation of performance indicators such as industrial symbiosis indicator (ISI), eco-connectance and by-product and waste recycling rate are being computed to predict the system's performance over time. Therefore, this allows the EIP designer to explore various scenarios and make adjustments in a safe virtual environment to attain a desired level of performance through obtaining feedback from the performance metrics.

Following the general scheme of design and feedback loop (Figure F-1, Appendix F), designers can adjust their designs accordingly towards positive improvement in those metrics upon obtaining the performance data.

In contrast, to design time performance metrics, post-implementation performance metrics are being performed on IS systems that have been realized (e.g. an operational EIP). Instead of providing predictive performance assessment, the role of such performance metrics is to provide descriptive information of the state of the IS system in a feedback loop that enables continuous improvement. Performance targets can be set and subsequently measured. Following that, actions can be then taken to correct any deviation from the desired performance (Figure F-2, Appendix F). In principle, post-implementation performance metrics can also be applied to the pre-implementation design phase, provided sufficient data is available at design time. Among the wide variety of techniques proposed in the literature for appraising IS systems, the life cycle assessment (LCA) technique is the most frequently mentioned in our sample[vi]. The LCA provides a collection of environmental indicators that profile the environmental performance of the IS system. In relation to the standard LCA technique to obtain environmental performance, other studies have also proposed a custom set of indicators to measure IS performance as summarized in Table 3.

Table 3: List of performance assessment methods

Performance assessment method	Reference
Value flow analysis	(Fang and Zhou 2009)
List of indicators	(Geng et al. 2009)
Emergy based measurement	(Geng *et al.* 2014)
Discounted cash flow, Multi-attribute global inference of quality	(Jung *et al.* 2013)
Constructs of roundput and diversity; COD BOD, CO2 emissions	(Korhonen and Snäkin 2005; Yu *et al.* 2015)
Eco-efficiency computation	(Park and Behera 2014)
Metrics based performance assessment	(Tian *et al.* 2014)
Eco-connectance, By-product and waste recycling rate	(Dai 2010)
Exergy	(Valero *et al.* 2013)
Direct quantification, Qualitative description of benefit	(Van Behkel *et al.* 2009)
Emergy based measurement	(Wang *et al.* 2006, 2005)
Industrial symbiosis indicator (ISI) Eco-connectance By-product and waste recycling rate	(Mantese and Amaral 2016; Felicio et al. 2016)

Due to the multiplicity of indicators that are potentially available for use in measuring the performance of IS-based systems, multi-criteria decision making techniques such as analytic network process (Li 2011) and fuzzy analytic hierarchy process (Hui 2011) have been employed in an attempt to construct a single index with an underlying set of elementary indicators.

Apart from the indicator based approaches of appraising IS-based systems, a network based approach is also employed by examining the underlying structure of the IS relationships. For instance, network resilience has been studied by Chopra and Khanna (2014) and Zeng *et al.* (2013) through the study of the flow structure of among the entities and applying cascading failure model to study the impact of potential risks and vulnerabilities of the system. Additionally, social network analysis studies have also been conducted to explore the relation of social relationships on the actual formation of physical IS connection among firms (Ashton 2008; Zhang et al. 2013; Zheng et al. 2012).

Presently, whilst there is a wide variety of performance measurement metrics proposed to measure the economic, environment and social performance of EIPs, there is no standard way of performance measurement. The use of relevant performance measurements depends on the goal of the EIP and the different emphasis on the three dimensions of sustainability. There has yet to be any conclusive evidence of a consistent set of performance measurements for EIPs.

3.7.2 Application context

The tools to perform appraisals for IS performance are applicable for IS of various scales as well as in the three contexts whereby IS is driven. For instance, IS performance evaluation has been performed on co-located firms (Chertow and Lombardi 2005), industrial park level (Geng et al. 2009) as well as at the national level (Laybourn and Morrissey 2009). It is also observed that regardless of IS driving mechanism, ranging from self-driven IS (Dai 2010), intermediary driven (Laybourn and Morrissey 2009) to top-down driven (Jung et al. 2013), performance evaluation remains relevant. The underpinning motivation for establishing IS projects or programmes is its environmental, economic and social benefits they entails (Martin et al. 2015; Chertow and Lombardi 2005) and it is often hypothetically presumed at the outset (Cecelja et al. 2015a; Chertow and Lombardi 2005). Therefore, IS performance assessment tools provide the function of monitoring and supports reporting of IS benefits in IS linked projects and programmes regardless of scale.

3.8 Documentation and reinforcement

As described by Grant *et al.* (2010), a part of the IS creation process consists of communicating the success of individual firms and their associated synergies after implementation. Massard and Erkman (2007) described presenting individual report to companies on promising opportunities fulfilling technical, economic and environmental benefits to get their participation. Furthermore, it is opined that reinforcing the business engagement stage is crucial as it is required to maintain the momentum over time (Laybourn 2017a). Therefore, this stage comprises the act of capturing relevant information (i.e. documentation) with the purpose of feeding back into the steps of engaging businesses and finding synergy opportunities to strengthen and propagate the IS creation process (i.e. reinforcement).

Based on literature discussions and practitioner opinion (Benedetti *et al.* 2017; Laybourn 2017a), capturing tangible and sharable case information is required to support instilling confidence in participants during the business engagement stage, as well as to foster idea generation for finding synergy opportunities from past successes.

3.8.1 Tools, techniques and approaches

Tools that are available for use at this stage appear to be heterogeneous in form while sharing the general function of disseminating information of actual IS cases. In general, two main types of tools are applicable at this stage. First, text-based repositories are available to store and diffuse knowledge about IS cases with a wider base of audience. Second, individual reports targeting specific companies are utilized to inform prospective companies on the potential synergies that they are able to participate in.

An early attempt at a text-based repository described was the Centre for Sustainable Resource Processing (CSRP) Global Synergy Database (van Beers *et al.* 2007b), which aimed to maintain a publicly available database of synergy examples globally for search and retrieval. Presently, this concept of recording IS case studies continues to exist. Enipedia, for instance, is a wiki-style website designed initially for “energy and industry issues” (Delft University of Technology 2014). Documented case studies from NISP can be retrieved from Enipedia in their original raw form for further learning and analysis. Efforts to enhance the Enipedia project include an ontology designed for representing case studies, as well as accompanying procedure and techniques enabling the contribution towards the ontology (Nooij 2014). Industrial Symbiosis Data Repository (ISDATA 2017), a spin-off from the original efforts from Enipedia’s “Industrial Symbiosis Data Sources” section, self-described as “open platform for collecting and supplying structured information on industrial symbiosis”. Text-based repository is also a feature in the closed-access tool used by the NISP (i.e. CRISP) (Grant *et al.* 2010b), which its successful application was reported in the literature (Jensen *et al.* 2011; Paquin and Howard-Grenville 2012; Lombardi and Peter 2006; Grant *et al.* 2010a; Laybourn and Morrissey 2009). One of its key function include the storage of completed synergies to provide information for future IS implementation (Grant *et al.* 2010b; Jensen *et al.* 2011; Grant *et al.* 2010a). This feature facilitates the learning process among the closed-group of users as they are able to consult the shared knowledge repository and propagate the process of facilitating new synergies (Jensen *et al.* 2011). Other similar repositories for IS case studies include the 50 case studies shared by Nordregio (Nordregio 2016) in the European Nordic region and the Materials Marketplace (US BCSD 2016) in the US. In terms of technology aiding information organization, Benedetti *et al.* (2017) developed a technique and proof-of-concept database to categorize past IS cases, searchable by Nomenclature des Activités Économiques dans la Communauté Européenne (NACE) and European Waste Catalogue (EWC) codes.

An approach that IS facilitators may take in the process of reinforcing IS propagation is through the use of reports specifically written to target companies (Massard and Erkman 2007; Laybourn 2017a). In general, these reports are produced after potential IS opportunities are shortlisted and evaluated in order convey viable opportunities and to attract companies to commit to these opportunities. Once successful, IS opportunities will progress to implementation and full materialization. These reports may contain the benefits and the costs of viable opportunities for target companies' consideration.

3.8.2 Tool requirements

Due to the heterogonous nature of this category of tools, the tool requirement characteristics will be generalized to provide a high level overview. It is observed that a key common characteristic of tools such as CRISP (Grant *et al.* 2010b; Jensen *et al.* 2011; Grant *et al.* 2010a), exchanges database (Benedetti *et al.* 2017) and ISDATA (ISDATA 2017), is the presence of a repository documenting historical IS case studies. These case studies are systematically documented in structured tabular format, such as describing business activity and waste streams in terms of NACE and EWC codes, respectively (Benedetti et al. 2017; ISDATA 2017). This implies that a conscious effort is required to maintain and update the database as new cases occur. Another key component present is the search and retrieval function (Benedetti *et al.* 2017) to enable the retrieval of stored historical information for future reference. Therefore, such tools typically comprise data storage and query functions.

3.8.3 Application context

While case study repository has been developed (Benedetti et al. 2017; ISDATA 2017), and it is observed to have been used in practice for intermediary driven IS (Laybourn 2017a), in principle, the function of such tools do not restrict its application in terms of scale or driving mechanism of IS. Historical cases of IS equally serve as useful informational aid to initiate further investigation of opportunities for all forms of IS. Therefore, we argue that such tools are universally applicable in all context of IS. IS orchestrators are able to reference historical cases for suggesting IS exchanges to participating firms, while self-driven firms can utilize these historical cases to search for IS possibilities applicable to their specific context.

4 Discussion and outlook

4.1 Practical implications

This review paper has gathered a broad range of IS-related tools that has been discussed in the literature as well as instances of tools used in industrial practice. Using the holistic perspective of the generic end-to-end framework of creating IS networks at various scales, these ostensibly disparate discussions on IS tools are positioned with respect to the IS creation process. The tools' key functions, target audiences/users and requirements were abstracted and associated to the key steps in the IS creation framework. This information provides IS practitioners a landscape of available state-of-the-art tools to fulfil specific tasks in their day-to-day routine.

Additionally, for the field of IS research, this review provides an opportunity to identify research gaps that warrants further research and development. For instance, it is well recognised in the academic literature that inter-firm trust, communication and "mental distance" are key determinants during implementation stage (Walls and Paquin 2015). However, based on the sample of articles yielded, relevant tools focus on performance evaluation, whilst discussion on tools for managing participants and stakeholders appear to be less discussed. This suggests a possible lack of tools and discussion directly addressing issues such as closing the "mental distance" and fostering trust amongst the participants.

4.2 The future role of ICT

As suggested by Jensen *et al.* (2011), purpose-built IS ICT platform "never replaces a practitioner's personal knowledge of a given resource or company". While human reasoning and analysis has worked reasonably well in the formation of symbiotic links, Cecelja *et al.* (2015a) suggested that this approach remains empirical due to the closed system nature of considering symbiotic links, and that practitioners may be biased towards own individual expertise or industries. Through their observation of ICT based IS tools, Capelleveen *et al.* (2018) proposed that machine learning based recommendation algorithms is an area that shows promising prospects for the field of IS amidst the context of rapidly growing availability of knowledge that doubles every nine years (Mortenson and Vidgen 2016). Therefore, we argue that human intelligence will remain the dominant and crucial source of knowledge to assist in identifying symbiotic links among businesses. However, moving forward, we propose that the way in which human knowledge is utilized can be improved. Instead of relying on decentralized individual expertise to perform the task of identifying IS opportunities, with the advent of machine learning algorithms tailored for the purpose of IS, the collective knowledge created by humans can be unlocked to maximize the utility of created knowledge. More generally, the role of ICT could potential aggregate knowledge and help leverage collective intelligence to assist and enhance human competency in the area of facilitating IS identification.

4.3 Limitation of this study

Whilst this review applied the systematic literature review methodology to maintain the thoroughness of the review, practical implementation of the process invariably resulted in the limitation of this study due to the presences of subjective elements. This review does not claim full comprehensiveness, but the results and findings yielded a representation of the current literature reflected by our sample.

During the sample selection process, the search string determination is based on the knowledge derived from prior preliminary literature search and review by the authors. This prior knowledge was referenced in seeding the initial generation of candidate concepts. Therefore, the dependence on the individual author’s prior knowledge introduced subjectiveness to the process. The authors mitigated the subjectiveness by maintaining independence among authors during the divergent search and brainstorming process, and a convergent process whereby the information are themed and combined. The final search strings subsequently determined the papers captured within the sample. The authors acknowledge that invariably, false negatives will arise during the process, which resulted in relevant papers not captured within the sample. Therefore, geographically specific case examples may have been excluded in this review. Despite the false negatives, the sample articles captured common general concepts related to industrial symbiosis such as feasibility assessment, engaging businesses (Park et al. 2016) and performance criteria (Shi et al. 2010) typically associated to establishing eco-industrial parks in Korea and China.

5 Conclusion

In summary, this review covers the literature discussing the tools supporting the process of creating IS. A plethora of tools from multiple disciplines was found in the literature, addressing various aspects of creating IS. While existing reviews exist, providing a good initial understanding of the various critical functions of the tools, each review was scoped to address specific disciplines (e.g. network optimization, information systems). A review to analyses the role of each set of tools with respect to the overarching process of creating IS was lacking. Moreover, in terms of methodology, a systematic literature review in this area is still absent. Therefore, this review provides a holistic view of the broad range of tools available for the purpose of organizing and creating IS. We provided a framework comprising the steps of the IS creation process and analyzed the available tools with respect to each step. Furthermore, the tools were analyzed based on the specific techniques and approaches used, their requirements and application contexts. In general, large focus is placed on tools that assist in finding synergy opportunities, which is a critical and hallmark activity of IS. In terms of future research, we propose that while the critical activity of finding synergistic links among businesses remains reliant on human knowledge, the way in which human knowledge is utilized has room for innovation. We further propose that amidst the current trend of growing amount of digitalized knowledge, coupled with machine learning algorithms, collective intelligence can be tapped by aggregating and further analyzing such vast reservoir of untapped knowledge sources to uncover new knowledge to help identify novel, synergistic and environmentally benign IS process chains.

6 Acknowledgement

We would like to sincerely thank Peter Laybourn, Chief Executive of International

Synergies Limited, for sharing his vast experience in establishing the National Industrial Symbiosis Programme (NISP) and his valuable feedback on the proposed IS creation process.

References

Aid, G., N. Brandt, M. Lysenkova, and N. Smedberg. 2015. Looplocal - a heuristic visualization tool to support the strategic facilitation of industrial symbiosis. *JOURNAL OF CLEANER PRODUCTION* 98: 328–335.

Albino, V., L. Fraccascia, and T. Savino. 2015. Industrial Symbiosis for a Sustainable City: Technical, Economical and Organizational Issues. *Procedia Engineering* 118: 950–957.

Andiappan, V., R.R. Tan, and D.K.S. Ng. 2016. An optimization-based negotiation framework for energy systems in an eco-industrial park. *JOURNAL OF CLEANER PRODUCTION* 129: 496–507.

Ardente, F., M. Cellura, V. Lo Brano, and M. Mistretta. 2010. Life cycle assessment-driven selection of industrial ecology strategies. *Integrated Environmental Assessment and Management* 6(1): 52–60.

Ashton, W. 2008. Understanding the organization of industrial ecosystems - A social network approach. *Journal of Industrial Ecology* 12(1): 34–51.

Aviso, K.B., R.R. Tan, A.B. Culaba, and J.B. Cruz. 2011a. Fuzzy input-output model for optimizing eco-industrial supply chains under water footprint constraints. *Journal of Cleaner Production* 19(2–3): 187–196.

Aviso, K.B., R.R. Tan, A.B. Culaba, and J.B. Cruz Jr. 2010. Bi-level fuzzy optimization approach for water exchange in eco-industrial parks. *Process Safety and Environmental Protection* 88(1): 31–40.

Aviso, K.B., R.R. Tan, A.B. Culaba, D.C.Y. Foo, and N. Hallale. 2011b. Fuzzy optimization of topologically constrained eco-industrial resource conservation networks with incomplete information. *Engineering Optimization* 43(3): 257–279.

Ayres, R. 1997. Toward zero emissions: is there a feasible path?

BCSD-US. 2016. The Materials Marketplace. *The Materials Marketplace*. http://materialsmarketplace.org/. Accessed October 27, 2017.

Beers, D. van, A. Bossilkov, and C. Lund. 2009. Development of large scale reuses of inorganic by-products in Australia: The case study of Kwinana, Western Australia. *RESOURCES CONSERVATION AND RECYCLING* 53(7): 365–378.

Beers, D. van, G. Corder, A. Bossilkov, and R. van Berkel. 2007a. Industrial symbiosis in the Australian minerals industry: The cases of Kwinana and Gladstone. *Journal of Industrial Ecology* 11(1): 55–72.

Beers, D. van, G.D. Corder, A. Bossilkov, and R. van Berkel. 2007b. Regional synergies in the Australian minerals industry: Case-studies and enabling tools. *Minerals Engineering* 20(9): 830–841.

Behkel, R. Van, T. Fujita, S. Hashimoto, and M. Fujii. 2009. Quantitative Assessment of Urban and Industrial Symbiosis in Kawasaki, Japan. *Environmental Science & Technology* 43(5): 1271–1281.

Benedetti, M., M. Holgado, and S. Evans. 2017. A Novel Knowledge Repository to Support Industrial Symbiosis. In , 443–451. Springer, Cham, September 3.

Boix, M., L. Montastruc, C. Azzaro-Pantel, and S. Domenech. 2015. Optimization methods applied to the design of eco-industrial parks: a literature review. *Journal of Cleaner Production* 87(1): 303–317.

Boix, M., L. Montastruc, L. Pibouleau, C. Azzaro-Pantel, and S. Domenech. 2011. Eco Industrial Parks for Water and Heat Management. In *21ST EUROPEAN SYMPOSIUM ON COMPUTER AIDED PROCESS ENGINEERING*, ed. by Pistikopoulos, EN and Georgiadis, MC and Kokossis, AC, 29:1175–1179. Computer-Aided Chemical Engineering.

Boons, F., M. Chertow, J. Park, W. Spekkink, and H. Shi. 2016. Industrial Symbiosis Dynamics and the Problem of Equivalence: Proposal for a Comparative Framework. *Journal of Industrial Ecology* 21(4): 938–952.

Boons, F., W.W.. Spekkink, and Y.. Y. Mouzakitis. 2011. The dynamics of industrial symbiosis: A proposal for a conceptual framework based upon a comprehensive literature review. *Journal of Cleaner Production* 19(9–10): 905–911.

Branson, R. 2016. Re-constructing Kalundborg: the reality of bilateral symbiosis and other insights. *Journal of Cleaner Production* 112, Part: 4344–4352.

Brown, J., D. Gross, and L. Wiggs. 1997. The MatchMaker! System: Creating Virtual Eco-Industrial Parks. *Yale F&ES Bulletin*(106): 103–136.

Capelleveen, G. van, C. Amrit, and D.M. Yazan. 2018. A literature survey of information systems facilitating industrial symbiosis identification. In *From*

Science to Society.

Casavant, T.E. and R.P. Côté. 2004. Using chemical process simulation to design industrial ecosystems. *Journal of Cleaner Production* 12(8–10): 901–908.

Cecelja, F., T. Raafat, N. Trokanas, S. Innes, M. Smith, A. Yang, Y. Zorgios, A. Korkofygas, and A. Kokossis. 2015a. E-Symbiosis: Technology-enabled support for Industrial Symbiosis targeting Small and Medium Enterprises and innovation. *Journal of Cleaner Production* 98: 336–352.

Cecelja, F., N. Trokanas, T. Raafat, and M. Yu. 2015b. Semantic algorithm for Industrial Symbiosis network synthesis. *COMPUTERS & CHEMICAL ENGINEERING* 83: 248–266.

Chae, S.H., S.H. Kim, S.-G. Yoon, and S. Park. 2010. Optimization of a waste heat utilization network in an eco-industrial park. *APPLIED ENERGY* 87(6): 1978–1988.

Chang, C., Y. Wang, and X. Feng. 2015. Indirect heat integration across plants using hot water circles. *Chinese Journal of Chemical Engineering* 23(6): 992–997.

Chen, P.C. and H.W. Ma. 2015. Using an Industrial Waste Account to Facilitate National Level Industrial Symbioses by Uncovering the Waste Exchange Potential. *Journal of Industrial Ecology* 19(6): 950–962.

Chertow, M. 2000. Industrial symbiosis: Literature and taxonomy. *ANNUAL REVIEW OF ENERGY AND THE ENVIRONMENT* 25: 313–337.

Chertow, M. 2007. ‘Uncovering’ industrial symbiosis. *Journal of Industrial Ecology* 11(1): 11–30.

Chertow, M. and J. Ehrenfeld. 2012. Organizing Self-Organizing Systems: Toward a Theory of Industrial Symbiosis. *Journal of Industrial Ecology* 16(1): 13–27.

Chertow, M. and D.R. Lombardi. 2005. Quantifying economic and environmental benefits of co-located firms. *Environmental Science and Technology* 39(17): 6535–6541.

Chertow, M. and J. Park. 2016. Scholarship and Practice in Industrial Symbiosis: 1989–2014. In *Taking Stock of Industrial Ecology*, 87–116. Springer.

Chopra, S.S. and V. Khanna. 2014. Understanding resilience in industrial symbiosis networks: Insights from network analysis. *Journal of Environmental Management* 141: 86–94.

Cimren, E., J. Fiksel, M.E. Posner, and K. Sikdar. 2011. Material Flow Optimization in By-product Synergy Networks. *JOURNAL OF INDUSTRIAL ECOLOGY* 15(2): 315–332.

Clayton, A., J. Muirhead, and H. Reichgelt. 2002. Enabling industrial symbiosis through a web-based waste exchange. *Greener Management International*(40): 93–106.

CORDIS. 2017a. European Commission : CORDIS : Projects and Results : Periodic Reporting for period 1 - SHAREBOX (Secure Management Platform for Shared Process Resources). http://cordis.europa.eu/result/rcn/201150_en.html. Accessed September 11, 2017.

CORDIS. 2017b. European Commission : CORDIS : Projects and Results : Secure Management Platform for Shared Process Resources. http://cordis.europa.eu/project/rcn/198388_en.html. Accessed September 11, 2017.

Côté, R.P. and E. Cohen-Rosenthal. 1998. Designing eco-industrial parks: a synthesis of some experiences. *Journal of Cleaner Production* 6(3–4): 181–188.

Dai, T. 2010. Two quantitative indices for the planning and evaluation of eco-industrial parks. *Resources, Conservation and Recycling* 54(7): 442–448.

Delft University of Technology. 2014. Enipedia - Enipedia. http://enipedia.tudelft.nl/wiki/Main_Page. Accessed September 11, 2017.

Denyer, D. and D. Tranfield. 2009. Producing a Systematic Review. *The SAGE Handbook of Organizational Research Methods*.

Desrochers, P. 2001. Eco-industrial parks: The case for private planning. *Independent Review* 5(3): 345–371.

Dhanorkar, S., K. Donohue, and K. Linderman. 2015. Repurposing Materials and Waste through Online Exchanges: Overcoming the Last Hurdle. *PRODUCTION AND OPERATIONS MANAGEMENT* 24(9): 1473–1493.

Dong, H., Y. Geng, F. Xi, and T. Fujita. 2013. Carbon footprint evaluation at industrial park level: A hybrid life cycle assessment approach. *Energy Policy* 57: 298–307.

Ehrenfeld, J. and N. Gertler. 1997. Industrial ecology in practice: The evolution of interdependence at Kalundborg. *Journal of Industrial Ecology* 1(1): 67–79.

Evans, D.S. and R. Schmalensee. 2010. Failure to Launch: Critical Mass in Platform Businesses 9(1).

Fang, Y. and H. Zhou. 2009. Value flow analysis based on EAP industrial chain: case of Huaning in Xichang, Sichuan. *Journal of Cleaner Production* 17(2): 310–316.

Felicio, M.M., D. Amaral, K. Esposto, and X. Gabarrell Durany. 2016. Industrial symbiosis indicators to manage eco-industrial parks as dynamic systems. *JOURNAL OF CLEANER PRODUCTION* 118: 54–64.

Fernández, I. and M.C. Ruiz. 2009. Descriptive model and evaluation system to locate sustainable industrial areas. *Journal of Cleaner Production* 17(1): 87–100.

Fichtner, W., M. Frank, and O. Rentz. 2004. Inter-firm energy supply concepts: an option for cleaner energy production. *Journal of Cleaner Production* 12(8–10): 891–899.

Fortuna, L.M. and V. Diyamandoglu. 2015. NYC WasteMatch - An online facilitated materials exchange as a tool for pollution prevention. *Resources Conservation and Recycling* 101: 122–131.

Frosch, R.A. and N.E. Gallopoulos. 1989. Strategies for Manufacturing. *Scientific Ameria* 261(3): 144–152.

Geng, Y., M. Haight, and Q. Zhu. 2007a. Empirical analysis of eco-industrial development in China. *Sustainable Development* 15(2): 121–133.

Geng, Y., Z. Liu, B. Xue, H. Dong, T. Fujita, and A. Chiu. 2014. Emergy-based assessment on industrial symbiosis: a case of Shenyang Economic and Technological Development Zone. *ENVIRONMENTAL SCIENCE AND POLLUTION RESEARCH* 21(23): 13572–13587.

Geng, Y., P. Zhang, R.P. Cote, and T. Fujita. 2009. Assessment of the national eco-industrial park standard for promoting industrial symbiosis in China. *Journal of Industrial Ecology* 13(1): 15–26.

Geng, Y., Q. Zhu, and M. Haight. 2007b. Planning for integrated solid waste management at the industrial Park level: A case of Tianjin, China. *WASTE*

MANAGEMENT 27(1): 141–150.

Genovese, A., A.A. Acquaye, A. Figueroa, and S.C.L. Koh. 2016. Sustainable supply chain management and the transition towards a circular economy: Evidence and some applications. *Omega*.

Ghali, M.R., J.-M.M. Frayret, and J.-M.M. Robert. 2016. Green social networking: concept and potential applications to initiate industrial synergies. *Journal of Cleaner Production* 115: 23–35.

Golev, A., G.D. Corder, and D.P. Giurco. 2015. Barriers to Industrial Symbiosis: Insights from the Use of a Maturity Grid. *Journal of Industrial Ecology* 19(1): 141–153.

Grant, G.B., T.P. Seager, G. Massard, and L. Nies. 2010a. Information and communication technology for industrial symbiosis. *Journal of Industrial Ecology* 14(5): 740–753.

Grant, G.B., T.P. Seager, G. Massard, and L. Nies. 2010b. Supporting Information for: Information and communication technology for industrial symbiosis. *Journal of Industrial Ecology* 14(5): S-1-S-8.

Green Future Solutions. 2017. About Us | Waste is not Waste | Business Waste and Material Exchange in Singapore. *WasteIsNotWaste, Online Waste Exchange*. http://www.wasteisnotwaste.com/about-us/. Accessed October 29, 2017.

Hackl, R., E. Andersson, and S. Harvey. 2011. Targeting for energy efficiency and improved energy collaboration between different companies using total site analysis (TSA). *Energy* 36(8): 4609–4615.

Hardy, C. and T.E. Graedel. 2002. Industrial ecosystems as food webs. *Journal of Industrial Ecology* 6(1): 29–38.

Hein, A., M. Jankovic, R. Farel, and B. Yannou. 2016. A Data- and Knowledge-Driven Methodology for Generating Eco-Industrial Park Architectures. In *Proceedings of the ASME 2016 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2016*.

Herndon, R.C. and E.D. Purdum. 1985. Proceedings of The Second National Conference on Waste Exchange. In *Proceedings of The Second National Conference on Waste Exchange*, 9–60.

Hipólito-Valencia, B.J., E. Rubio-Castro, J.M. Ponce-Ortega, M. Serna-González, F. Nápoles-Rivera, and M.M. El-Halwagi. 2014. Optimal design of inter-plant waste energy integration. *Applied Thermal Engineering* 62(2): 633–652.

Hui, Z. 2011. Study on the fuzzy analytic hierarchy integrated evaluation method of Eco-Industrial Parks. *Energy Procedia* 5: 1944–1948.

International Synergies. 2016. SYNERGie(TM) - Essential Resource Management Platform.

International Synergies. 2017. SHAREBOX update: SYNERGie® 2.0 is coming soon - International Synergies. http://www.international-synergies.com/news/sharebox-update-synergie-2-0-coming-soon/. Accessed October 14, 2017.

ISDATA. 2017. ISDATA | Industrial Symbiosis Data Repository. http://isdata.org/. Accessed February 10, 2017.

iWasteNot Systems. 2011. Minnesota Materials Exchange. *Minnesota Materials Exchange*. http://mnexchange.org/?content=news.view;news_id=1309. Accessed October 29, 2017.

Jacobsen, N.B. 2006. Industrial symbiosis in Kalundborg, Denmark: A quantitative assessment of economic and environmental aspects. *Journal of Industrial Ecology* 10(1–2): 239–255.

Jensen, P.D., L. Basson, E. Hellawell, M. Bailey, and M. Leach. 2011. Quantifying ‘ Geographic Proximity ’: Experiences from the United Kingdom’s National Industrial Symbiosis Programme. *Resources, Conservation and Recycling* 55(7): 703–712.

Jensen, P.D., L. Basson, E.E. Hellawell, and M. Leach. 2012. Habitat Suitability Index Mapping for Industrial Symbiosis Planning. *Journal of Industrial Ecology* 16(1): 38–50.

Jung, S., G. Dodbiba, S.H. Chae, and T. Fujita. 2013. A novel approach for evaluating the performance of eco-industrial park pilot projects. *JOURNAL OF CLEANER PRODUCTION* 39: 50–59.

Kantor, I., A. Betancourt, A. Elkamel, M. Fowler, and A. Almansoori. 2015. Generalized mixed-integer nonlinear programming modeling of eco-industrial networks to reduce cost and emissions. *JOURNAL OF CLEANER PRODUCTION*

99: 160–176.

Kantor, I., A. Elkamel, and M.W. Fowler. 2014. Optimisation of material and energy exchange in an eco-park network considering three fuel sources. *International Journal of Advanced Operations Management* 6(4): 285–308.

Kantor, I., M. Fowler, and A. Elkamel. 2012. Optimized production of hydrogen in an eco-park network accounting for life-cycle emissions and profit. *International Journal of Hydrogen Energy* 37(6): 5347–5359.

Karlsson, M. and A. Wolf. 2008. Using an optimization model to evaluate the economic benefits of industrial symbiosis in the forest industry. *JOURNAL OF CLEANER PRODUCTION* 16(14): 1536–1544.

Kastner, C.A., R.R. Lau, and M.M. Kraft. 2015. Quantitative tools for cultivating symbiosis in industrial parks: a literature review. *Applied Energy* 155(152): 599–612.

Kim, S.H., S.G. Yoon, S.H. Chae, and S. Park. 2010. Economic and environmental optimization of a multi-site utility network for an industrial complex. *Journal of Environmental Management* 91(3): 690–705.

Klewitz, J. and E.G. Hansen. 2014. Sustainability-oriented innovation of SMEs: A systematic review. *Journal of Cleaner Production* 65: 57–75.

Korhonen, J. and J.P. Snäkin. 2005. Analysing the evolution of industrial ecosystems: Concepts and application. *Ecological Economics* 52(2): 169–186.

Kuznetsova, E., E. Zio, and R. Farel. 2016. A methodological framework for Eco-Industrial Park design and optimization. *Journal of Cleaner Production* 126: 308–314.

Laybourn, P. 2017a. Personal interview.

Laybourn, P. 2017b. Industrial symbiosis and circular economy: best practices from the UK National Industrial Symbiosis Programme (NISP).

Laybourn, P. and M. Morrissey. 2009. The Pathway To A Low Carbon Sustainable Economy. *National Industrial Symbiosis Programme* 44(0): 2009–2010.

Lee, D. 2012. Turning Waste into By-Product. *M&SOM-MANUFACTURING & SERVICE OPERATIONS MANAGEMENT* 14(1): 115–127.

Lee, J.-Y., C.-L. Chen, C.-Y. Lin, and D.C.Y. Foo. 2014. A two-stage approach for the synthesis of inter-plant water networks involving continuous and batch units. *CHEMICAL ENGINEERING RESEARCH & DESIGN* 92(5): 941–953.

Leong, Y.T., J.-Y. Lee, and I.M.L. Chew. 2016a. Incorporating Timesharing Scheme in Ecoindustrial Multiperiod Chilled and Cooling Water Network Design. *Industrial and Engineering Chemistry Research* 55(1): 197–209.

Leong, Y.T., R.R. Tan, K.B. Aviso, and I.M.L. Chew. 2016b. Fuzzy analytic hierarchy process and targeting for inter-plant chilled and cooling water network synthesis. *Journal of Cleaner Production* 110: 40–53.

Li, W. 2011. Comprehensive evaluation research on circular economic performance of eco-industrial parks. In *2010 INTERNATIONAL CONFERENCE ON ENERGY, ENVIRONMENT AND DEVELOPMENT (ICEED2010)*, ed. by W Zhang, 5:1682–1688. Energy Procedia.

Li, W., Z. Cui, and F. Han. 2015. Methods for assessing the energy-saving efficiency of industrial symbiosis in industrial parks. *Environmental Science and Pollution Research International* 22(1): 275–285.

Liew, P.Y., W.L. Theo, S.R. Wan Alwi, J.S. Lim, Z. Abdul Manan, J.J. Klemeš, and P.S. Varbanov. 2016. Total Site Heat Integration planning and design for industrial, urban and renewable systems. *Renewable and Sustainable Energy Reviews*.

LifeM3P. 2017. Life M3P – Material Match Making Platform. *LifeM3P Project Homepage*. http://www.lifem3p.eu/en/. Accessed October 27, 2017.

Linnhoff, B., D.W. Townsend, D. Boland, G.F. Hewitt, B.E.A. Thomas, A.R. Guy, and R.H. Marsland. 1982. *A user guide on process integration for the efficient use of energy*. 1st ed. Rugby, UK: Institution of Chemical Engineers.

Liu, Q., P. Jiang, J. Zhao, B. Zhang, H. Bian, and G. Qian. 2011. Life cycle assessment of an industrial symbiosis based on energy recovery from dried sludge and used oil. *JOURNAL OF CLEANER PRODUCTION* 19(15): 1700–1708.

Liu, W., J. Tian, L. Chen, W. Lu, and Y. Gao. 2015. Environmental Performance Analysis of Eco-Industrial Parks in China: A Data Envelopment Analysis Approach. *Journal of Industrial Ecology* 19(6): 1070–1081.

Lombardi, D.R. and P. Laybourn. 2012. Redefining Industrial Symbiosis: Crossing Academic-Practitioner Boundaries. *Journal of Industrial Ecology* 16(1): 28–37.

Lombardi, D.R. and L. Peter. 2006. *Industrial Symbiosis in Action*.

Low, J.S.C., T.B. Tjandra, F. Yunus, S.Y. Chung, D.Z.L. Tan, B. Raabe, N.Y. Ting, et al. 2018. A Collaboration Platform for Enabling Industrial Symbiosis: Application of the Database Engine for Waste-to-Resource Matching. In *Procedia CIRP*, 69:849–854. The Author(s).

Lowe, E.A. 1997. Creating by-product resource exchanges: Strategies for eco-industrial parks. *Journal of Cleaner Production* 5(1–2): 57–65.

MAESTRI. 2017. Home - MAESTRI - Energy and resource management systems for improved efficiency in the process industries. *MAESTRI Project Homepage*. https://maestri-spire.eu/. Accessed October 27, 2017.

Mamoune, A. and A. Yassine. 2011. Creating an Inductive Model of Industrial Development with Optimized Flows for reducing its Environmental Impacts. *Energy Procedia* 6: 396–403.

Mantese, G.C. and D.C. Amaral. 2016. Comparison of industrial symbiosis indicators through agent-based modeling. *Journal of Cleaner Production*.

Martin, M. 2015. Quantifying the environmental performance of an industrial symbiosis network of biofuel producers. *JOURNAL OF CLEANER PRODUCTION* 102: 202–212.

Martin, M., N. Svensson, and M. Eklund. 2015. Who gets the benefits? An approach for assessing the environmental performance of industrial symbiosis. *Journal of Cleaner Production* 98: 263–271.

Massard, G. and S. Erkman. 2007. A regional industrial symbiosis methodology and its implementation in Geneva, Switzerland. *3rd International Conference on Life Cycle Management* 27: 29.

Massard, G. and S. Erkman. 2009. A web-GIS tool for industrial symbiosis. Preliminary results and perspectives. *23rd International Conference on Informatics and Environmental Protection* 2009: 261–268.

Mattila, T., S. Lehtoranta, L. Sokka, M. Melanen, and A. Nissinen. 2012.

Methodological Aspects of Applying Life Cycle Assessment to Industrial Symbioses. *Journal of Industrial Ecology* 16(1): 51–60.

Mattila, T., S. Pakarinen, and L. Sokka. 2010. Quantifying the Total Environmental Impacts of an Industrial Symbiosis - a Comparison of Process-, Hybrid and Input-Output Life Cycle Assessment. *Environmental Science & Technology* 44(11): 4309–4314.

Mattiussi, A., M. Rosano, and P. Simeoni. 2014. A decision support system for sustainable energy supply combining multi-objective and multi-attribute analysis: An Australian case study. *Decision Support Systems* 57(1): 150–159.

Mirata, M. 2004. Experiences from early stages of a national industrial symbiosis programme in the UK: Determinants and coordination challenges. *Journal of Cleaner Production* 12(8–10): 967–983.

Mortenson, M.J. and R. Vidgen. 2016. A computational literature review of the technology acceptance model. *International Journal of Information Management* 36(6): 1248–1259.

Nair, S.., Y. Guo, U. Mukherjee, I.. Karimi, and A. Elkamel. 2016. Shared and practical approach to conserve utilities in eco-industrial parks. *Computers and Chemical Engineering* 93: 221–233.

Ng, R.T.L., D.K.S. Ng, and R.R. Tan. 2015. Optimal planning, design and synthesis of symbiotic bioenergy parks. *Journal of Cleaner Production* 87: 291–302.

Nguyen, H.P. and Y. Matsuura. 2016. Designing a sustainability framework for the initiation and management of coordination in an energy exchange. *Journal of Cleaner Production*.

Nooij, S. 2014. An ontology of Industrial Symbiosis: The design of a support tool for collaborative Industrial Symbiosis research with as test cases from Tianjin Economic Development.

Nordregio. 2016. GREEN GROWTH IN NORDIC REGIONS 50 ways to make it happen - Nordregio. *Nordregio Website*. http://www.nordregio.se/50cases. Accessed September 11, 2017.

Nothrow. 2017. Exchange your unwanted materials & recyclables for free - The Waste Exchange. *The Waste Exchange*. http://www.nothrow.co.nz/. Accessed October 29, 2017.

Noureldin, M.M.B. and M.M. El-Halwagi. 2015. Synthesis of C-H-O Symbiosis Networks. *AIChE Journal* 61(4): 1242–1262.

Oh, D.S., K.B. Kim, and S.Y. Jeong. 2005. Eco-Industrial Park Design: A Daedeok Technovalley case study. *Habitat International* 29(2): 269–284.

Paquin, R.L. and J. Howard-Grenville. 2012. The Evolution of Facilitated Industrial Symbiosis. *Journal of Industrial Ecology* 16(1): 83–93.

Paquin, R.L. and J. Howard-Grenville. 2013. Blind Dates and Arranged Marriages: Longitudinal Processes of Network Orchestration. *ORGANIZATION STUDIES* 34(11): 1623–1653.

Park, H.-S. and S.K. Behera. 2014. Methodological aspects of applying eco-efficiency indicators to industrial symbiosis networks. *Journal of Cleaner Production* 64: 478–485.

Park, J.M., J.Y. Park, and H.S. Park. 2016. A review of the National Eco-Industrial Park Development Program in Korea: Progress and achievements in the first phase, 2005-2010. *Journal of Cleaner Production* 114: 33–44.

Potts Carr, A.J. 1998. Choctaw Eco-Industrial Park: an ecological approach to industrial land-use planning and design. *Landscape and Urban Planning* 42(2–4): 239–257.

Raabe, B., J.S.C. Low, M. Juraschek, C. Herrmann, T.B. Tjandra, Y.T. Ng, D. Kurle, et al. 2017. Collaboration Platform for Enabling Industrial Symbiosis: Application of the By-product Exchange Network Model. In *Procedia CIRP*, 61:263–268.

Raafat, T., N. Trokanas, F. Cecelja, and X. Bimi. 2013. An ontological approach towards enabling processing technologies participation in industrial symbiosis. *Computers and Chemical Engineering* 59: 33–46.

Ramos, M., M. Boix, D. Aussel, L. Montastruc, and S. Domenech. 2016. Optimal design of water exchanges in eco-industrial parks through a game theory approach. Ed. by Kravanja Zdravko and Bogataj Miloš. *Computer Aided Chemical Engineering* Volume 38: 1177–1182.

Rosa, M. and A. Beloborodko. 2015. A decision support method for development of industrial synergies: Case studies of Latvian brewery and wood-processing industries. *Journal of Cleaner Production* 105: 461–470.

Şenlier, N. and A.N. Albayrak. 2011. Opportunities for sustainable industrial development in turkey: Eco-industrial parks. *Gazi University Journal of Science* 24(3): 637–646.

SHAREBOX. 2017. SHAREBOX – SECURE SHARING. http://sharebox-project.eu/. Accessed September 11, 2017.

Shi, H., M. Chertow, and Y.. Y. Song. 2010. Developing country experience with eco-industrial parks: a case study of the Tianjin Economic-Technological Development Area in China. *Journal of Cleaner Production* 18(3): 191–199.

Song, B., Z. Yeo, P. Kohls, and C. Herrmann. 2017. Industrial Symbiosis: Exploring Big-data Approach for Waste Stream Discovery. In *Procedia CIRP*, 61:353–358.

Song, B., Z. Yeo, S.C.J. Low, J.D. Koh, D. Kurle, F. Cerdas, and H. Christoph. 2015. A big data analytics approach to develop industrial symbioses in large cities. In *Procedia CIRP*, ed. by Sami Kara, 29:450–455. Procedia CIRP.

Sopha, B.M., A.M. Fet, M.M. Keitsch, and C. Haskins. 2010. Using systems engineering to create a framework for evaluating industrial symbiosis options. *Systems Engineering* 13(2): 149–160.

Sterr, T. and T. Ott. 2004. The industrial region as a promising unit for eco-industrial development - Reflections, practical experience and establishment of innovative instruments to support industrial ecology. *Journal of Cleaner Production* 12(8–10): 947–965.

Tan, R.R., V. Andiappan, Y.K. Wan, R.T.L. Ng, and D.K.S. Ng. 2016. An optimization-based cooperative game approach for systematic allocation of costs and benefits in interplant process integration. *CHEMICAL ENGINEERING RESEARCH & DESIGN* 106: 43–58.

Taskhiri, M.S., R.R. Tan, and A.S.F. Chiu. 2011. Emergy-based fuzzy optimization approach for water reuse in an eco-industrial park. *Resources, Conservation and Recycling* 55(7): 730–737.

Theo, W.L., J.S. Lim, S.R. Wan Alwi, N.E. Mohammad Rozali, W.S. Ho, and Z. Abdul-Manan. 2016. An MILP model for cost-optimal planning of an on-grid hybrid power system for an eco-industrial park. *Energy*.

Tian, J., W. Liu, B. Lai, X. Li, and L. Chen. 2014. Study of the performance of eco-industrial park development in China. *Journal of Cleaner Production* 64: 486–494.

Togawa, T., T. Fujita, L. Dong, S. Ohnishi, and M. Fujii. 2016. Integrating GIS databases and ICT applications for the design of energy circulation systems. *Journal of Cleaner Production* 114: 224–232.

Tong, L., X. Liu, X. Liu, Z. Yuan, and Q. Zhang. 2013. Life cycle assessment of water reuse systems in an industrial park. *Journal of Environmental Management* 129: 471–478.

Tranfield, D., D. Denyer, and P. Smart. 2003. Towards a methodology for developing evidence-informed management knowledge by means of systematic review *. *British Journal of Management* 14: 207–222.

Trokanas, N., F. Cecelja, and T. Raafat. 2014. Semantic input/output matching for waste processing in industrial symbiosis. *Computers and Chemical Engineering* 66: 259–268.

Trokanas, N., F. Cecelja, and T. Raafat. 2015. Semantic approach for pre-assessment of environmental indicators in Industrial Symbiosis. *Journal of Cleaner Production* 96: 349–361.

Tudor, T., E. Adam, and M. Bates. 2007. Drivers and limitations for the successful development and functioning of EIPs (eco-industrial parks): A literature review. *Ecological Economics* 61(2–3): 199–207.

Ubando, A.T., A.B. Culaba, K.B. Aviso, R.R. Tan, J.L. Cuello, D.K.S. Ng, and M.M. El-Halwagi. 2015. Fuzzy Mathematical Programming Approach in the Optimal Design of an Algal Bioenergy Park. In *PRES15: PROCESS INTEGRATION, MODELLING AND OPTIMISATION FOR ENERGY SAVING AND POLLUTION REDUCTION*, ed. by X Varbanov, PS and Klemes, JJ and Alwi, SRW and Yong, JY and Liu, 45:355–360. Chemical Engineering Transactions.

Ubando, A.T., A.B. Culaba, K.B. Aviso, R.R. Tan, J.L. Cuello, D.K.S. Ng, and M.M. El-Halwagi. 2016. Fuzzy mixed integer non-linear programming model for the design of an algae-based eco-industrial park with prospective selection of support tenants under product price variability. *Journal of Cleaner Production* 136, Part: 183–196.

United States Business Council for Sustainable Development. 2017. Materials — US BCSD. *Facilitating Company-To-Company Industrial Reuse Opportunities That Support the Culture Shift To A Circular, Closed-Loop Economy*. http://usbcsd.org/materials/. Accessed September 6, 2017.

US BCSD. 2016. Additional Case Studies — The Materials Marketplace. *The Materials Marketplace Website*. http://materialsmarketplace.org/case-studies/. Accessed September 11, 2017.

US EPA. 1994. Review of Industrial Waste Exchanges.

Vadenbo, C., S. Hellweg, and G. Guillén-Gosálbez. 2014. Multi-objective optimization of waste and resource management in industrial networks - Part I: Model description. *Resources, Conservation and Recycling* 89: 52–63.

Valentine, S.V. 2016. Kalundborg Symbiosis: fostering progressive innovation in environmental networks. *JOURNAL OF CLEANER PRODUCTION* 118: 65–77.

Valenzuela-Venegas, G., J.C. Salgado, and F.A. Díaz-Alvarado. 2016. Sustainability indicators for the assessment of eco-industrial parks: classification and criteria for selection. *Journal of Cleaner Production* 133: 99–116.

Valero, A., S. Uson, C. Torres, A. Valero, A. Agudelo, and J. Costa. 2013. Thermoeconomic tools for the analysis of eco-industrial parks. *ENERGY* 62: 62–72.

Varbanov, P.S. 2011. Heat Integration – History , Recent Developments and Achievements Ji ř í Jaromír Klemeš , Petar Sabev Varbanov Research Institute of Chemical Technology and Process Engineering.

Velenturf, A.P.M. 2016. Promoting industrial symbiosis: empirical observations of low-carbon innovations in the Humber region, UK. *JOURNAL OF CLEANER PRODUCTION* 128(SI): 116–130.

Walls, J.L. and R.L. Paquin. 2015. Organizational Perspectives of Industrial Symbiosis: A Review and Synthesis. *Organization and Environment* 28(1): 32–53.

Wang, L., W. Ni, and Z. Li. 2006. Emergy evaluation of combined heat and power plant eco-industrial park (CHP plant EIP). *Resources, Conservation and Recycling* 48(1): 56–70.

Wang, L., J. Zhang, and W. Ni. 2005. Emergy evaluation of Eco-Industrial Park with Power Plant. *Ecological Modelling* 189(1–2): 233–240.

Wang, Q. 2013. Knowledge transfer to facilitate Industrial Symbiosis: a case study of UK-China collaborators.

WRAP. 2013. Search Material Listings | Resource Efficient Scotland. *Resource Efficient Scotland*. http://cme.resourceefficientscotland.com/materials. Accessed October 29, 2017.

Yu, B., X. Li, L. Shi, and Y. Qian. 2015. Quantifying CO2 emission reduction from industrial symbiosis in integrated steel mills in China. *Journal of Cleaner Production* 103: 801–810.

Yuan, Z. and L. Shi. 2009. Improving enterprise competitive advantage with industrial symbiosis: case study of a smeltery in China. *Journal of Cleaner Production* 17(14): 1295–1302.

Zeng, Y., R. Xiao, and X. Li. 2013. A Resilience Approach to Symbiosis Networks of Ecoindustrial Parks Based on Cascading Failure Model. *MATHEMATICAL PROBLEMS IN ENGINEERING*.

Zhang, C., L. Zhou, P. Chhabra, S.S. Garud, K. Aditya, A. Romagnoli, G. Comodi, F. Dal Magro, A. Meneghetti, and M. Kraft. 2016. A novel methodology for the design of waste heat recovery network in eco-industrial park using techno-economic analysis and multi-objective optimization. *Applied Energy* 184: 88–102.

Zhang, Y., H. Zheng, B. Chen, and N. Yang. 2013. Social network analysis and network connectedness analysis for industrial symbiotic systems: model development and case study. *Frontiers of Earth Science* 7(2): 169–181.

Zheng, H.M., Y. Zhang, and N.J. Yang. 2012. Evaluation of an Eco-industrial Park Based on a Social Network Analysis. In *18TH BIENNIAL ISEM CONFERENCE ON ECOLOGICAL MODELLING FOR GLOBAL CHANGE AND COUPLED HUMAN AND NATURAL SYSTEM*, ed. by Yang, Z and Chen, B, 13:1624–1629. Procedia Environmental Sciences.

7 Endnotes

---

[i] Identifying IS opportunities is defined in this article as the activity of finding opportunities among businesses that enable waste resources of one to be a productive inputs of another; resources typically refers to non-labour resources, including (but not limited to): material, water, energy, spare capacity, etc.

[ii] For clarity, approaches refer to the underlying strategies to address problems; techniques refer to tactical means to achieve predefined objectives; tools refer to the practical implementation to realise techniques or approaches. To illustrate, an approach may refer to relying on free-market mechanism to match demand and supply of waste, whereas the technique would be to utilise electronic waste exchange and a corresponding tool would be the US Materials Marketplace.

[iii] These references may lead to other forms of data sources such as relevant websites as well as grey literature.

[iv] Search term: “online waste material exchange”

[v] These tools include Knowledge-Based Decision Support System (KBDSS), Designing Industrial Ecosystems Toolkit (DIET) (including Facility Synergy Tool (FaST), DIET and Regulatory, Economic and Logistics Tool (REaLiTY)), Industrial Materials Exchange Tools (IME), Dynamic Industrial Materials Exchange Tool (DIME), Industrial Ecology Planning Tool (IEPT), Industrial Ecosystem Development Project (IEDP), Residual Utilisation Expert System (RUES), Institute of Eco-Industrial Analysis Waste Manager (IUWAWM), Industrie et Synergies Inter-Sectorielles (ISIS) and Presto and SymbiosisGIS.

[vi] A total of eighteen studies in our sample have referenced LCA for evaluating the performance in the context of IS (Tong et al. 2013; Mattila et al. 2012; Liu et al. 2011; Dong et al. 2013; Felicio et al. 2016; Mattila et al. 2010; Martin et al. 2015; Genovese et al. 2016; Martin 2015; Geng et al. 2014; Korhonen and Snäkin 2005; Liu et al. 2015; Valenzuela-Venegas et al.

2016; Mantese and Amaral 2016; Valero et al. 2013; Jung et al. 2013; Rosa and Beloborodko 2015)