Lessons learnt & best practices

for enhancing industrial symbiosis in the process industry

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Deliverable 2.1

Lessons learnt and best practices for enhancing industrial symbiosis in the process industry

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Abstract

The objective of this report is to provide an evidence base of best practices in industrial symbiosis. We brought together multiple research methods to build a rich picture and triangulate our findings in order to cast light on the various approaches that companies may choose to adopt.

We identified critical success factors which we categorised as triggers, enablers and barriers in regard to the implementation of industrial symbiosis. We found that these factors can influence the outcome of resource synergy initiatives on multiple levels: national, regional, local/city and on the level of an individual firm. Successful implementation of industrial symbiosis is highly complex and occurs across multiple dimensions, both internal and external to the firm.

The findings on lessons learnt cast light on the processes of consideration, facilitation and scale up of resource synergies that occur in industries. The study concludes with recommendations for industry, research and policy.

This report will be used as a springboard for the subsequent deliverables in the SCALER project.

Introduction

The aim of this research is to identify best practices and lessons learnt for scaling up industrial symbiosis (IS). This report is part of a wider study which seeks to boost the application of IS in the process industry by considering non-technical and technical best practices, enabling technologies, key intermediaries and facilitating tools and methods. The study will support the definition of pathways to move from anecdotal one-off resource synergies to a systematic application of resource synergies as a means to increase resource productivity and competitiveness.

This report, Deliverable 2.1, is based on the SCALER Work Package 2, Deliverable 2.1, which includes tasks 2.1 and 2.2. The report is grounded in four main evidence components. A systematic literature review formed the first evidence component. This was identified as the most appropriate method to reveal the state of the art in the IS field. All papers reviewed had to be published between 2016 and 2018 in international peer-reviewed conferences and journals and contain 'industrial symbiosis' in the title, abstract, or keywords - 210 publications were reviewed in total. The second evidence component was the analysis of twenty-five IS case studies. It was considered that a wide cross-industry case study review would be effective in revealing the most important indicators for the scaling up of IS. The selection of the case studies was based upon the criteria that cases were published, covered a range of industries and geographies, represented a spectrum of IS practice from emergent to mature and included examples of self-organised IS systems as well as those created by external stakeholders. In order to support the triangulation of the findings from these two components, an expert enquiry in the form of a qualitative survey was designed and launched internationally in May 2018 to provide the third evidence component. The purpose of the survey was to interrogate best IS practice in industry. In total, 17 useable responses were received and analysed. Findings from these three evidence components were then synthesised and presented in the form of an interactive workshop to a focus group attended by an expert panel representing industry and academia. The results of the workshop comprised the fourth evidence component and were subjected to a further round of synthesis.

Finally, we outline a set of recommendations for industry practitioners, academics and researchers, and policy-makers involved in IS. This report will be used to inform the rest of the deliverables in WP2 including D2.2, D2.3 and D2.4 as well as D3.1 in WP3.

1. Research strategy

The study adopted *engaged scholarship* (Van de Ven, 2007) as a research strategy and utilised a mixed-method approach for data collection (Figure 1). Engaged scholarship is a form of participatory research, which investigates complex real-world problems by drawing upon a multitude of perspectives held by key stakeholders (Mathiassen, 2017). This study was carried out as a collaborative investigation with continuous sharing and collaboration between SCALER researchers, SCALER project partners, Advisory Board members and other project stakeholders.

The research combined multiple qualitative methods in order to triangulate the results emerging from multiple data sources so as to understand the best practices and lessons learnt for the scaling up of IS. Four research activities were undertaken, producing four evidence components. First, a systematic literature review was performed in order to understand the state of the art within the field of IS. Articles and reports published during the period 2016–2018 were analysed. Second, twenty-five cross-industry case studies were identified and analysed (Appendix 1). The cases were selected to represent a diverse sample of industries, geographical distribution and maturity of IS and include examples of self-organised

IS systems as well as those created by external stakeholders. Third, an expert enquiry was launched which surveyed key stakeholders from the field of IS engaged with SCALER and other SPIRE projects, as well as a wider group of international collaborators. Fourth, a focus group with IS experts from industry and academia was organised to refine and validate the findings on the lessons learnt and best practices in IS. The results from the four evidence components are presented in chapters 2–5.

Figure 1 - Mixed-method approach

2. State of the art on industrial symbiosis

In Circular Economy literature, studies follow three main lines of action: macro level, looking into economic and social factors; micro level, enabling firms to implement circular principles and to encouraging new consumer behaviours; and the third meso level, discusses IS experiences and eco-industrial parks (Merli, Preziosi, & Acampora, 2018). Thus, we can consider that IS is firmly nested within the Circular Economy field. To understand IS more specifically, Yap & Devlin (2017) proposed a multiple level framework as a lens for analysis of IS, which studied enablers and barriers at the levels of society, network, and enterprise (Yap & Devlin, 2017).

We used the two patterns, i.e. enablers and barriers, to help in the structuring of this systematic literature review and indeed the remainder of this report. In addition to enablers and barriers, within this review we added the triggers for IS. These are the catalysts that spark symbiotic activities.

2.1 Systematic literature review approach

In total, 210 peer-reviewed papers were interrogated. All were published from 2016 onwards and identified using *ScienceDirect*, *Scopus* and the internet search engine machine *Web of Science* with the keyword ‘industrial symbiosis’ in the title, abstract, or keywords. We performed a thematic analysis of the content of papers to identify emerging themes and common threads. We identified 85 key publications which underpin the following results.

2.2 Literature review findings

2.2.1 Triggers

Here, from literature to date, we offer knowledge on the factors that trigger IS.

At a macro level, the most prominent driver for IS is carbon dioxide emissions and the need to control these as agreed in 2015, at the Paris conference (COP21) (Patricio, Angelis-Dimakis, Castillo-Castillo, Kalmykova, & Rosado, 2017). This has produced a powerful catalyst for IS, for instance with the European Commission committing to reducing greenhouse gas emissions by 40% by 2030. For firms who capture and sell their by-product CO2 and those directly involved in Carbon Capture and Utilization (CCU), these goals are a powerful strategic lever. Not only are they able to contribute directly to CO2 emissions reduction but also to derive economic value via the generation of new products (Patricio et al., 2017).

Economic benefits (Maillé & Frayret, 2016) and increased profitability are likely to be initial drivers for IS. Most frequently these benefits result from by-product sharing or reduced costs associated with waste disposal. Gabriel, Schöggl and Posch (2017) identify a new trigger in the search for possibilities for waste recycling. Energy efficiency is cited as a significant driver (Karner, Theissing, & Kienberger, 2017) for energy intensive enterprises such as in the iron and steel industries (Wu, Wang, Pu, & Qi, 2016). Additionally, firms potentially see benefits in shared services, utilities and knowledge (Wu, Qi, & Wang, 2016).

One of the most widely discussed triggers is the need to improve environmental performance. This includes reducing carbon footprints in key sectors in response to the Paris Accord, e.g. with cement and steelmaking (Iacobescu, Angelopoulos, Jones, Blanpain, & Pontikes, 2016), and the need to address environmental degradation. Environmental degradation has been a key issue in the cement and steel industry, the pulp and paper industry (van Ewijk, Park, & Chertow, 2018), and oil and gas refining, which in some areas, such as the Taranto Industrial District (Italy), has created what is described as a place in a state of crisis (Notarnicola, Tassielli, & Renzulli, 2016).

In China, toxic emissions and effluent are identified as environmental problems (Wu, Qi & Wang, 2016), which have resulted in regulation and policy that are powerful motivational factors for development (Leong, Tan, Aviso, & Chew, 2017). Policies influence development in several ways, one of which is by the establishment of clear goals, for example on equipment/technological improvements and material inputs/waste outputs/pollutant emissions. Policy changes in the European Union with the Waste Framework Directive (WFD), which came in to force in 2008, more widely support the efficient use of industrial waste and by-products and this legislation is compelling more firms across all industries to focus on symbiotic initiatives (Husgafvel, Karjalainen, Linkosalmi, & Dahl, 2016).

In their study of the Guitang Group, one of the best known IS cases in the sugar industry, Shi and Chertow (2017) present “a historical view of the critical forces behind Guitang’s IS evolution since the 1950s; particularly how these changes were influenced by broader economic and institutional contexts of importance in China. These insights include the role of institutionalized R&D as well as technology-oriented leadership as driving forces for Guitang's innovation, particularly since the 1990s, when greater efficiency and productivity were emphasized, leading to the establishment of further symbiotic relationships in the company's evolutionary process" (Shi & Chertow, 2017, p.1).

Yedla and Park (2017) suggest that key factors which enable eco-industrial networking and its further development into Eco-Industrial Parks primarily include profits and environmental benefits. In their study of an eco-industrial greenhouse park development in Belgium, Verguts, Dessein, Dewulf, and Lauwers (2016) suggest that while the economic and energy crises and environmental factors have been at play, the Koekhoven greenhouse park development kicked-off only after municipal land-planning decisions were made.

Many IS clusters do arise from an organised effort to develop symbiotic or "sustainable" systems (Boons, Chertow, Park, Spekkink, & Shi, 2017) as in the Koekhoven greenhouse park development. Others, however, emerge organically in response to environmental regulations, resource constraints, volatile resource pricing or other external forces (Mulrow et al., 2017).

In summary, economic, environmental and policy triggers operate at multiple levels and there is frequently a bundle of factors which drive synergistic evolution.

2.2.2 Enablers

In this part of the review, we offer current knowledge on the components that help to support IS projects. It is useful in this context to use the analogy of a coin, which has two sides to it. A given factor could be an enabler on one side, but a barrier on the other. Its effect depends on the context and how it is managed.

2.2.2.1 Social/stakeholder interactions

Trust is particularly important in the emergence of IS networks (Albino, Fraccascia, & Giannoccaro, 2016), as is engagement (Freitas & Magrini, 2017). Some describe that one of the primary enablers is the partnering of firms through a multi-objective optimisation process that considers and ranks all the preferences of potential participants using specifically designed criteria, accepting each will have divergent interests. Thereafter, an optimal approach for the system can be designed by decision-makers (Leong et al., 2017).

Education to increase awareness is fundamental to helping IS networks (Liu et al., 2017), therefore there is a need to establish environmental management education programmes (Ceglia, Abreu, & Da Silva Filho, 2017). Prosman, Wæhrens & Liotta (2017) investigated social aspects of IS and the role of internal coordination in long-distance IS exchanges and determined that internal integration may increase the cognitive proximity through engagement and education of purchasing managers, improving the understanding of the supplier's processes, fostering quality of communication with the supplier, and working closely with suppliers to improve their understanding of the needs of the buyers (Prosman, Wæhrens & Liotta, 2017).

In addition, the construction of learning networks and forums (Ceglia et al., 2017) allows for enduring relationships built on trust (Velenturf & Jensen, 2016; Yedla & Park, 2017) to develop among companies within an industrial park. In turn, these relationships encourage information sharing (Liu, Adams, Cote, Geng, & Li, 2018a), creative solutions, long term planning and governance among stakeholders (Ceglia et al., 2017). Social aspects increase interactions among stakeholders and strengthen collaborations (van Capelleveen, Amrit, & Yazan, 2018) and partnerships (Aid, Eklund, Anderberg, & Baas, 2017), including international ones (Liu et al., 2018a).

Building institutional capacity for IS includes the development of policy, technological and network facilitation knowledge, and relational resources (e.g. through training courses and periodic meetings) along with mobilisation capacity (Wang, Deutz, & Chen, 2017). Ceglia et al. (2017) note that developing networking knowledge amongst national/federal, state/regional and local governments is also germane.

Social aspects such as establishing effective communication channels help to create conducive conditions for various participating stakeholders (Yedla & Park, 2017). Additionally, the communications should promote green consumerism and optimal resources utilisation (Yedla & Park, 2017).

2.2.2.2 Intermediaries/knowledge brokers/coordinating bodies

The role of intermediaries, which can also be termed as knowledge brokers or coordinating bodies, is critical to accelerating symbiosis (Capelleveen et al., 2018; Freitas & Magrini, 2017; Notarnicola et al., 2016), as these external actors provide managerial (Sun et al., 2017a), financial and regulatory support to firms at the initiation of a system, over its monitoring over time. They can also evaluate and entice new firms by sharing experiences and help develop incentive policies (Felicio et al., 2016). As coordinating "neutral players" they help to facilitate communication and cooperation among parties; furthermore, they provide a knowledge conduit between industrial clusters.

Part of their knowledge building role is to support eco-industrial development by establishing collaborations between the industrial clusters and research bodies (Sun et al., 2017a; Yedla & Park, 2017). In addition to the development of new business models and harnessing of key knowledge and innovations, synergistic relationships are further supported by building partnerships and navigating between the primary and recycling sectors (Aid et al., 2017).

Some authors have investigated Innovation Poles (IPs) that operate in a somewhat similar fashion to intermediaries such as the UK National Industrial Symbiosis Programme (NISP). Taddeo, Simboli, Ioppolo and Morgante (2017) note that these government-sponsored consortia offer a new model of development whereby IPs are created as part of EU-funded programmes. Another interesting concept was introduced by Siskos and Wassenhove (2017), whereby a synergy management services company (SMSCO) acts as coordinator for the realisation of IS synergies within industrial parks on a commercial basis.

At a more granular level intermediaries and other knowledge agents can help advance IS networks and enhance eco-efficiency through eco-efficiency reviews, opportunity and implementation assessments, and workshops for pollution prevention (Liu et al., 2018a). According to Felicio et al., (2016) in order to function effectively these agents require appropriate tools and processes with simple indicators (these are described in 2.2.2.9 later in this review).

2.2.2.3 Geography

Close geographic proximity is cited as a strong enabler (Velenturf & Jensen, 2016), not only due to the physical position of plants, but due to the "short mental distance between managers" (Branson, 2016, p.4344). This infers that where there is wider geographic dispersal (as in Australia) the potential for IS is greatly diminished. However, Branson's (2016) study of symbiosis showed that location or even financial cost may not be as important as commercial proximity.

Multiple authors suggest that industrial diversity in a location can unlock new opportunities for by-product and waste exchange (Albino et al., 2016; Freitas & Magrini, 2017; Ghali, Frayret, & Robert, 2016; Wang, Li, Wang, Wan, Song, & Liu, 2017). Jensen (2016) concurs by identifying that "local richness of industry types is the primary driver behind the distances materials travel from their point of origin to a point of reuse by a company from an unrelated industry" (Jensen, 2016, p.101).

Certain industries appear in a location (within this mix) to act as pivotal players in IS, for example steel-making which provides a constant flow of waste including energy (Notarnicola et al., 2016). Suitable physical infrastructure that can be shared in an area is another strong factor (Liu et al. 2018a; Sun, Spekkink, Cuppen, & Korevaar, 2017a). Other physical anchoring activities include expropriating land for IS construction (Sun et al., 2017a).

For some types of industry and particularly those producing and dealing with hazardous waste, physical facilities are of paramount importance in establishing symbiosis. Waste needs to be stored and the term redundancy is used to describe this) unless it can be used immediately by the recipient, therefore appropriate storage facilities need to be considered in the detailed design of any system (Wu, Guo, Li, & Qi, 2017).

2.2.2.4 National government instruments

At a national level, central actors play a fundamental role in facilitating the development of symbiotic networks in industries.

Intervention in the form of financial incentives (Ceglia et al., 2017), e.g. taxation is frequently cited as an acceleration method (Notarnicola et al., 2016), e.g. as "tax incentives can encourage stakeholders to become genuinely and actively involved" (Liu et al., 2017, p. 94). For example, in Finland tax relief is used (it does not have direct policy instruments) to encourage uptake (Daddi, Iraldo, Frey, Gallo, & Gianfrate, 2016). In order to implement an IS strategy, Kim et al., (2018) argue there is a need to more directly encourage stakeholder participation (where there are long payback periods) through compensation via carbon credits and government funds.

Yet, Valentine (2016, p.85) notes when there are "low hanging cherries", which can be simply picked governmental support is not required as firms will self-guide themselves to reap the benefits from an opportunity. Whereas, any symbiotic interaction that needs technical knowledge is helped by external support such as that funded by governments (Valentine, 2016) for example through specialist knowledge actors including universities and other research organisations. Other governmental support strategies included the provision of hosted workshops, e.g. by NISP in the UK, in which practitioners had facilitated engagements to identify where potential synergistic opportunities lay (Bellantuono, Carbonara, & Pontrandolfo, 2017). Greater detail is offered on the role of intermediaries in chapter 3.

Governments can provide assistance by stimulating private sector investments related to reuse and recycling of waste; and through the provision of subsidies for the development of waste exchange networks and projects (Ceglia et al., 2017). Governments can further promote IS through indirect instruments (Sun et al., 2017a), including promoting closed loop systems, higher taxes on fuels and transport, and specific limits to lower emissions (Ceglia et al., 2017; Daddi et al., 2016; Sacchi & Ramsheva, 2017). In Tuscany, where IS is well embedded a more innovative approach based on "voluntary cooperation, bottom-up policy making and a third-party certification scheme" is encouraging the propagation of synergies (Daddi et al., 2016, p.64). Yedla and Park (2017) offer a wide range of activities at a national level to stimulate IS activity like producing a long-term sustainable development vision in IS alongside an integrated approach to policy making, and involving the business community in planning to achieve eco-industrial development among others.

2.2.2.5 Legal and Regulatory

Development can be stimulated by legislation and regulation, for example in Italy a law is enshrined in a model for 'Ecologically Equipped Industrial Areas' (EEIAs) to guide local developments "based on shared services, utilities and common infrastructures" (Taddeo, 2016, p.189). To date it represents a useful model in nurturing localized symbiotic systems and provides evidence of the positive impact of policy on IS adoption. Many other geographies have catalysed activity through conducive regulation as in US and Dutch cities (Notarnicola et al., 2016). China is known to have engaged in durable governmental enablement of Sustainable Industrial Parks (SIPs) through stimulating EIPs and advancing Circular Economy Industrial Parks (CEIPs) (Jiao, Boons, Teisman, & Li, 2018).

Ceglia et al. (2017) note that the development of national and state solid waste policy should go hand in hand with an increase in enforcement mechanisms to support national and state (regional) solid waste policies. In doing so barriers that are commonly cited at an industrial park and firm level can be alleviated. Husgafvel et al. (2016) propose that "new legal thinking is needed to enable such residue utilisation in a way that safeguards environmental and health standards and contributes to sustainable development" (Husgafvel et al., 2016, p.1187). Learnings from the Korean EIP are particularly helpful in this respect as they reveal that there was an intensive focus on setting up appropriate legal and regulatory systems to drive EIP projects from the beginning of the program (Park et al., 2016).

2.2.2.6 Regional/local authorities

Horvath and Harazin (2016) explore the roles and responsibilities of local authorities and recognise "that a new interpretation of industrial ecology may provide new opportunities of cooperation between authorities and businesses, with the authorities acting not only as legislators but as active participants" (Horvath and Harazin, 2016, p. 222). Some authors recognise that there are certain processes where loops may be closed by regional/local governments rather than other businesses, for instance, through the integration of a region's/city's waste with an industrial park for better material recovery and resource utilization (Yedla & Park, 2017).

Other support mechanisms include developing orientation plans for setting up eco-industrial parks (Ceglia et al., 2017), and the provision of an institutional setting locally (Sun et al., 2017a). Measures such as developing preferential policies and actively recruiting companies to IS are helpful. Furthermore, authorities can help facilitate firms' settlement in IS and seek funding for scaling up IS (Sun et al., 2017a).

Authorities should allocate sufficient budgets, which potentially in association with administrative support from industrial parks, can be utilized to build capacity through academic training and workshops, and disseminate information through multi-media channels including TV programs (Guo et al., 2016). Governments at this level also provide support in the forms described in the Social/stakeholder interactions section earlier in this review.

2.2.2.7 Industrial park level

Common services such as the joint provision of transport and landscaping, in addition to shared infrastructure management is a practice adopted in EIPs that accelerates IS. Collaboration in essence leads to administrative simplification, which acts as an inducement to new players in a network (Freitas & Magrini, 2017).

Yedla and Park (2017) build on this by providing a list of activities that help to stimulate symbiosis at the level of an EIP including carrying out site assessments of individual parks and developing infrastructure to enable the exchange of resources and employing public-private partnerships among others.

To increase EIP development opportunities and network connections between industrial complexes, Park et al., (2016) recommend that any industrial complex with the potential for scale to an EIP, should be designed as the central node with three/four neighbour complexes connected in as 'spokes'. Other authors (Mulrow, Derrible, Ashton, & Chopra, 2017) endorse this notion as part of their analytical framework, which consists of three practical approaches: the first is the anchor manufacturer, the second a project organizer (as identified in the intermediary section). The third is a business incubator for accelerating IS and sustainable manufacturing practices at the facility scale.

2.2.2.8 Firm level

It is critical for the development of IS that firms have an economic drive, i.e. lower transaction costs (Sacchi & Ramsheva, 2017), and according to Yedla and Park (2017) "major economic factors that influence the successfulness of eco-industrial networking are cost savings and enhanced competitiveness, as well as reduced infrastructure costs and improved revenue generation" (Yedla & Park, 2017, p. 393). They need enhanced opportunities for investment (in the form of new businesses), job creation prospects and improved human resources. Help for firms extends beyond to having access and input into the development of new technologies.

Political support, i.e. with specific goals for lowering emission levels and promoting closed-loop systems (Sacchi & Ramsheva, 2017) and the renegotiation of regulations for restricting of recycling of waste within firms can act as other incentives (Yedla & Park, 2017).

Risk to critical infrastructure is identified as a barrier later in this review and to help mitigate this an Input-Output Inoperability Model is offered, which helps firms within a system to identify and develop resilience strategies and technical solutions (Kuznetsova, Louhichi, Zio, & Farel, 2017). Involving the top management of firms is critical (Bacudio et al., 2016) and this crosses over with parts described in the social/stakeholder interactions section above and later in chapter 3 with the role of leadership.

Collaboratory platforms

One of the biggest barriers for firms in engaging with IS occurs when they "lack the understanding of the economic viability of participating in IS" (Raabe et al., 2017, p. 268) - this is expanded in the Barriers part that follows below. Multiple authors in response propose collaborative platforms as enablers of IS, for example the: Waste-to-Resource Matching platform (Low et al. 2018), Waste Electrical and Electronic Equipment (WEEE) platform (Marconi, Gregori, Germani, Papetti, & Favi, 2018), By-product exchange network (BEN) model (Raabe et al., 2017). More broadly, scholars argue functional information platforms are essential (Guo et al., 2016), such as networking platforms for waste exchanges information (Ceglia et al., 2017).

Innovation

Continuous innovation fosters both ongoing participation in a network and encourages newcomers (Ceglia et al., 2017; Taddeo et al. 2017), which in one form relies upon the integration of the best available technologies. Alternatively, or in addition, scholars (Ceglia et al., 2017; Sun et al., 2017a) note are more classical forms of R&D for process redesign, reorganisation and creating building blocks for circularity, which provide fertile conditions for synergies. Furthermore, the development of new business models allows for innovations to be harnessed (Aid et al., 2017).

2.2.2.9 Enablers at multiple levels

Collaboration

Strong partnerships, i.e. promoting long term partnerships is one of the key strengthening factors to mitigate a few of the anticipated risks of implementing IS. Since IS, "although beneficial for the system as a whole, could be locally inefficient for the single firm, it requires the establishment of either a central authority imposing IS (the so called top-down approach) or of a contractual mechanism that incentive firms to spontaneously pursue it, in a self-organized model" (Albino et al., 2016. p. 4364). Some of the approaches for promoting long-term partnerships could include the formation of innovative PPPs, joint ventures, and cluster platforms (Aid et al., 2017).

Broader collaboration among different organizations should be encouraged (Guo et al., 2016). Stimulation should occur at all points through the value chain (Hodgson et al., 2016), whereby international collaboration could be crucial (Guo et al., 2016).

Evaluation/indicators/enabling tools

Alongside the propositions already described Liu et al. (2018b) propose that there must be appropriate indicators and tools to facilitate and evaluate symbiotic relationships. Capelleveen et al. (2018) for example identified multiple existing tools, which were categorised into six different types including: open online waste markets; industry sector synergy identification; and IS repositories and region identification systems for IS among others. The SymbioSyS Tool for example corresponds to industry sector synergy identification as it helps to promote the efficient use of resources and new business models (Alvarez & Ruiz-Puente, 2017).

Multiple other tools and indicators are available to streamline IS initiatives, each designed for a particular aspect such as supporting decision-making (Dong, Wang, Scipioni, Park, & Ren, 2018). The Recovery Potential Indicator for instance allows for the value to be quantified that is technically feasible to recover from specific waste streams globally, e.g. in relation to paper throughout the entire life-cycle (van Ewijk et al., 2018). This indicator takes data on individual waste streams and then reveals the absolute quantities of waste generated plus the percentages of current, benchmark and potential future recovery. Consequently, it provides firms and policy makers with macro level future scenarios that help resolve a key barrier identified in the section above where that is a lack of transparency in terms of the value embedded in waste.

Zhe et al. (2016) have however developed an emergy-based hybrid method for assessing IS of an industrial park. Hu et al. (2017) introduced the Adjusted Raw Material Consumption (ARMC) method to uncover the hidden actual resource consumption and environmental impact. Another approach is the Industrial Symbiosis Indicator, which has been developed for use in eco-parks, this helps measure both the flow of materials and impact of activity. However, this tool has limitations and should therefore be used in conjunction with others (Felicio et al., 2016).

Modelling

In association with the wide variety of evaluation, indicator and enabling tools outlined above many models are positioned in the literature (these are listed in table 1 below for brevity).

Technology

In order to advance IS it is imperative to advance CE related technologies at the same time. Guo et al., (2016) suggest that advanced recycling technologies for example can enable new synergy opportunities. Others recognise that effective monitoring using simple indicators is required both in the set-up stage and thereafter as any dynamic system develops over time (Felicio et al., 2016). One way to address the barrier created by a lack of robust data in relation to waste streams is through big data approaches (Song et al., 2017). In the case of a specific location such as Singapore this involves a three-step process:

1. Conduct internet and web page searches for relevant firms and data.
2. Identify input resources and output waste.
3. Estimate material quantities (where these figures are not readily available calculations can be used based upon the firms' revenue versus industry average. Machine learning algorithms using figures from existing databases can then be deployed to identify potential symbioses within specified geographic areas such as the city of Singapore.

Another technological enabler that is promoted is Multi-Layer Stream Mapping (MSM), which is an innovative process of efficiency assessment that marries what are termed 'donors' to 'receivers' to promote symbiosis (Holgado et al., 2018). The MSM approach is based upon Value Stream Mapping, which is an established Lean tool that quantifies value- and non-value-added activities in systems, in addition to dimensions beyond time that include water, energy, raw materials etc. In so doing MSM enables practitioners to understand the feasibility of various scenarios, i.e. the costs and value before engaging in symbiotic relationships.

In order to advance certain relationships, it is vital to add granularity to the process of matching donors to receivers. One such approach is a detailed framework, which has been tested in Sweden and captures specific CO2 user needs (technologies), geographies and technical criteria, and matches the CO2 between them in terms of its purity, pressure, temperature and inclusion of any catalysts (Patricio et al., 2017).

Technical data can also help to generate simulations where it is important to increase the confidence in a synergy, e.g. in relation to energy. Simulations of the economic implications are attractive to firms as the modelling process allows the sensitivity of different parameters to be adjusted, for instance to reflect how prices may fluctuate (Karner, Theissing, & Kienberger, 2017). Thus, a best- and worst-case scenario may be produced which helps lower the threshold particularly for newcomers to IS.

Where it is possible to access actual data from firms it is possible through technical analysis or more specifically total site integration (TSI) methods to mathematically model how processing facilities in whole clusters should be integrated to extract maximum value from for example biomass feedstock. In so doing, firms in industrial clusters, e.g. in a New Zealand one centred on pulp/wood processing can be shown to be more economically competitive through a higher degree of integration (Atkins, Walmsley, & Walmsley, 2016).

Life cycle assessment (LCA) is an alternative and widely used quantitative approach not only to understand how waste can be substituted for virgin materials (Husgafvel et al., 2016), but also to build a case to advance collaborations (Dong et al., 2018; Zhang, Duan, Li, Shao, Wang, & Zhang, 2017a). Other evaluations such as land use, water footprints and the availability of waste in conjunction with LCA help provide stronger assessments of the opportunities and potential trade-offs (Dias et al., 2017).

Transparency through auditing, for example of energy consumption and GHG emissions, is important not only as this allows firms to demonstrate reductions in line with regulations and financial incentives, but also in improving the design of eco parks. Well-designed eco parks in turn help to attract more enterprises (Huang, Jiang, Wang, Zhao, & Wu, 2016).

Many of the enablers described above use digital technology, and technological advancements have provided the means to further accelerate continuous improvement in IS systems for example with the Internet of Things (IoT) (Baptista et al., 2018; Hu et al., 2016; Zhang, Romagnoli, Zhou, & Kraft, 2017b).

The MAESTRI Total Efficient Framework (MTEF) for instance is able to simultaneously assess the economic, environmental and efficiency performance in complex production systems through the use of an IoT platform and management system (Baptista et al., 2018). This framework is of benefit as the feasibility and uptake of IS as described in the Triggers section strongly correlates to the firm's perceptions of the economic benefits derived. By undertaking detailed comparative quantitative analysis of non-symbiotic versus symbiotic systems, particularly for energy intensive industrial processors (e.g. with CO2 as waste in tandem for example with horticultural facilities with greenhouses), strong cases can be demonstrated of the cost benefits of mutuality (Marchi, Zanoni, & Pasetti, 2018).

Greater detail on technology in relation to advancing synergies will be provided in WP2.2.

Table 1 - Models

AUTHOR	MODEL
Afshari, Jaber, & Searcy (2018)	*Multi-objective mixed integer linear programming (MILP) model to optimise energy exchange flows between energy suppliers and users*
Albino et al. (2016)	*Agent-based simulation model for symbiotic exchange networks*
Dong et al. (2017)	*Hybrid evaluation model integrating process-based life cycle assessment (LCA) and input-output (IO) model*
Leurent, Da Costa, Sylvestre, & Berthelemy (2018)	*Techno-economic model to assess feasibility of transferring steam to industrial users*
Liu, Hao, Zhou, Yang, Zhang, & Su (2016)	*Logarithmic Mean Divisia Index (LMDI) Model*
Maillé and Frayret (2016)	*Multi-objective mathematical programming model for the optimization of by-product flows, synergy configurations, and investment decisions in eco-industrial networks*
Pan, Sikorski, Akroyd, Mosbach, Lau, & Kraft (2016)	*Multilevel modelling and optimisation in EIPs*
Ramaswami et al. (2017)	*Multi-scale modelling of linkages across intra-city, hinterland, provincial, grid region and national scales*

Ren, Liang, Dong, Sun, & Gao (2016)	*Model for sustainable design of integrated industrial system*
Renzulli, Notarnicola, Tassielli, Arcese, & Di Capua (2016)	*Life Cycle Assessment (LCA) of steel production with cradle to casting plant gate approach that covers stages from raw material extraction to solid steel slab production*
Røyne, Hackl, Ringström, & Berlin (2017)	*Life Cycle Assessment (LCA) for environmental evaluation of industry cluster strategies*
Sun et al. (2017b)	*Integrated material flows analysis (MFA) and emergy evaluation model*
Wang, Wang, & Song (2017)	*Integrated stability analysis*

In summary, from this review of state of art literature it was found that IS is enabled by a broad range of social elements, political instruments, and economic benefits. These findings align with the view of Mulrow et al. (2017). Environmental aspects are evident but to a lesser extent. We also found that there are a significant number of tools, indicators and models which are positioned in the literature.

2.2.3 Barriers

Within the literature a wide range of challenges have been identified. In this section we draw these out - it is, however, valuable to recall the analogy of a coin. Factors given as enablers might operate as a barrier depending on the context and how they are managed. Therefore, although we set out the barriers found to date, there will be others that the reader may identify by reflecting back upon the enablers.

2.2.3.1 Materials

In some instances, the current waste market is not sufficiently developed on both the demand and supply sides, and there is an insufficient amount of wastes as substitutes (Ohnishi, Dong, Geng, Fujii, & Fujita, 2017). Too little or too much diversity presents an alternative barrier, as is high dependency either on other firms within a system or on a specific material that may have fluctuating supplies (Ashton, Chopra & Kashyap, 2017).

Iacobescu et al. (2016) take another angle and argue that while the majority of materials are able to be exchanged in push-pull interactions, some present substantial technical challenges. For example, stainless steel slags include EAF (Electric Arc Furnace), AOD (Argon Oxygen Decarburization) and LM (Ladle Metallurgy) slags, which have potential as feedstocks in cement-making; however, intensive research is required to identify a viable route.

2.2.3.2 Technology and data

As already identified in the Enablers section of this chapter, technology plays a major role in advancing IS. Where this is missing or there are shortfalls in infrastructure readiness, sustainable by-product exchanges become more difficult (Bacudio et al., 2016).

Related to the finding above, another critical barrier is the paucity or poor quality of data on waste (Felicio et al., 2016). The volumes, quality and types of data, and the different locations the data is generated in mean that a significant proportion is challenging to collect and process economically (Holgado, Benedetti, Evans, Baptista, & Lourenço, 2018; Song et al., 2017). Other authors point out the need for an initial firm or an intermediary to precipitate the analysis to understand which others are potential candidates for symbiotic resource exchanges (Holgado et al., 2018).

2.2.3.3 Legal and regulatory

Closely linked to the issues surrounding material feedstocks are multiple legal and regulatory obstacles. In some cases, this relates to either a lack of regulation; in others, overly rigid environmental regulations (Ashton, Chopra, & Kashyap, 2017; Low et al., 2018). Waste regulation, for instance, remains a major challenge in Korean EIP development even when recycling technologies are available and potential users are specified. In one project, the Waste Control Act (which regulates and limits the uses of industrial by-products) (Park et al., 2016).

Exchanges of wastes can be particularly problematic as in some instances these cannot legally be exchanged. In order to overcome this, negotiations are needed with regulatory authorities that may be brokered by intermediaries (Taddeo, 2016). This links back to the findings in the Enablers section.

2.2.3.4 Policies to incentivise

Government policies to incentivise initiatives of IS are also needed (e.g., tax relief) as well as to regulate IS, particularly at the level of industrial parks. More broadly, there is a lack of funding to promote IS and disseminate information (Bacudio et al., 2016) — directly linked to the point below.

2.2.3.5 Information

Multiple authors identify as a major barrier a lack of information and knowledge of what by-product exchanges are possible and available (Raabe et al., 2017). Low et al. (2018) concur and identify the problem of missing information about possible processes and materials. Further issues include a paucity of information sharing among locators and conflicts between locators created by different stakeholder objectives, which result in limited sharing of resources, including information (Bacudio et al., 2016).

2.2.3.6 Coordination and management and leadership support

Institutional support is imperative; where this is lacking there is little integration, coordination and communication. Poor management is a major cause of this problem, which may inhibit the development of an IS network (Bacudio et al., 2016).

Directly connected to the barrier above are issues related to poor top management support. IS approach needs to be incorporated in standard industrial parks management practices as part of their policy (Bacudio et al., 2016). A cascade of other problems comes from unengaged leaders, which includes a resistance to collaboration. Industrial plants and the people within them must be amenable to forming synergies and adapting to structural changes.

From a different perspective on leadership, according to Ashton, Chopra and Kashyap (2017), the loss of key stakeholders, e.g. individual champions or firms, can have catastrophic impacts on either emergent or more mature networks.

2.2.3.7 Skills shortages

Training for implementing IS also suffers from poor leadership and management practices. Many people do not have awareness of IS concepts or sufficient expertise of IS terminologies and the lack of processes and policies for educating stakeholders should be addressed (Bacudio et al., 2016).

2.2.3.8 Business as usual

For firms with long histories and stable contexts a more basic problem emerges: a deep-seated reluctance to change existing practices (Taddeo, 2016). Associated with this, the role of entrepreneurs is raised as a serious constraint as they focus intensively on driving what they perceive as the core business and potentially view symbiosis as a distraction. Resources, both human and financial, would in entrepreneurial thinking also need to be diverted from current business as usual (Notarnicola et al., 2016).

2.2.3.9 Economic and operational

Added to the concern above is the time taken for a return on initial investment (Taddeo, 2016). This financial aspect is compounded by a frequent lack of external financial support (Taddeo, 2016), which is often sought from regional or national government unpinning the finding of Bacudio et al. (2016) in section 2.2.3.4. However, any financial support provided may entail burdensome bureaucracy as public funding requires an auditable trail. Taddeo (2016) adds that a bureaucratic approach may create an inflexible development process.

Many businesses typically see waste not as a valuable commodity but as material to be disposed of as rapidly and cheaply as possible (Notarnicola, Tassielli, & Renzulli, 2016). From an operational perspective, there are issues of uneconomic waste-to-resource exchanges, e.g. end of life processes such as collection, sorting and recycling (Low et al., 2018).

According to Tan, Andiappan, Wan, Ng, and Ng (2016, p. 46) citing Jackson and Clift (1998), every firm is a “self-interested maximizer of individual profit” who might not necessarily be interested in optimizing the benefits for the entire system; the challenge, therefore, remains in allocating the benefits among partners in an equitable manner. Power or status asymmetries are added to this list by Ashton, Chopra and Kashyap (2017).

2.2.3.10 Over planning

Over planning rather than allowing spontaneous interactions is highlighted as a hindrance to engendering relationships between firms. The Kalundborg Symbiosis in Denmark, which has been evolving over the past forty years, is what is described as “an organically-evolving network of strategically unassociated economic entities” which came into being with limited collaboration for the purpose of sharing water and by-products: steam, heat and gas (Valentine, 2016, p. 66).

2.2.3.11 Trust and risk

We turn now to two of the most important findings in literature; firstly, trust. For almost any waste, there are available technologies to convert (recycle) it into a resource, however, often the significant barriers are non-technical, such as, a lack of trust (Low et al., 2018). Issues of trust which may hinder companies that want to become involved in relationships include concerns about sharing information. Trust for many organisations is problematic where competition is the norm (Taddeo, 2016), and this rejoins with the findings above on business as usual and mindsets.

For firms, there is a constant requirement to understand risk, and one major impediment is the potential failure of what are deemed critical infrastructures, which include electricity, water and telecommunications. When operating alone this risk is significant, however in a complex interconnected industrial system there is the added danger of cascading and therefore systemic failure, particularly when a disruption starts from outside the system (Kuznetsova et al., 2017). Ashton, Chopra and Kashyap (2017) underline the issue of external perturbations in a study of self-organised industrial ecosystems, some of which have ceased to exist and others of which are continuing.

Other risks are evident for individual firms, particularly those which produce hazardous waste such as in the iron and steel industry. Parts of these industries are characterised by high environmental risk, for example, coking plants. Not only do these plants have environmental risks, e.g. landfill leaks and dispersions, but they also carry an economic risk in situations where there are no viable long-term solutions to the wastes produced through inter-firm collaborations. For these firms the risk increases further with the prospect of tighter legal frameworks (Leong et al., 2017; Wu, Pu, Ma, Qi & Wang, 2017) which are being enacted across the globe.

In summary, as a result of interrogating the literature, we recognise many barriers that exist at multiple levels. Many are of a non-technical nature and these require strong and consistent leadership. We return to this topic later in the report.

2.2.4 Concluding remarks

In conclusion of this review, we offer the following observations.

Evidence was gathered of a wide range of triggers that spark, enablers that assist, and barriers that deter or slow synergistic activities. Overall, what comes to the fore is the complexity of IS.

On one side are the highly technical elements, which are illustrated by the plethora of tools, models, indicators and frameworks that are offered to help advance synergies. However, few are rigorously tested, and many are tested on single sites and on specific parts of the IS process within these.

We find on the other side intensely human aspects of IS, particularly highlighted by the role of leadership and communication. In our opinion these aspects require far greater focus than they have received to date.

Moreover, there is a paucity of research on an end-to-end process that would enable individuals or organisations to follow a logic that accelerates the journey towards IS. This is indicative of an immature field, and at the end of this report we make recommendations to guide future research efforts in order to address the gaps in knowledge.

3. Best practices in industrial symbiosis: lessons learnt from twenty-five cross-industry case studies

The analysis and synthesis of existing case studies offers a valuable means of not only understanding the broader landscape of a phenomenon, but also the underlying principles. In relation to this project, twenty-five case studies were reviewed by the authors. This helped build a rich picture across multiple geographies of IS at different stages in their evolution and led to the identification of the triggers, enablers and barriers to the implementation of IS. The case study review is designed to complement the other components of this work package (literature review and survey). Together these provide a portfolio of best practices for scaling IS.

This chapter is organised in three parts. First, the methodology used for the case studies review is described; an analytical framework is introduced, based on the triggers, enablers and barriers regarding IS, which was used to guide the analysis and synthesis phases. Second, the case studies review results are presented, beginning with the triggers, then the enablers and finally the barriers. Last, a conclusion follows.

The case studies in this chapter are referenced using the number assigned in the spreadsheet in Appendix 1. Case study 1 is denoted CS 1, and so on.

3.1 Case studies methodology

It was important to develop a robust approach to the selection of the twenty-five case studies of IS. Twenty-five was concluded as the number of case studies that allowed for in-depth knowledge to be gained regarding key criteria, developed by the UCAM team in alignment with the objectives of the overall project. Factors considered in choosing this number of case studies were that twenty-five enabled a saturation point (beyond which no new substantive knowledge emerges and patterns in data are repeated) to be reached and that twenty-five was a feasible number to analyse while keeping within the time and resource constraints of the work package. A number of criteria were used in the selection of which case studies to analyse.

The first of these criteria was the need for it to be published in a reputable, publicly accessible source. Therefore, these case studies are distinctly different from those that may be derived from anecdotal evidence. This criterion was important in order to give us strong evidential support for the analytical framework. The analytical framework shown in Figure 2 below was used to conduct thematic analysis and identify the key concepts which appear to be relevant for catalysing initial, and thereafter scaling up IS systems. The framework shows that there are triggers, enablers and barriers that act to influence the development, or, in some cases, demise of IS systems.

The second criterion was for the case studies to cover a range of industries.

A breadth of geographies was the third criterion with examples drawn from Europe, including Italy, Spain, Sweden, Denmark, Germany, Portugal and the UK, as well as Australia, Japan, Korea and China.

The fourth criterion was to ensure that there was a broad spectrum of IS maturity. At one end of the spectrum are emergent systems at an early experimental stage, potentially with just two stakeholders involved; at the other, mature, long established systems. For example, the Kalundborg industrial cluster in CS 3 is very mature in IS terms (circa 40 years old), as it started in 1961 and by the late 1980s was well developed.

The fifth criterion set was the need to include self-organised IS systems as well as those created by external stakeholders such as intermediaries, e.g., NISP in the UK (see for example CS 13).

3.2 Case studies findings

3.2.1 Triggers

Before looking in detail at the triggers it is important to note that within the triggers, enablers and barriers, sections 3.2.1, 3.2.2 and 3.2.3, there are common themes that will become evident.

To enable the triggers to be understood in a more meaningful way they are presented at a national government level, regional/local government level and then firm levels. However, it is acknowledged that there are interplays between these levels. Moreover, there are shifts over time, which reflect the case studies' breadth of focus on emergent to mature IS activities.

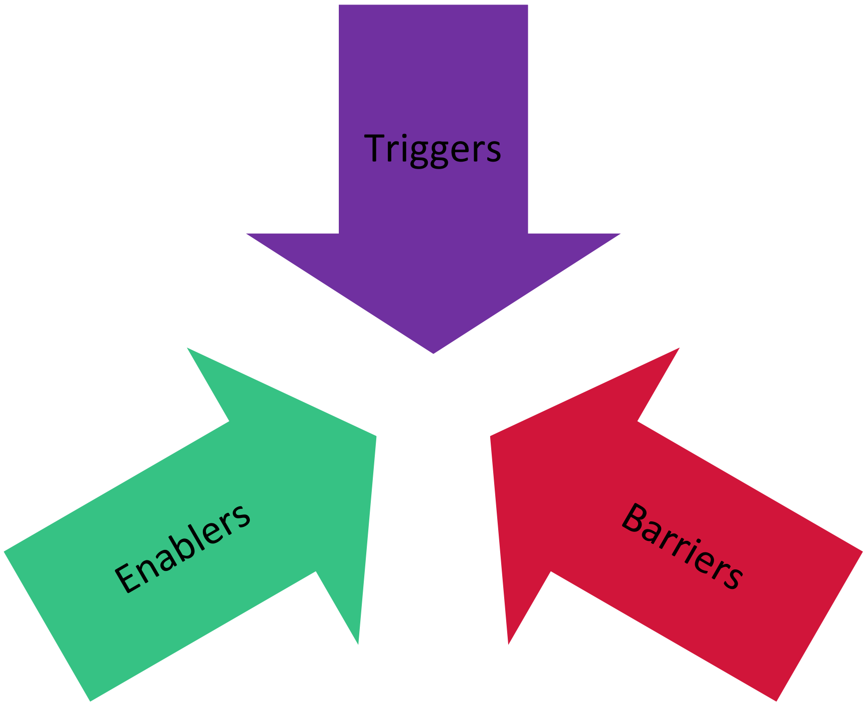

Figure 2 - Analytical framework

3.2.1.1 National level

At the most macro level there are certain global factors that are strongly driving national governments' activities in relation to legislation, policy-making and taxation in this field. The most important of these are the Paris Accord, with the need to meet GHG emissions targets, and the United Nations Sustainable Development Goals (SDGs). Both have activated trickle-down effects from national governments to regional/local governments and then on to firms, triggering the instigation or ramp up of IS. These impacts are evident in CS 12, 16, 17 and 23. Other case studies do not overtly refer to these factors, but they are implicit in most of the twenty-five analysed. See for example CS 14 where more sustainable farming practices have important implications for GHG reductions.

Governmental activity is noticeable when they have sought to join global organisations where previously they have existed outside of these spheres of influence. For example, China's governmental policies to protect its sugar industry were weakened when it entered the World Trade Organization, due to stringent rules on subsidisation and the new competition with cheaper sugar from other countries. In effect, this caused the Chinese sugar industry to seek ways to organize itself more efficiently and thereby reduce costs and protect jobs (CS 21).

In order to meet the targets set out in the Paris Accord, pressure to modify industrial activity is applied by national governments through the imposition of climate change levies (CS 10) and end of life regulations for products. In Europe, this is shifting the automotive industry and associated metals and plastics industries towards IS (CS 9). Many governments are also seeking to future-proof against shifts towards more stringent targets by tasking, for instance, the food production industry and regional and local authorities with organising waste collection schemes (CS 13). Policy levers have been applied successfully by Germany's government to drive firms with high outputs of waste, such as paper mills, to seek alternative routes for their waste products.

Tax incentivisation and subsidies, which work in the opposite way to punitive levies, have been successfully operated in Sweden to help the biofuel industry of Händelö embrace symbiotic relationships in the Norrköping area (CS 12). Positive intervention is evident in several other case studies, for example in Portugal (CS 2) and Japan (CS 22) governments have actively intervened to slow economic erosion or to improve stagnating regions using subsidies.

When the Relvão project started in Portugal (CS 2), a proposal for the setup of a large integrated centre for recovery, treatment and elimination of hazardous waste was already in progress within the Chamusca region. This region was then selected by the national government for the implementation of an IS strategy to slow the decline in the area's economic and social fabric, which was compromising regional welfare. The Portuguese Government, Chamusca Municipality Government and the Technical University of Lisbon, together with industrial companies and entrepreneurs, worked in collaboration to use highly targeted investment to provide social, economic and environmental improvements through IS.

From the points given above it is evident that national governments, under pressure to meet global challenges and targets, and the need to stimulate growth or prevent economic decline, play significant roles in triggering and accelerating IS.

3.2.1.2 Regional/local including city level

Many of the forces described in section 3.2.1.1 have a trickle-down effect to drive regional/local governments and city authorities to instigate triggers that impact not only firms within their catchments but also on their own activities. Most prominent are the pressures that are exerted from their national governments to meet the GHG emissions targets ratified via the Paris Accord and the SDGs. However, other factors also come into play at this level.

Cited in the case studies is role of authorities in controlling the negative impacts of production within a particular region/location. Pollution from industry in some areas has caused significant negative impacts on the environment, in addition to serious implications for the local population. In Italy, there are examples (such as within the Taranto district in CS 1) where local authorities have made efforts to control local pollution. In China, significant negative impacts on the health of people and the environment led to direct interventions to stimulate IS systems, as seen in CS 21 with the Nanning Sugar Co. Ltd.

Local governments frequently have had an impact on IS initiatives by strategically driving sustainable development in a particular location. Their overarching objectives are not only to reduce the environmental impact of emissions, but also to stimulate economic growth. In CS 2, an industrial park with pulp and paper, and agro-industries; chemical companies (mainly fertilisers); and waste treatment facilities has prospered through the intervention of the local Chamusca Municipality Government. City authorities have particularly pressing needs to control pollution and reduce waste. In the city of Lidköping in southern Sweden (CS 19), the city authority ownership of the energy producer and waste treatment company provides evidence that direct control in an IS system is a valuable catalyst.

Following the 2008 global financial crisis, many areas and industries foundered, leading to a need for revitalisation strategies. CS 8 provides an example of the implementation of initiatives by a regional authority, in which the local government supports chemical producers and power suppliers in the Abruzzo region of Italy. The Bussi Chemical Site, one of Italy's oldest industrial clusters, was identified as in dire need of economic and social revitalisation due to the impacts of the financial crisis and increasing unemployment. As a result, the local government decided to stimulate interest in IS within the Bussi area through its legislation entitled ‘Ecologically Equipped Estates’. This legislation gave incentives, in the form of priorities, to businesses that use coordinated systems in relation to the management of air, water and soil pollution in addition to service facilities, infrastructure and technologies.

State-owned companies in China have been incentivised by local government to invest in and implement innovations to help spur symbiotic development. In CS 20, a smeltery for zinc and tin production in South West China has developed innovations in technology, equipment and production techniques that allow output materials to become feedstocks for a cement factory. The innovations will in future enable a battery producer to become part of the system.

Regional bodies have offered a further stimulus to IS with what may be described as spill over or knowledge transfer via one coordinating body or intermediary that operates in one region to another. An example of this phenomenon is provided in CS 10 with a Regional Development Authority’s (RDA) support for the NISP, which took learnings and interest from the Humberside IS programme (HISP) and began the setup of another IS programme in the processing industries within the West Midlands. The NISPs, which are located across multiple regions, were set up and supported by central UK government with a primary objective to catalyse IS — see CS 4, 7, 9 and 10. More recently NISP has moved from being government-financed to become a private enterprise (the impact of this shift is described later in section 3.2.3).

Similar to the effect described in the previous paragraph has been the inter and intra-regional linking role played by other intermediary organisations. For example in the Midlands, the Midlands Environmental Business Company MEBC has an arm called Environmental Business Communications (EBC) that engages and then builds firms’ confidence and capacity in IS through communications and workshops (CS 10).

Overall, the findings reveal the critical role played by this level not only in driving top down governmental initiatives but also through lateral and downward action to encourage uptake of symbiosis. In this way, we can see that this level acts as a valuable IS conduit.

3.2.1.3 Firm level

At a firm level there are numerous triggers that have been identified in the case studies, some as a direct consequence of those outlined above at national and regional/local levels. However, there are other distinctive factors that initiate symbiotic developments, and these are often strongly economic in nature.

Cost-cutting and increasing competitiveness featured in several case studies. These include CS 1, where symbiotic relationships between players in Taranto, such as the ILVA steelworks, oil refiners, cement companies and smaller agro firms, have become vital in order for the district to remain commercially viable. Similar financial drivers are evident in CS 6 as leather producers in Italy and Spain struggle in the face of global competition. With the help of the Italian National Agency for New Technologies, Energy and the Environment (ENEA), the producers collaborate with several agro industries, including poultry processing, that donate waste materials as inputs for use in the tanning process.

Closely related to the preceding trigger was a widespread incentive for firms to reduce the disposal costs of outputs. CS 7 offers an interesting example of a Scottish beverage manufacturer with textile packaging waste that was originally landfilled. Other firms have needed to prepare for/avoid specific landfill tax schemes — see CS 13 where a UK food producer has been spurred into action. Within CS 5, the symbiotic exchange between the Hamburger Rieger GmbH pulp and paper mill and the Spremberg Power Plant was triggered by the need not only to deal with the high disposal costs of the pulp and paper mill wastes but also to meet Germany's regulation on waste. Germany, as in certain other EU countries, bans the direct disposal of waste into landfill.

Another prominent factor that emerged was the recognition by firms of the value in by-products previously considered to be waste. Furthermore, symbiotic exchanges of materials were identified as valuable to each player. In CS 10, companies located in the Mersey Banks industrial area within the chemical, oil and gas sectors realised that symbiosis could be extended to broader synergies involving paper, automotive, aerospace and metals companies.

Security from fluctuations in the supply and/or costs of energy and heat emerged as stimulus in CS 12, which investigated the emergence of symbiotic relationships between companies on the island of Händelö. Constant energy is required to meet the needs of the Norrköping municipality, therefore firms sought out a mutually conducive method of securing a continuous supply of electricity and heat at competitive prices, ensuring they were independent from market fluctuations and geopolitical instability. See also CS 4.

Resources also feature where firms need to find dependable suppliers of key raw materials, or cheaper or additional quantities of input materials. For instance in CS 7, one of the players had to establish a cheaper source of sustainable materials, used as packaging for products, which led to a partnership with a beverage manufacturer. The exchange gave the beverage manufacturer an avenue for its waste hessian sacks that previously went to landfill.

IS in other case studies has been supported as firms seek to deliver a growth strategy where resources are scarce or limited. Water is a common constraint, and this has driven leather producers in specific locations to establish relationships with other industrial partners as discussed in CS 6. Factors regarding water scarcity have acted as powerful motivational forces in other locations such as in the Kalundborg industrial cluster in Denmark (CS 3).

At this level a further, and fundamental, driver was apparent in many of the case studies (CS 10, 12, 15, 16, 17, 20 and 21): reducing greenhouse gas emissions (predominantly CO2) in line with national government and international targets set in Paris, in addition to meeting the SDGs. The high environmental pollution from its plants compelled the Nanning Sugar Co. Ltd. in China to remodel its traditional, linear process and transition to a circular, symbiotic one (CS 21). Part of the remodelling process allowed it to diversify successfully, which brought economic benefits.

Diversification as a strategy to extract greater value from materials and raise barriers to entrants in core markets is a further motivational factor, as in CS 17. This case study explored the strategy of British Sugar (now part of AB Sugar), which is highly vertically integrated. The strategy focused on developing alternative business models using sugar refining by-products. The case study offered insights into the triggers for internal symbiosis, since only limited external synergies have been needed. The company had to navigate challenging times, particularly with the opening of the UK market to global competition and subsequent rivalry with low-cost sugar production in developing countries. Environmental protection only became a driver for symbiosis more latterly.

Marketing benefits in the form of raised CSR profiles have provided another incentive, evident in CS 12 and 16. By implementing a resource synergy, ThyssenKrupp (CS 16) improved its environmental credentials in line with its company policy. This aluminium alloy technology solutions provider introduced a more sustainable (and cheaper) solution to dispose of tarpaulins, which were usually sent to landfill. Some firms have pursued an IS pathway with the strategic aim of sending zero waste to landfill, see for example CS 15 of Michelin in Northern Ireland.

Certain cases revealed long-standing IS practice for players in certain industries and particular locations. Of note was where there are clusters of firms operating in industries such as chemicals, oil and gas and process industries, i.e. pulp and paper. These clusters have evidently acted as best practice examples that firms in other geographies have sought to emulate. Kalundborg has frequently been held up as a beacon, helping in the germination of the Relvão Eco Industrial Park project (CS 2). Spread of leading practice is cited in another case (CS 9), where a global player operating in oil and gas moved into another geographic location to operate alongside chemical processors. In so doing, IS knowledge was transferred from Tampico in Mexico to Humberside in the UK.

3.2.2 Enablers

The enablers are organised in a different format to the triggers as they follow different dimensions. The reader will however, see how these two sections relate to one another. As in the literature review findings, it is helpful to keep in mind the analogy of a coin when considering these enablers and barriers. On one side of each factor could be an enabler; on the other, a potential barrier.

3.2.2.1 Government/regional authorities

One of the most powerful forces evident in the case studies was that of direct state or regional intervention in the form of financial contributions or investment in IS. Public investment in CS 2, particularly in infrastructure, utilities and services, created a favourable context for IS development. Further details are provided in CS 20 and 22 on the positive impact of government intervention.

Policy is another important tool that helps to provide an appropriate framework for IS development (CS 24). Interactive processes identified in CS 2 between the government, other institutions and the firms themselves helped towards their alignment and collaborative efforts. One notable, specific element of support for IS has been national and regional government policies derived from regulation. Examples are: the Danish Government's regulations on pollution control, emissions reduction and resource and energy efficiency (CS 3), and the German government's ban on direct disposal to landfill (CS 5).

Government investment in supportive innovation processes (CS 20) and in coordinating bodies featured prominently in many of the studies. Of note is the UK government's decision to invest heavily in the establishment of the NISP, which operated (and continues to do so) as the connector and knowledge broker between firms and research bodies (CS 7, 9 ,10 and 13).

Regional, city and even local governments help in another way by acting as a form of bridge between national government and businesses. This feature has proved vital as they are aware of local conditions and contexts and can help shape national policy accordingly. Additionally, this awareness has allowed them to develop more tailored policies and support emergent synergies (CS 2).

Favourable conditions have also been created through the use of green marketing. Specific marketing has proved a powerful tool and helped raise environmental awareness in municipalities (as in CS 19 of Lidköping, Sweden), serving to attract new businesses to the region.

Overall, from all the case studies it is evident that consistent investment and policy-making/regulation have been the most effective form of support from government at any level.

3.2.2.2 Intermediaries/knowledge agents

What emerged from many of the case studies was the vital role played by intermediaries. For example, the NISP and Business Council for Sustainable Development-United Kingdom (BCSD-UK) were fundamental to catalysing the development of new IS systems in the UK and ensuring effective ongoing function of these systems (CS 4). Their primary role was to identify, connect and coordinate firms and stakeholders within the Humber region Industrial Symbiosis Programme (HISP), with the scientific support of researchers from the University of Lund, Sweden. Other examples of intermediary activity are provided in CS 2, 6, 7, 9, 10, 11, 13, 15 and 16.

In some cases, intermediaries have worked in great detail, providing informational support to identify synergy feasibilities (CS 11) and negotiating the terms of engagement to enable the setup of systems. In CS 4, the intermediaries brokered the contracts and the timings, which were critical as there were multiple firms in the network. Their role helped to build confidence and trust, both of which are essential factors in propagating IS. In many cases, intermediaries have brokered relationships and built shared knowledge and understanding, in addition to securing investment and funding (CS 10).

Another aspect of many intermediaries' facilitative role was assessing what other specialist knowledge was required and where could it be sourced from, e.g. in CS 2 with the Technical University of Lisbon. See also CS 6, where the Italian National Agency for New Technologies, Energy and the Environment established a programme between various leather and agro producers and research institutes. Universities, research organisations and specialist consultancies themselves have played a vital part in enabling synergies to be established through the provision of highly specialised knowledge (CS 12) and the involvement of researchers (CS 11). In CS 11, the researcher actively worked alongside the NISP to take the learnings from previous IS projects, including those in other geographies, to assist in the establishment of new synergistic networks.

Intermediaries have assisted further by providing a negotiation pathway to authorities such as the Scottish Environment Protection Agency in CS 7, which was contacted so as to reclassify hessian that was previously listed as waste on the PPC license to a by-product so that it could be reused. Frequently the agents that work as intermediaries, or within agencies that provide this function, have extensive knowledge due to their industry backgrounds. This knowledge can relate to resource stream capabilities, chemistry, extraction and reprocessing techniques and technologies (see CS 13 for instance). Background knowledge of legislation also proved valuable in bridging the gap between an existing state and one involving symbiosis. Knowledge sharing across networks and geographies (CS 10) added to the importance of intermediaries.

Within CS 9 and CS 10 were examples of project coordinators based in local companies with backgrounds as high-ranking managers, who provided both credibility and visibility, encouraging IS activities. In China (CS 20), the involvement of managers embedded within firms appeared to be pivotal — they usually had a role within local government. This finding underlines the importance of having 'conduits' between the various levels (firm, local and national government). In some cases managers had formal roles of coordination, as in the cases just mentioned, while in other cases managers of different firms formed informal relationships that enabled initial synergies to be coordinated and thence larger IS networks to flourish. The Kalundborg system (CS 3) offered evidence of this phenomenon.

3.2.2.3 Social/relationships

Fundamental to many of the other enablers were social enablers that allowed IS to develop. Trust, either between individuals or firms or with the intermediaries/coordinating bodies, was a strong factor e.g. in CS 9. In this case, the Midlands Environmental Business Communications (MEBC) had an established presence in the area with several existing connections, encouraging other companies to trust the process and thus allowing IS to kick-start in a meaningful way.

CS 18 revealed how trust between various firms and the City Government of Helsingborg created a strong system of interdependencies. In both CS 9 and CS 18, trust was built on the basis of embeddedness in particular vicinities and long-termism.

Trust building between stakeholders in a specific place extended further in CS 8, which focused on Bussi sul Tirino, in the Abruzzo Region of Italy. Local community involvement and trust building activities were evident here, and this case revealed how important long-term participation and social relationship building were in identifying and seeding the development of symbiotic opportunities. Specifically in this case, the local population had deep-seated negative views based on previous experiences.

Close working relationships appeared critical in many case studies and extended to other stakeholders, for example intermediaries, such as the NISP and Regional Development Agencies (RDAs) in the UK (CS 9), and academic institutions. In CS 9, a further notable example of the power of trust in generating engagement in IS was evident in that a confidentiality agreement between those involved was deemed unnecessary due to the credibility of North West Chemical Initiative (NWCI). In cases such as Kalundborg (CS 3), self-organised and brokered relationships between individuals, firms and authorities provided ideal conditions for synergies to develop. See also CS 8.

Confidence in collaboration was noted in CS 4 as an enabler, and it was based on cognitive rather than social proximity — this also emerged from the literature review in section 2.2. Certainty in CS 4 was centred on the economic benefits, resource security and reliability of technology, made transparent by BCSD-UK who acted as the programme coordinator. From this point we see how intermediaries perform vital roles in establishing IS, in this case acting in a 'hands-on' leadership capacity.

3.2.2.4 Leadership

Leadership has acted at various levels to encourage the development of IS systems. At an individual level in CS 10, a highly credible Managing Director of a large-scale refinery with a collaborative mindset assumed the project leadership role. In the same study, the Project Coordinators had backgrounds as senior managers in the companies involved. Leadership of IS therefore was not only evident at an executive level but also disseminated within organisations.

From an organisational level perspective, a leadership role was occupied by a major company in CS 9 at the start of an IS programme with a strong commitment. This generated a gravitational pull centred on a collaborative culture that encouraged other stakeholders to participate.

Strong sustainability leadership at a more macro level was found in CS 18 as local/regional/city strategies in Sweden helped overcome IS barriers that related to geographic location. This was through active city planning in addition to facilitating strong relations with neighbouring municipalities, resulting in synergies that generated the district heating corridor between Helsingborg and Landskrona.

3.2.2.5 Geographical/spatial

Geographic proximity is a critical factor in the development of synergies (CS 23), for instance, in cases where firms have been able to take advantage of waste materials that converge in the vicinity (CS 2) or where they have been close to disposal structures and/or resource partners. Many cases underpinned these findings (CS 1, 3, 4, 18).

Relative isolation and the small size of a region/place helped, in particular cases, to create favourable conditions as social interactions both between workers and managers occurred regularly, demonstrated in the Kalundborg industrial cluster example (CS 3). The nature of the industries in a place/region played a part in the development of IS; in some, the homogeneity was a positive attribute; in others, heterogeneity (CS 8). All cases depended on the specific needs of the industries, authorities and broader communities present.

The role of a lead firm in a location was noted in CS 9 and 25, where they established initial synergies and then provided a ‘gravitational pull’ effect that enabled the network to extend. In a similar way, a specific place focused investment (CS 22) or provision of a special status (CS 1, 24) by national governments or regional/city authorities — often due to economic, environmental or social needs (or all of these) — generated a powerful incentive for firms to aggregate and develop synergistically.

3.2.2.6 Process

What emerged from some of the case studies was that various processes were important factors in driving IS.

In some cases, there was evidence of a spontaneous process of IS activity; in Ulsan City (CS 24), companies made one-to-one negotiations for economically beneficial exchanges, driven by the need to respond to stringent Korean government environmental legislation.

Many other synergistic cases were the result of systematic, planned activity, typically coordinated by an intermediary or organising committee who used a process of information collection to gather the necessary technical, legal and economic information. This process then led to the identification of the ideal firms, and/or other stakeholders such as municipalities, for involvement in synergies — for examples see CS 1, 2, 4, 7, 10, 11, 13, 15 and 16.

The typical overall process adopted by intermediaries emerged as an important enabler. Of note were the following elements: the dissemination of information in a clear/open format to appropriate firms/stakeholders; the setting up and running of awareness raising programmes, such as formal launch/awareness building workshops; the negotiation of formal agreements to realise synergies (and develop confidence); the agreement of timings between stakeholders; and the careful monitoring and feeding back of information to guide initiatives and/or develop further synergies (CS 2).

Evident in CS 4 was the process of experience transfer to other geographies. In this case, the lead firm’s previous experience of IS was used to disseminate knowledge and seed wider IS practice in other geographies. The company was a global oil and gas producer with experience in Tampico (Mexico) that was transferred to Humberside and further areas of the UK.

3.2.2.7 Technology

Here, the findings on technology enablers from the case studies are set out. Greater detail on the role of technology will be offered in WP 2.2.

Technology has driven understanding of what is the most effective area to intervene in and to monitor, through the establishment of initial benchmarks or baselines (CS 2) and the live feeding of data over time. This was fundamental to shifting towards widespread synergistic practice (CS 2, 3). The Internet of Things (IoT) allowed intelligent decision-making processes through, for example, the streaming of data. Remote data from embedded IT components reduces the need for human interactions and interventions and has enabled IS networks — see CS 2 in particular for details.

Industry 4.0, which has been enabled by the IoT, has extended the ability to link singular smart factories to modular networks by the monitoring of physical materials and processes. Optimal future scenarios have been produced which allow for decentralised decision-making in these contexts. Digital communication technologies (ICT) have allowed information to flow dynamically around networks (CS 9).

In so doing, technology has become a powerful synergies support.

3.2.2.8 Tools, modelling and measurement

Tools in various forms featured in several of the case studies, for example, in CS 9, an Online Information Tool was developed and used as an electronic data collection interface. This tool shortened the time and reduced the effort required of companies working towards IS by providing the capacity to rapidly handle the large volumes of data frequently generated in systems.

Other cases described the use of web-based resource management systems to identify stakeholders (firms) for synergies, as used by the NISP in the UK (CS 10). See also the description of matchmaking in CS 15 using an IT tool. In addition to the tools, databases have become useful in accelerating the IS process, e.g., the SYNERGie database (CS 16). SYNERGie helped validate the value of potential synergies, assisted in negotiations by verifying the cost benefit data, and it also calculated the reduction in emissions, landfill savings, job creation numbers, investment requirements and projected profits.

Quantitative methods in several forms featured, e.g. Life Cycle Assessments (LCAs) in CS 4 and CS 22, which were used to understand the baseline case and give projected savings. More innovative modelling helped to calculate the benefits of materials exchanges in complex systems such as the bio fuels system in CS 12. In this study of Norrköping (Sweden), various scenarios were modelled to test the interactions and sensitivity to a change of variables (e.g. of material flows/time). Interestingly here, the inputting and sharing of data by firms with intermediaries/connecting agents/researchers accelerated the use of modelling/data driven approaches that then drove synergies (CS 12).

3.2.3 Barriers

From the case studies, a wide variety of obstacles were identified. As already alluded to, the reader will identify linkages between these and the triggers and enablers.

3.2.3.1 Materials

At the most basic level it was found that there was uncertainty surrounding the procurement of sufficient inputs of the right quality at a predictable flow rate (CS 14 and 18). In the first case (CS 14) with a regular supply of organic materials from olive oil farms, in the second CS 18 there were issues centred on the composition of waste materials, particularly those that had been produced using a complex combination of starting materials, e.g., the composition of tyres in CS 15 that required highly specialist knowledge and technologies in order to extract materials that could be reused. Technical challenges were also identified in CS 6 as poultry dejections (PoDe), while suitable for use in preparing hides in the leather tanning process, were unsatisfactory due to the high olfactory impact.

The classification of materials as waste rather than useable by-product arose in several of the studies, most explicitly in CS 7 with hessian sacks and the difficulty in reclassifying them with regulators. Some other raw materials requirements presented barriers as they were challenging to fulfil. This was the reason that in CS 19, not all of the potential waste material feedstocks could be used to produce biogas marked with the Nordic Ecolabel.

3.2.3.2 Capacity and capability

From a firm level perspective there were various constraints that came to the fore. The first being that the data collection necessary for an IS programme required time input by firms, which was often difficult to secure due to competing activities, predominantly these related to the running of the core business (CS 10). A similar issue surfaced in another study (CS 8), in the form of insufficient human resources being available to seek out and understand the potential uses of the wastes and avenues for waste streams as feedstocks for others, acting as an information barrier. Linked to this point, skills shortages more broadly have been identified (CS 10) relating to understanding how IS could be made to work. This occurred in CS 17, where shortfalls arose in innovation skills, and in CS 7, where the need emerged for knowledge transfer capabilities in coordinating bodies.

Potential mismatches in the capacity/capabilities of partners in an IS network created another problem evident in CS 16. Here, a larger lead company potentially had greater volumes of PVC tarpaulins than could be absorbed by a smaller manufacturer of bespoke products for the boating, banner and trailer market.

From CS 18 and 19 it was found that firms that are part of larger international groups had limited autonomy because major (strategic) decisions needed head office approval. Typically, the head office would be geographically distant. This led to situations where centralised top management was not interested in the possibilities of synergies at local levels.

3.2.3.3 Complexity and continuity

The transition to an IS system requires a multitude of changes across all dimensions with a variety of levels of how major they are considered. These changes have been met by strong resistance forces that operate within existing industrial regimes (CS 3). Inertia emerged in CS 17 in the form of bindings to dominant practices or technologies.

Strategic approaches of businesses more broadly have been oriented towards the highest levels of care regarding the primary product (the core business) — see CS 1, 3 and 25. The identification of possible uses of waste streams has therefore been viewed as a diversion of capital and human resources from core business, making IS seem unattractive. This unwillingness to consider IS became more pronounced during periods of economic crisis.

Uncertainty surfaced in several studies as a barrier, taking various forms. In CS 9, funding/investment issues led to a loss of momentum of IS implementation, which was compounded when the lead player ceased trading in the Humberside (UK) region. In CS 18, the insecure nature of continued government support was a barrier in Helsingborg (Sweden), exacerbated by the deregulation of the district heating market, forcing companies to be driven by short-term strategies.

3.2.3.4 Communications and coordination

Given the importance ascribed to the role of intermediaries and coordinators in the triggers and enablers, sections 3.2.1 and 3.2.2, it is evident that any shortcomings in their function would raise barriers. In CS 13, the lack of an intermediary/coordinator to undertake vital functions was described. These functions have been identified as information gathering, identification of synergy feasibilities and the support given to set up a viable system, in addition to helping to secure investment.

Assumptions that an IS programme, e.g. the HISP in CS 9, was only relevant for large energy provider/users in region rather than other sectoral firms revealed the effect that poor communications can have. These assumptions slowed down the exploratory process and caused firms not to engage. The paucity of effective and continuous communication emerged from another study (CS 19), where there was a poor understanding due to technical language barriers.

3.2.3.5 Leadership and mindset

As already described above in section 3.2.3.3, the loss of leadership when a major company in an IS network ceases trading in the region was particularly problematic (CS 9). Social inertia has been found not only to result from loss of leadership but also from incumbent management that directs a firm's activities, particularly in regard to directing the efforts of engineers and technologists, of whom different activities are required for transformation to IS (CS 3). A similar effect has been noted in relation to policy-makers' attentions (CS 3), which may have been caused by what is identified in CS 1 and 8: self-interest and a lack of motivation due to an absence of clear economic/environmental/social benefits. Social inertia was compounded by stable platforms (business models) that reinforced the leadership/management mindset that the current model worked effectively in CS 17.

Fierce competition in certain industries created another mindset barrier that has blocked collaborative efforts. This occurred most notably in non-manufacturing industries (CS 10), whereas manufacturers, in contrast, have been identified in cases as needing to cooperate in order to remain economically viable. Mindsets resulting from previous negative experiences of collaboration are cited in CS 8 as a further impediment to symbiosis. One particularly vivid example of attitudinal negativity is provided in the study of Lidköping (Sweden), where CHP plant employees had negative opinions towards sewage that provided synergistic opportunities (CS 19).

3.2.3.6 Geographical/spatial

Within specific locations the nature of the existing businesses created barriers; in CS 19 the area consisted of heterogeneous businesses rather than a homogeneous industry, which aggravated the cooperation between companies. This was primarily due to the lack of knowledge of other companies' activities. Large distances between companies acted as a barrier by decreasing the economic viability of collaboration and causing a negative environmental impact through the transportation of materials (CS 25). From CS 3, the difficulties of confined geographic locations were identified in that unless there was co-existence, severe difficulty would be realised in attempting to (re)locate heavy/power industries to a common region. The difficulties are a consequence of the complexity and sheer physical scale inherent in firms from these industries.

Shortages of basic materials such as water have precluded any further industrial development in certain places, which is raised in CS 3. Similarly, a lack of infrastructure, utilities and services (and maintenance) in a zone/area/region in CS 3, and lack of suitable facilities in CS 5, emerged as barriers to IS.

Opposition from local communities to additional industrialisation was evident in CS 8 and a lack of active community engagement was evident in CS 25. These can act as powerful impediments to IS.

3.2.3.7 Technology

Three specific technological elements emerged from the case study analysis: firstly, the obstacle generated by what was termed format heterogeneity in the data fusion process — or, more simply, the use of different identifiers for an identical concept. Secondly, the availability of reliable material recovery technologies. This related to the third, which was the lack of initial and ongoing investment in appropriate technologies and skilled technologists, engineers and IT specialists (CS 3).

3.2.3.8 Economic and environmental

Multiple barriers emerged in relation to economic/environmental factors. The first was raised in CS 8 and 20 and related to weak/unstable demand factors. This was partly due to relatively low costs for waste disposal/utility resources (CS 25), along with difficulties experienced by firms in identifying what value was embedded in the waste streams of other firms. Another barrier was firms not having sufficient resources to be able to find out what synergistic linkage opportunities existed and what would be required to implement them (CS 1, 13 and 18).

A further hurdle was the need to partition the economic/environmental benefits and negative consequences for all system parties. The sheer complexity of partitioning and calculating benefits (the overall system impacts must be calculated before apportioning to each element), which are essential to entice parties to engage, was raised in CS 12.

Two further specific economic elements emerged. Firstly, the “invisible hand” of market not being enough, by itself, to optimize an industrial system in environmental terms (CS 1). Secondly, funding issues were of particular note in CS 9 as these led to a loss of motivation — which underpins the point earlier about how negative previous experiences become deeply problematic when trying to re-engage stakeholders in IS.

3.2.3.9 Policy/regulation (firm/network level) and contracts

In CS 2, where Chamusca is controlled by Lisbon and Tagus Valley Regional Development Agency (CCDR-LVT), permits for industrial development proved difficult to acquire. Existing environmental regulation, e.g. where intensive approval procedures for by-product reuse are stipulated (CS 9 and 25), and water and energy utility regulations (CS 25), have the potential to create substantial barriers to IS.

Contractual issues were noted, such as in CS 9, with the requirement to sign a contract at an early stage specifying a given percentage of any economic gains to go to a coordinating body. Confidentiality issues added to the disincentives and had the capacity to derail synergistic propositions (CS 25). All of these contractual elements had the potential to create anxiety and lead to stakeholders continuing to be locked into a business as usual paradigm.

3.2.3.10 Policy, regulation and investment at a government/regional/ local/city authority level

A significant set of barriers at this level has been identified. One of the most prominent is where regulations and policy directives have been found to limit the ability of firms to alter their business processes, for example the issue of the deregulation of the district heating market forcing companies into short-sighted strategies in CS 18, as mentioned earlier. Another example of this is the complicated synergies for the CHP plant in CS 19 due to the prohibition of the use of fly ash in Sweden. Part of this problem has been found to lie in a lack of knowledge at this level of new sectors/materials and processes (CS 4).

Another deeply embedded barrier was the influence of an ingrained market model, where the benefits of IS are not recognised. This is found in CS 18 regarding public procurement laws.

A lack of specific IS policy is identified in CS 23, in other cases uncertainty in relation to the future direction of national politics towards the environment/waste/IS has compounded many of the issues identified as barriers. An example of a change of direction evident in the case studies was the removal of government funding for the NISP, a key intermediary in the UK which as a result became a commercial organisation largely independent of the Government (CS 13).

3.2.4 Concluding remarks

Overall, from the case studies review, there are some powerful factors that have emerged for the scaling up of IS. These were used to develop the recommendations given later in this report in conjunction with the findings from the other three evidence components of WP 2.1: the literature review, survey and focus group.

4. Expert enquiry on industrial symbiosis

The SCALER project launched an expert enquiry on adopting IS in Europe. We invited international IS experts to share their experience. The enquiry was intended for businesses and practitioners that are involved in various stages of IS implementation — from emergent to fully implemented — in all sectors. The data collected is for use in research activities to help SCALER develop key tools, methodologies and guides to support effective implementation of IS at a European level. The survey was launched internationally in May 2018 and closed in July 2018. The survey questionnaire was designed to inform multiple tasks in WP2 and contribute to D2.1, D2.2 and D2.3. In this report, only responses to questions that inform the present deliverable (D2.1) are analysed and presented.

4.1 Survey design

The aim of the survey was to collect data from different sources and through a different method to the others used in this study in order to support the triangulation of findings. The survey was designed to be of an exploratory nature rather than to test or generate statistical significance for any of the themes included in it. The enquiry incorporated 24 open-ended and multiple-choice questions in a qualitative, online, anonymous survey.

It was important to create a shared understanding around the key underlying concept of “resource synergies” for all participants, regardless of their industry or IS maturity level. For the purpose of the survey, resource synergies are defined as the exchange or sharing of resources (including energy, water, capital, residues, recycled materials, equipment, infrastructures) and services (including utility services, transportation, training) between different industrial processes from different sectors.

The survey questionnaire was informed by the literature and the case study analysis and embedded the following key themes and dimensions: *triggers*, *stakeholders*, *benefits*, *relationships*, *decision-making*, *enablers*, *barriers*, *incentives*, *challenges*, *intermediaries*, and *tools and technologies.*

The complete survey questionnaire is presented next.

4.1.1 Survey questionnaire

1. Name of the company.
2. Which **industrial sector(s)** are you operating in?
3. Where are you **located**? Please provide address and country.
4. **How long** have you been involved in resource synergy initiatives?
    - 0 (no synergy implemented)
    - 0-6 months (new initiative)
    - 6 months - 3 years (ongoing resource synergy)
    - 3+ years (long lasting resource synergy that could be considered normal business practice)
5. What **resource synergy initiatives** are you involved in or considering? Select all that apply.

- Material exchange (e.g. use of resource for its intrinsic property such as iron compounds or slag)
- Combustible (e.g. resource burnt to produce energy)
- Energy exchange (e.g. heat recovery)
- Shared utilities (e.g. water treatment, steam generation)
- Shared services (e.g. transportation, fire suppression)
- Co-ordination of resource exchanges
- Other (please specify)

6. Please specify the **resources** involved in your resource synergy initiatives.

7. How did the resource synergy initiative **start**?
   - Who initiated the resource synergy?
   - What problems did you try to solve with the resource synergy?

8. Who are the **actors** involved in the resource synergy?
   - Who is involved internally within the organisation (internal business units/roles)?
   - Who are your external partners?
   - How did you identify your external partners?
   - In what industries are your external partners?
   - What other stakeholders are affected (positively or negatively) by the resource synergy?

9. What **benefits** do the stakeholders derive from the resource synergy?
   - Economic benefits
   - Environmental benefits
   - Social benefits

10. How is the **business model** of the resource synergy defined?
    - In open negotiations with cost/benefit analyses clearly defined for the whole partner system.
    - In closed negotiations with separate value propositions for each partner.
    - Other (please specify)

11. How would you describe the **relationship** between the partners in the resource synergy?
    - Transactional
    - Contractual
    - Relational
    - Integrated
    - Other (please specify)

12. Who takes part in the **decision-making** for considering and/or adopting resource synergies and what is their role in the organisation?
    - Who was responsible for the decisions made (e.g. project manager)?
    - Who approved the decisions (e.g. CEO, finance director)?
    - Who was consulted about the decisions (e.g. business unit leaders)?
    - Who was informed about the decisions (e.g. HR department)?
    - What were the key decision-making criteria?

13. What **issues** make it difficult to take the decisions to adopt resource synergies? Select all that apply.
    - Many different stakeholders involved.
    - High levels of uncertainty about possible outcomes.
    - We did not have the information we needed.
    - It was difficult to define the scope of the decision.

- We did not have a standard decision-making process (such as a capital allocation process) that was suitable for evaluating the decision.
- Other issues (please specify)

14. What are the key **enablers** for implementing resource synergies?
    - Internal enablers (e.g. expertise among employees, investment in innovation, availability of capital)
    - External enablers (e.g. willing partners, incentives, external capacities)

15. What are the main **incentives** for developing and implementing resource synergies? Select all that apply.
    - Policy and regulatory frameworks (e.g. landfill taxes)
    - Industrial park regulation (Eco-Park)
    - Co-financing funds (by the state or other financing programmes)
    - Economic gains (value added, cost reduction, etc.)
    - Willing partners and/or intermediaries
    - Technical motivation
    - Other (please specify)

16. What are the **challenges** in implementing resource synergies, e.g. what is difficult, what failed?

17. What are the **barriers** that are preventing scaling up of resource synergies (i.e. what is preventing the partners from doing more of the existing exchanges or expanding to other resources and exchanges)?

18. Have you worked with **facilitating actors** to identify and implement resource synergies?
    - Yes
    - No

19. If yes, what organisations, entities or individuals were the key **intermediaries** that helped to identify and implement the resource synergies?

20. What has been the main **role** of the facilitating actors? Select all that apply.
    - Co-ordination
    - Facilitation
    - Convening
    - Provision of knowledge
    - Recycling of waste
    - Collection of waste
    - Other (please specify)

21. Did you have to **invest** in a new technology in order to implement the resource synergy? If yes, how much was your investment in the new technology?

22. What type of **technology** did you use to implement the resource synergy? Please provide details.
    - IT technology
    - Non-IT technology

23. Do you use specific **tools** to help with the identification and implementation of resource synergies? If yes, please specify.

24. What **other tools**, existing or not, would help you identify and implement resource synergies?

4.2 Analysis of survey responses

Seventeen respondents representing twelve sectors and eight countries participated in the expert enquiry. The results of the survey data analysis are presented below.

4.2.1 Industrial sectors of respondents

Participants in the survey represented 12 different sectors:

- Chemical industry - 2 respondents
- Scientific research - 4 respondents
- Industry R&D - 2 respondents
- Consultancy - 1 respondent
- Cement manufacturing - 1 respondent
- Software development - 1 respondent
- Biological solutions - 1 respondent
- Metal components and assembly - 1 respondent
- Plastic injection and mould manufacturing - 1 respondent
- Paint manufacturing - 1 respondent
- Water and waste water treatment - 1 respondent
- Cork composite solutions - 1 respondent

4.2.2 Geographical location of respondents

Respondents from 8 countries took part in the survey, as shown in Figure 3.

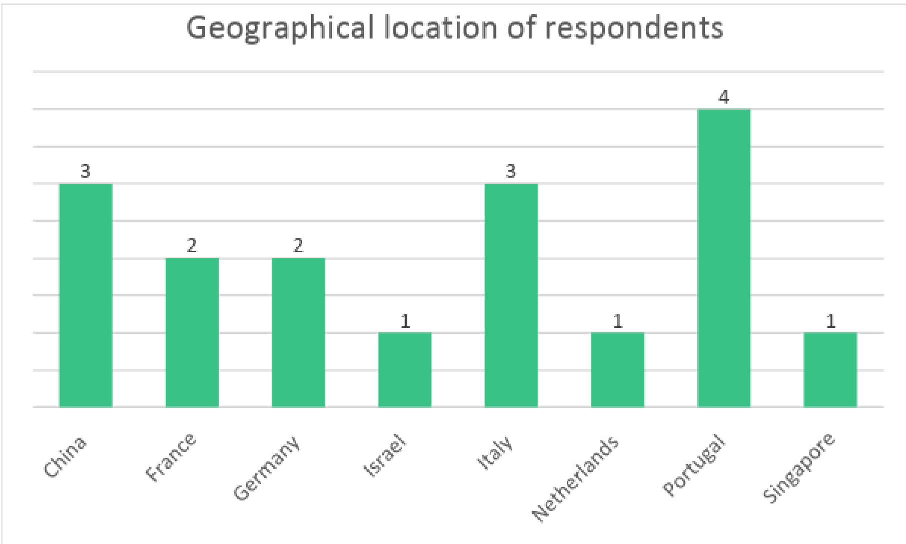

Figure 3 - Geographical representation of survey respondents

4.2.3 Industrial symbiosis maturity of respondents

Most survey participants in the survey have been involved in long-term resource synergies; 9 of the respondents have been involved in a long lasting resource synergy of 3+ years that could be considered normal business practice, 6 of the respondents have been involved in a developing synergy of 6 months to 3 years and only one respondent reported involvement in a new, emerging resource synergy (Figure 4). This level of IS maturity would suggest that the respondents bring significant expertise to the study.

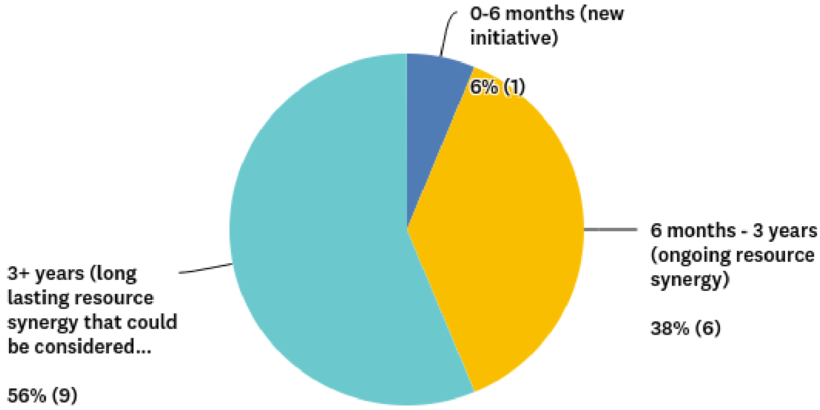

Figure 4 - IS maturity of respondents

4.2.4 Types of resource synergy initiatives

A variety of resource synergy initiatives were represented in the results with the highest number of survey respondents being involved in a form of material exchange.

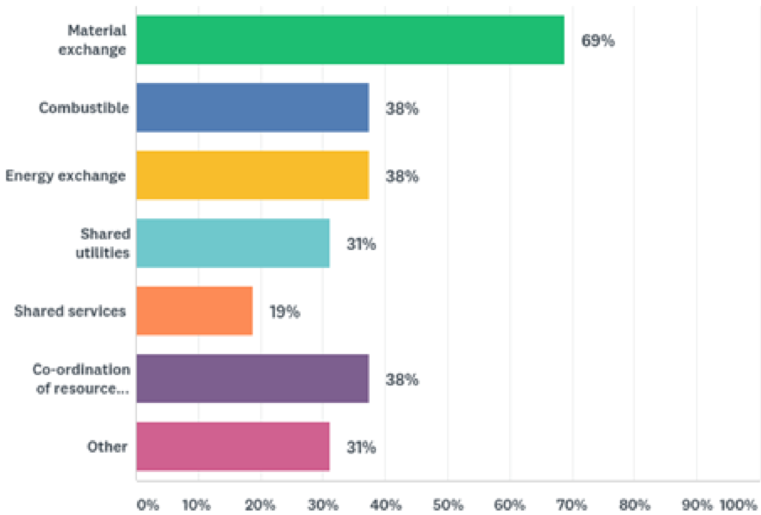

Figure 5 - Resource synergy initiatives

4.2.5 Triggers for resource synergy initiatives

We enquired about what triggers resource synergies by asking respondents about who had initiated the resource synergy and what kind of problems lead to the consideration and implementation of resource synergies. A summary of the triggers is presented below.

Initiating stakeholders. Most respondents suggested that they initiated their own resource synergy. They suggested that the focal firm in the IS, i.e. the one who offers their output as a resource, is the one who initiates the resource synergy. In fewer instances, a project partner or an intermediary, e.g. an environmental consulting firm or University research partner, was the initiating stakeholder.

The main factors that triggered resource synergies for the respondents included:

Economic pressures:

- Looking to increase the long-term profitability of the business in the understanding that the past usage pattern of raw materials and utilities is not sustainable.
- Increasing prices of resources.
- Looking to create new products and enter new markets.
- Looking to utilise secondary, i.e. low volume/low value, waste streams.
- Looking to improve load factor and sharing of costs.
- Looking to decrease operational costs.
- Looking to address a gap in production period of two resources.
- Looking to address the seasonality of resources (for "batch" resource types), e.g., for the agroindustrial sector.

Environmental pressures:

- Looking to reduce waste and increase utilisation of resources.
- Looking to address a lack of organic matter in the soil.

Regulatory pressures:

- Regional environmental protection policies and requirements for highly polluting industries.
- Legal, administrative and technical standards requirements.

4.2.6 Actors involved in resource synergies

The respondents gave information regarding actors involved in or affected by their resource synergies.

Internal actors: Quality Manager; Marketing Office; research and development units; researchers; raw material procurement department; Innovation and Production Department; current manufacturing clients; industrial association interested in the broader outcome; energy, chemicals and information technology experts; environmental specialist; logistics responsible for company environment; Supply Chain Management/Logistics Department; subsidiary companies.

External partners: Firms in other industries in various sectors, public (enabling) parties, NGOs, transportation company, institutional bodies, local agencies, project partners, financial partners, neighbouring companies including general manufacturing, retail and waste management/operator companies, landscape engineering company, foundries, companies from the fertilizer sector, farmers, cement and ceramic industries, recycling companies, transporters.

Finding external partners. Several approaches for finding external partners were suggested by respondents:

- On a regional scale: collaborating with large industries.
- By means of operative meetings with enterprises and other stakeholders in a specific territory over the development of several projects.
- Using existing project partnerships.
- Using knowledge of the territory and networking, e.g., industry roundtables.
- Checking the local services/market.
- Tasking the Department for Procurement of New Raw Materials with the search for new and different partners (using the internet, conferences and visits).

Other stakeholders affected (positively or negatively) by the resource synergies: Public parties (municipality, province, water board), NGOs, other local industries, agriculture, local public administration and controllers, government agencies, residents of nearby villages, customers of authorised waste handling agents (DIY superstores and warehouses).

4.2.7 Benefits for stakeholders from resource synergies

We enquired about the economic, environmental and social benefits that can be derived from the implementation of resource synergies. A summary of the responses is presented below. Multiple respondents suggested that benefits are difficult to quantify and that they vary depending on the distance between the companies involved in the resource synergies.

Table 2 - Stakeholder benefits

ECONOMIC BENEFITS	ENVIRONMENTAL BENEFITS	SOCIAL BENEFITS
More efficient use of materials and energy streams leading to lower overall costs. Less wasted resources. Lower waste management cost or no disposal cost. (Rather than the waste producer incurring disposal costs, with IS a waste management company can take on all the logistics costs. In some cases, the waste management company pays for the waste material; the waste product becomes an economic asset.) Reduced management costs for residues disposal and raw materials supply. Raw material sourced at a lower cost. Cost sharing.	Reduction or avoidance of raw materials consumption. Reduced consumption of energy. Reduced waste. Alternatives to raw materials. Address water scarcity and preserve organic matter. Reduced impacts of disposal residues and raw materials supply. Reduced pollution, including less emissions from incineration. Less transport leading to less fuel being required leading to lower CO2 emissions. Landfill is avoided. Largely reduced municipal garbage in nearby rural areas.	Less road occupation. Less pollution, leading to a better quality of life. Waste management improvements. (A waste management plan introduced for municipal garbage for nearby villages.) Low water services cost due to low operation costs. Residues can be valorised in the same territory in which the product is used and the raw materials are bought. New supply chains (residues treatment and transportation, for example) can provide new occupation and more jobs. Existing jobs maintained, and new jobs and employment created.

Company compliance with environmental protection policy (becomes an "environmental protection" enterprise) means production can continue. Highly efficient circular economy business development.	Can guarantee that the waste produced by industries is totally recovered and well treated. Align industry with sustainability and circular economy goals including reduction of CO2 emissions.	Cooperation of companies generating a positive vibe in a region. Catalysation of the circular economy.

4.2.8 Defining the business model of the resource synergy

In response to how the business model of the resource synergies was defined, most participants suggested that this occurs in closed negotiations with separate value propositions for each partner.

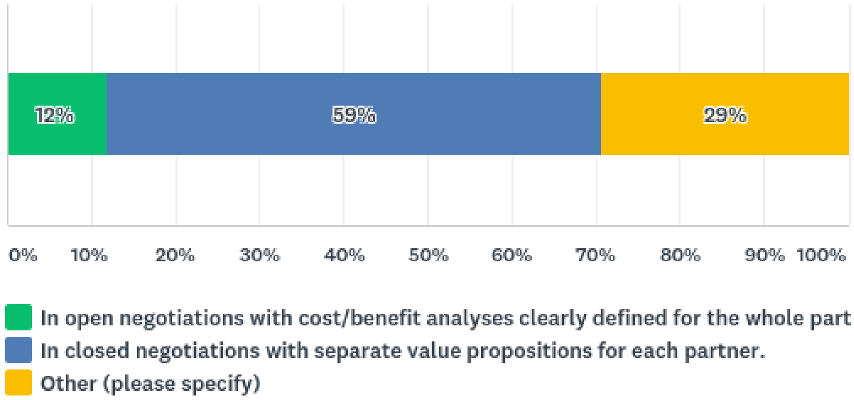

Figure 6 - Defining the business model of the resource synergy

4.2.9 Relationship between the partners in the resource synergy

The respondents to the survey have been involved in a spectrum of types of relationship with their resource synergy partners without a dominant type of relationships emerging. The suggested types of relationship included transactional, contractual, relational, integrated or a combination of several types of relationships.

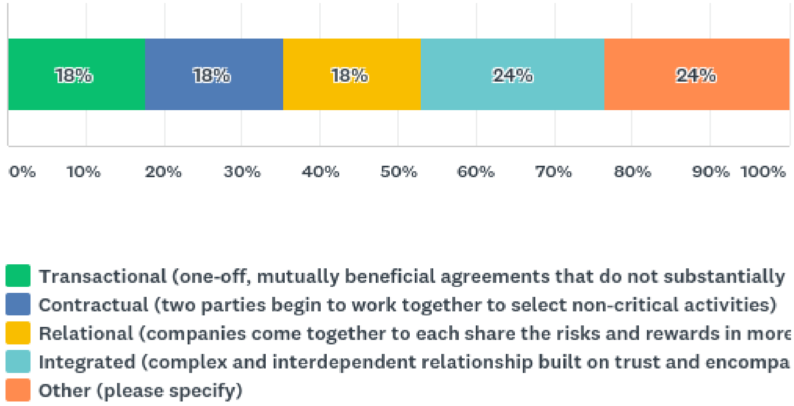

Figure 7 - Relationships between partners

4.2.10 Decision-makers for adopting resource synergies and their role in the organisation

The respondents identified a set of stakeholders who are involved in the decision-making for adopting resource synergies.

Responsible for decisions: CEO; board of directors of the company; R&D manager; Site Manager; Project Manager; Environmental Manager; Chief Sustainability Officer; Quality, Environment and Safety Director; Head of Supply Chain Management.

Approved decisions: C-suite, including CEO, CFO and COO; Site Director; financial and operational officers; environmental and safety global departments; board of directors of the company in terms of public contracting law.

Consulted about decisions: both local and business leaders, industrial directors, Logistics Director, production directors, logistics departments, haulier, project managers, research expert team, administration.

Informed about decisions: all relevant functions (broadly communicated through updates of sustainability goal programs), all employees, local government, environmental specialist executive board, The Maintenance Department, all organisation participants.

4.2.11 What were the key decision-making criteria?

Key **decision-making criteria** suggested by the respondents include:

- A sound business case with clearly outlined economic benefits.
- Impact on and alignment to organisational goals.
- Environmental criteria - generation of environmental benefits.
- Legal compliance - compliance with environmental protection policies.
- Operational feasibility considering waste composition and volumes.
- Reduction of costs of raw materials.
- Reduction of dependency on virgin material.

- Creation of new products.
- Reduction of gas consumption.
- Favourable results of proof vs. opportunity analysis.
- Sharing of resources and costs.

4.2.12 Difficulties for taking the decisions to adopt resource synergies?

The difficulty for taking decisions to adopt resource synergies that was most referred to was that many different stakeholders are involved in the process. This was followed by: high levels of uncertainty about possible outcomes, and, within the "other issues" category, high levels of uncertainty in the economic and environmental benefits related to the synergies, and uncertainty regarding legal regulations.

Figure 8 - Decision-making difficulties

4.2.13 Key enablers for implementing resource synergies

The respondents identified a set of internal and external factors that could enable the implementation of resource synergies, as described next.

4.2.13.1 Internal enablers

Expertise. This refers to the expertise among employees in IS domain knowledge as well as in areas that will facilitate the implementation of IS, such as, specialised expertise in traditional manufacturing processes, warehouse and transportation logistics, and data science.

Mindset. This refers to the drive of employees, their open-mindedness to change and freedom to act. A high level of trust and company support is required to foster this mindset.

Investment. This includes securing capital and development funds to allow for investments in innovation, expertise, operations and communication. A key enabler was investment in the development of a strong business case which outlines the economic, environmental and social advantages, and offers attractive pricing. In some instances, legislation might support the investment in innovation.

4.2.13.2 External enablers

Partners. Partners can include participating manufacturers, project partners external to the companies involved in the resource synergy, external environmental policy experts, industry-wide partners, public parties and regional government. Trust among partners is important. It is critical that partners and facilitators are motivated and willing to share targets.

Government. This refers to external pressures from government, regional support and incentives.

Market acceptance. This refers to the acceptance of the new products in the market and identifying end customers with interest in the final price.

4.2.14 Main incentives for developing and implementing resource synergies

The majority of respondents indicated that achieving economic gains is the main incentive for developing and implementing resource synergies. The second most important incentive appeared to be the existence of willing partners, followed by policy and regulatory frameworks, e.g., landfill taxes and obligatory CO_2 emissions reduction targets.

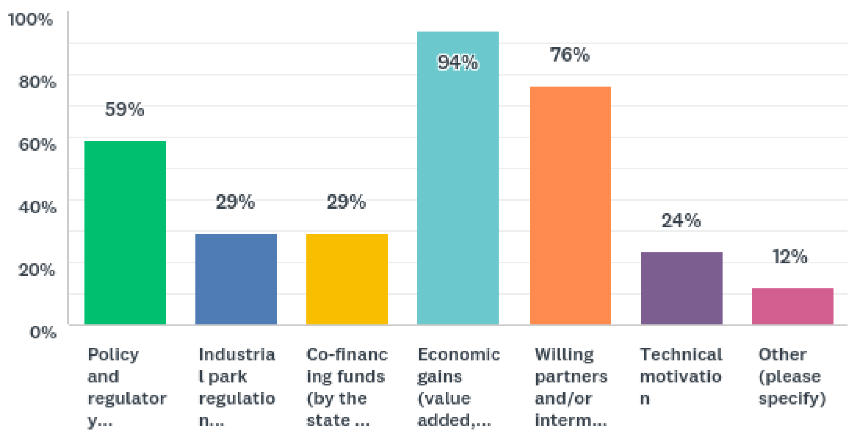

Figure 9 - Incentives

4.2.15 Challenges in implementing resource synergies

The respondents gave a set of challenges which hinder the implementation of resource synergies.

Challenges with partners. With multiple stakeholders involved, it is difficult to synchronise the decision-making due to the need to have all parties willing to decide and at the same levels of understanding and urgency all at the same point in time. Another challenge is the coordination of transporting goods among partners while assuring quality and quantity. It can be difficult to implement a definite way for "moving" the shared resource from one partner to another while meeting all the requirements that have to be fulfilled. Having access to and exchanging information is critical, otherwise value can be wasted. Accidents can happen if detailed information is not exchanged. Leadership from both sides is critical to enable resource synergies due to the way leadership affects negotiations. It can be hard to justify a difficult separation by material grade within each material type, since it is hard to match this with strong interest from a potential buyer. In some cases, there has been hesitation due to a lack of anonymity in many of the exchanges.

Technical challenges. Examples of technical challenges were complex logistics, ingrained existing methods of dealing with waste (e.g. food waste), lack of know-how and a high degree of uncertainty about the outcome. New processes present technical challenges as they first have to be proven that they work by research and analysis. In some cases, material exchanges have failed due to a low volume and low value of transactions, due to the complexity of recording waste streams at a granular level and matching this with granular solutions. In other cases, insufficient processing capacity and resource backlog presented challenges. Variability and uncertainty in quantities of materials were other challenges.

Regulatory challenges. Respondents suggested that in some instances waste management is not in compliance with the environmental regulations present. In some cases, it is not possible to obtain government subsidies regarding waste management of rural household waste so the business investment required can be too high. It was suggested that some legal changes in the regulatory framework are required, e.g., definitions of waste. In one instance, the law would not allow the resource synergy, so the business had to work with government employees to resolve the challenge.

Public perception. One respondent referred to public opinion being very important in terms of safety and the safe use of alternative materials in food production. Another respondent suggested that it is difficult for some in agriculture to understand the value of treated water. Others referred to a general negative public perception about certain materials.

4.2.16 Barriers preventing scaling up of resource synergies

The respondents identified a set of barriers that could prevent scaling up resource synergies.

Cost barriers. These included costs related to infrastructure, logistics and transportation distances between potential cooperating partners.

Uncertainties. These regarded new requirements, needs and regulations.

Regulatory barriers. These related to existing regulatory frameworks, de-regulation, and legal updates for new requirements, as well as issues of confidentiality.

Lack of incentives. Lack of incentives for increasing the scale of operation, e.g., where small foundries are required to pay more for special scrap metal grades.

Regional barriers. These are related to regional issues such as different policies in different regions or the environmental protection requirements of a country or region.

Limitations of the business. These include the company's current production scale, the company's current technological level and receiving capacity, limitations of industrial processes themselves, and difficulties in finding new sources of specific raw materials or finding raw materials at competitive costs.

Information platform. The lack of a truly efficient, anonymous and intelligent information platform.

4.2.17 Concluding remarks

This chapter has presented the analysis and synthesis of the responses from seventeen participants in the international expert enquiry on IS as part of the SCALER WP2 on identifying pathways to foster resource synergies. This is the third evidence component in this report for the identification of best practices in IS.

The next chapter reports on the findings of the focus group from the workshop organised by the authors where the results from the three previous evidence components were discussed for the purpose of refinement and validation, allowing triangulation of results.

5. Focus group

A one-day SCALER focus group with IS experts from industry and academia was held in the format of an interactive workshop on the 19th of June 2018 at the Institute for Manufacturing, University of Cambridge, Cambridge, UK. The objective of the focus group event was to refine and validate the results to date from the three previous evidence components: the literature review, the case studies analysis and the expert enquiry. The following attendees were present at the event:

- ISQ - Cristina Ascenço and Marco Estrela
- DECHEMA - Christina Jungfer
- Strane Innovation - Stéphane Ogé
- Knowledge Transfer Network (KTN) - Lampros Litos
- University of Helsinki - Dr Markku Anttonen and Dr Minna Lammi
- Aguas de Portugal - Nuno Brôco (Skype)
- Tenova - Enrico Malfa (Skype)
- JRC - Carla Caldeira (Skype)
- University of Cambridge - Professor Steve Evans, Dr Doroteya Vladimirova, Dr Karen Miller, Dr Curie Park, Dr Yuan Tao, Dr Daniel Summerbell and Hanmin Huang

5.1 Workshop design

The workshop began with a brief introduction before the results of the case studies review were presented by Dr Karen Miller. The aim of the case studies review evidence component (presented in chapter 3) was to analyse and synthesise twenty-five published case studies to generate a rich picture and determine the triggers, enablers and barriers in regard to the implementation of IS. Dr Yuan Tao then provided the literature review (presented in chapter 2) update. This literature review gathered secondary data and insights in order to understand the state of the art within the field of IS. Subsequently, Dr Doroteya Vladimirova described the interim results from the expert enquiry on IS (presented in chapter 4). The enquiry was designed to elicit responses from practitioners to enrich our understanding of IS and help triangulate the findings from the case studies review and literature review.

The second part of the day was a session that was undertaken by all attendees. The attendees were split into three groups and each group was facilitated by one of the Cambridge team working on SCALER. The objective of the session was to help refine and validate the findings presented earlier in the day.

Each group was asked to undertake the following three tasks:

1. Provide three recommendations to firms wanting to implement industrial symbiosis — what do firms need to do in order to implement and scale up industrial symbiosis?
2. Provide three research questions to academics wanting to advance the field of industrial symbiosis — what are the three key research gaps in knowledge about how to implement and scale up industrial symbiosis?
3. Provide three recommendations to policy-makers in order to drive the implementation and scale up of industrial symbiosis — what are the three key policy interventions that will provide a support framework in order to drive the implementation and scale up of industrial symbiosis?

Each group then fed back the results, given below, to the whole group of attendees.

5.2 Workshop results

5.2.1 Task 1: What do firms need to do in order to implement and scale up industrial symbiosis?

Group 1

- Identify alternative sources of input raw materials/energy and find internal/external users for waste outputs.
- Investigate/invest in new business models/markets/innovations that underpin IS systems.
- Recognise that change management is needed in order to identify/drive IS opportunities. Ascertain what is a resource, what is waste, how waste is classified and who will manage this.

Group 2

- Identify the value of waste and implement shift. Consider mass flows/content (trust data)/market value.
- Need to find customer/partner to sell product (show value)/determine processing requirements.
- Exploit economy of scale — work with competitors for mutual advantage.
- Determine supply/demand balance — scale of demand/stability/logistics/transport/storage/reaction of market to changes in supply and demand.
- Start with the question: “What would it take to make it viable/valuable?”

Group 3

- Make waste visible by monitoring in detail using digitalisation (quantitative and qualitative) and avoid using the term ‘waste’.
- Find customers by shifting internal cultures that are deeply embedded in old ways of working (nurture a thinking-hard culture).
- Map existing business case and then invest in building/modelling of new business case, taking into consideration internal/external resources and capabilities (materials, time, human, finance etc.).

5.2.2 Task 2: What are the three key research gaps in knowledge about how to implement and scale up industrial symbiosis?

Group 1

- How can effective policy be formulated to ensure IS becomes the default position?
- Develop a way to understand product/waste ratio. (Technical challenges are significant.)
- How can the design aspect of an IS system be optimised?
- Develop a transparent and open simple database.

Group 2

- Business wants ready-made solutions, e.g. waste company pays £5/ton for 200g — therefore technical studies should be top priority:
    - How to extract value.
    - Is the new use technically viable?
    - Can we design for reuse/circularity?
    - Economics of particular market.
- Develop a database that puts value on waste or yield which leads to systemic flow evaluation.

Group 3

- What are the types and levels of detail in information that companies need in order to make a decision to transform, i.e., costs/benefits/risks?
- How to establish a new type of relationship with intermediary bodies etc.
- How to value intensify at the intra-firm level — intrapreneur/process optimisation and how to move from intra-firm level value addition to inter-firm value addition.

Within this task a research initiative emerged outside of the group responses which is worth noting:

- What is the IS hierarchy that embraces both narrow and wider definitions?

5.2.3 Task 3: What are the three key policy interventions that will provide a support framework in order to drive the implementation and scale up of industrial symbiosis?

Group 1

- Reduce complexity of regulations.
- Increase percentage of items that can be reclassified as non-waste.
- Policy is currently focusing on waste, are there other areas that would be important to focus on?
- Offer a secure transactional environment for industry.

Group 2

- Increase economic value by providing rebate for customers of companies that use high percentage of exchanged materials (exploit consumer responses, e.g. as plastic bag scenario, and drive firm behaviours).
- Reduce regulatory barriers — increase two-way communication on impact of regulations on IS and create conditions to increase speed of response.
- Special case exemptions for pilot projects.
- Encourage cooperation using a voluntary approach with backstop of tax/regulation to drive IS activities.

Group 3

- For low-cost labour countries, help the informal/low-tech waste management sector upgrade from generating commodity with waste to higher value generation by providing mechanisms to identify appropriate customers.
- Make the “waste” information more transparent and publicly available for industry and policy-makers to create market movement.
- Provide a stable climate and reduce regulatory barriers.

5.2.4 Concluding remarks

In summary, we gathered evidence by means of four components. We conducted a systematic literature review of IS literature from 2016 to 2018. We selected twenty-five case studies and performed a thematic analysis for best practices in IS. We designed and launched an international expert enquiry on IS, and analysed and synthesised the responses from seventeen participants. Finally, we organised and hosted a focus group to refine and validate our findings in order to create a robust evidence base as part of the SCALER WP2 on identifying pathways to foster resource synergies.

In the next chapter, we outline our first set of recommendations for industry practice, academic research and policy based on our findings.

6. Recommendations

We have gathered and analysed ample evidence that scaling up IS is a complex endeavour, requiring a coordinated effort among multiple public and private stakeholders. In this chapter, we outline a set of recommendations for industry practitioners, academics and researchers, and policy-makers involved in IS.

6.1 Recommendations for business practice

Our recommendations to the business community involved in or considering IS are the following:

1. **Leadership.** There must be strong leadership and commitment from top management in order to shift organisational/corporate mindsets away from the current unsustainable paradigm towards IS.

2. **Long-term commitment.** It is vital to underpin IS with a long-term strategy in order for even modest economic, social and environmental benefits to be realised. At the outset synergistic initiatives need to be small scale to build capability, capacity and most importantly confidence before attempting bolder steps.

3. **Internal organisational IS structure.** A dedicated organisational function to explore and drive synergistic opportunities is required. This will deliver more rapid progress than project-based assignments that are typically given to individuals, often in addition to them undertaking ongoing business as usual commitments.

6.2 Recommendations for research

Our recommendations to the academic and research community are the following:

1. **Cross-disciplinary research.** The academic field of IS can be described as multi-disciplinary and mature. However, we would recommend that more cross-disciplinary studies are designed and carried out in order to enable a more robust foundation for wider adoption of IS practices. Such cross-disciplinary studies would need to bring insights from disciplines outside industrial ecology and IS in order to cross-pollinate the field with external knowledge. This will enable the development of a more robust theoretical foundation, advance the debate and, overall, extend the IS field.

2. **Multi-stakeholder engagement in IS research.** Recognising the complexity of the IS field, the academic and research community needs to conduct research in close collaboration with industry and policy stakeholders. This will enable sharing of knowledge among stakeholders and will allow for creation of new knowledge in a collaborative way whereby each stakeholder is encouraged into an early buy-in into the potential solutions.

3. **Practice-oriented research.** We would recommend that research is designed to solve real world problems from the IS field and generate insights with direct high utility for business practice. In our systematic literature review, we discovered a substantial quantity of modelling studies. In our view, this type of research is valuable on the micro level of the individual resource synergies, whereas more studies relevant to the meso-level (company and network) and macro-level (regional, national, EU) are required in order to allow for a systematic adoption of IS practice on a large scale.

6.3 Recommendations for policy

In relation to policy we recommend the following:

1. **Standardisation.** There is an acute need for standardisation across Europe, similar to the approach taken for foods. This will allow stakeholders at all levels to develop a shared understanding. Currently, there is a multiplicity of approaches, terminologies, measurements, standards, etc., which create confusion rather than clarity. We believe standardisation will allow for accurate benchmarking and target setting.

2. **Investment.** Our second recommendation is to have a concerted and enduring effort to support IS through direct EU and national and regional government investment in IS. It became evident

through our research that this is a pivotal enabler in starting networks and supporting the expansion of existing networks.

3. **Metrics and targets.** In addition, we recommend that metrics be devised and targets be set to allow direct and measurable links to be made between IS and higher productivity, while simultaneously reducing environmental impacts.

7. Next steps

For this report, we developed and presented four comprehensive evidence components based on a systematic literature review, twenty-five case studies, an expert enquiry and a focus group. Using each one of these components, we considered a wide range of best practices for IS and thus identified a set of recommendations for its scale up.

Our next steps following this report include planning a public outreach activity in the form of a webinar to share our key findings and recommendations with business practitioners and policy-makers.

In the forthcoming deliverable D2.2 of WP2, we will look into enabling technologies and key intermediaries for IS.

The four evidence components presented in this report lay the foundation for D2.2, D2.3 and D2.4 in WP2 as well as informing individual tasks in WP3 and WP4 of the SCALER project.

References

Adamides, E.D. and Mouzakitis, Y. (2009) Industrial ecosystems as technological niches, *Journal of Cleaner Production*, 17(2), pp.172-180. doi:10.1016/j.jclepro.2008.04.003.

Afshari, H., Jaber, M. Y. and Searcy, C. (2018) 'Extending industrial symbiosis to residential buildings: A mathematical model and case study', *Journal of Cleaner Production*. 183, pp. 370–379. doi: 10.1016/j.jclepro.2018.02.148.

Aid, G., Eklund, M. Anderberg, S. and Baas, L. (2017) 'Expanding roles for the Swedish waste management sector in inter-organizational resource management', *Resources, Conservation and Recycling*, 124(May), pp. 85–97. doi: 10.1016/j.resconrec.2017.04.007.

Albino, V., Fraccascia, L. and Giannoccaro, I. (2016) 'Exploring the role of contracts to support the emergence of self-organized industrial symbiosis networks: An agent-based simulation study', *Journal of Cleaner Production*. 112, pp. 4353–4366. doi: 10.1016/j.jclepro.2015.06.070.

Álvarez, R. and Ruiz-Puente, C. (2017) 'Development of the Tool SymbioSyS to Support the Transition Towards a Circular Economy Based on Industrial Symbiosis Strategies', *Waste and Biomass Valorization*, 8(5), pp. 1521–1530. doi: 10.1007/s12649-016-9748-1.

Ashton, W. S., Chopra, S. S. and Kashyap, R. (2017) 'Life and death of industrial ecosystems', *Sustainability (Switzerland)*, 9(4), pp. 1–15. doi: 10.3390/su9040605.

Atkins, M. J., Walmsley, M. R. W. and Walmsley, T. G. (2016) 'Integration of new processes and geothermal heat into a wood processing cluster', *Clean Technologies and Environmental Policy*. Springer Berlin Heidelberg, 18(7), pp. 2077–2085. doi: 10.1007/s10098-016-1171-6.

Bacudio, L. R., Benjamin, M.F.D., Eusebio, R.C.P., Holaysan, S.A.K., Promentilla, M.A.B., Yue, K.D.S. and Aviso, K.B. (2016) 'Analyzing barriers to implementing industrial symbiosis networks using DEMATEL', *Sustainable Production and Consumption*, (7), pp. 57–65. doi: 10.1016/j.spc.2016.03.001.

Baptista, A. J., Lourençoa, E.J., Silva, E.J., Estrela, M.A. and Peçasc, P. (2018) 'MAESTRI Efficiency Framework: The concept supporting the Total Efficiency Index. Application case study in the metalworking sector', *Procedia CIRP*. 69(May), pp. 318–323. doi: 10.1016/j.procir.2017.11.119.

Bellantuono, N., Carbonara, N. and Pontrandolfo, P. (2017) 'The organization of eco-industrial parks and their sustainable practices', *Journal of Cleaner Production*. 161, pp. 362–375. doi: 10.1016/j.jclepro.2017.05.082.

Boons, F., Chertow, M., Park, J., Spekkink, W. and Shi, H. (2017) 'Industrial Symbiosis Dynamics and the Problem of Equivalence: Proposal for a Comparative Framework', *Journal of Industrial Ecology*, 21(4), pp. 938–952. doi: 10.1111/jiec.12468.

Branson, R. (2016) 'Re-constructing Kalundborg: The reality of bilateral symbiosis and other insights', *Journal of Cleaner Production*. 112, pp. 4344–4352. doi: 10.1016/j.jclepro.2015.07.069.

van Capelleveen, G., Amrit, C. and Yazan, D.M. (2018) A Literature Survey of Information Systems Facilitating the Identification of Industrial Symbiosis, *From science to society, Springer International Publishing*, Cham, pp. 155-169 https://doi.org/10.1007/978-3-319-65687-8_14.

Ceglia, D., Abreu, M. C. S. and Da Silva Filho, J. C. L. (2017) 'Critical elements for eco-retrofitting a conventional industrial park: Social barriers to be overcome', *Journal of Environmental Management*, 187, pp. 375–383. doi: 10.1016/j.jenvman.2016.10.064.

Celander, F., Enquist, R., Friman, K., Karlsson, P., Lundqvist, E., Persson, A., Rudolfsson, E., Sterne, A., Svanström, L. and Öhnerud, M, (2013) Industrial Symbiosis in Helsingborg. Available at: http://www.industriellekologi.se/documents/Helsingborg.pdf.

Costa, I. and Ferrão, P. (2010) A case study of industrial symbiosis development using a middle-out approach, *Journal of Cleaner Production*, 18, pp. 984-992. doi:10.1016/j.jclepro.2010.03.007.

Daddi, T., Iraldo, F., Frey, M., Gallo, P. and Gianfrate, V. (2016) 'Regional policies and eco-industrial development: The voluntary environmental certification scheme of the eco-industrial parks in Tuscany (Italy)', *Journal of Cleaner Production*. 114, pp. 62–70. doi: 10.1016/j.jclepro.2015.04.060.

Dall'Ara, A., Billi, L., La Peruta, M.T., Cepparrone, A. and Roig, M. (2015) PODEBA: An Industrial Symbiosis Case. Available at: http://www.enea.it/it/seguici/pubblicazioni/pdfvolumi/ExperiencesofIndustrialSymbiosisinItaly_Proceedings.pdf.

Desrochers, P. and Szurmak, J. (2017) 'Long distance trade, locational dynamics and by-product development: Insights from the history of the American cottonseed industry', *Sustainability (Switzerland)*, 9(4). doi: 10.3390/su9040579.

Dias, G.M., Ayer, N.W., Khosla, S., van Acker, R., Yung, S.B., Whitney, S. and Hendricks, P. (2017) 'Life cycle perspectives on the sustainability of Ontario greenhouse tomato production: Benchmarking and improvement opportunities', *Journal of Cleaner Production*. 140, pp. 831–839. doi: 10.1016/j.jclepro.2016.06.039.

Dong, L., Fujita, T., Zhang, H., Dai, M., Fujii, M., Ohnishi, S., Geng, Y. and Liu, Z. (2013) Promoting low-carbon city through industrial symbiosis: A case in China by applying HPIMO model, *Energy Policy,* 61, pp. 864–873. doi.org/10.1016/j.enpol.2013.06.084.

Dong, L., Liang, H., Zhang, L., Liu, Z., Gao, Z. and Hu, M. (2017) 'Highlighting regional eco-industrial development: Life cycle benefits of an urban industrial symbiosis and implications in China', *Ecological Modelling*. 361, pp. 164–176. doi: 10.1016/j.ecolmodel.2017.07.032.

Dong, L., Wang, Y., Scipioni, A., Park, H.S. and Ren, J. (2018) 'Recent progress on innovative urban infrastructures system towards sustainable resource management', *Resources, Conservation and Recycling*, 128, pp. 355–359. doi: 10.1016/j.resconrec.2017.02.020.

van Ewijk, S., Park, J.Y. and Chertow, M.R. (2018) 'Quantifying the system-wide recovery potential of waste in the global paper life cycle', *Resources, Conservation and Recycling*. 134(November 2017), pp. 48–60. doi: 10.1016/j.resconrec.2018.02.026.

Felicio, M., Amaral, D., Esposto, K. and Durany, X.G. (2016) 'Industrial symbiosis indicators to manage eco-industrial parks as dynamic systems', *Journal of Cleaner Production*, 118, pp. 54–64. doi: 10.1016/j.jclepro.2016.01.031.

Freitas, L.A.R.U. and Magrini, A. (2017) 'Waste management in industrial construction: Investigating contributions from industrial ecology', *Sustainability (Switzerland)*, 9(7), pp. 6–8. doi: 10.3390/su9071251.

Gabriel, M., Schöggl, J.P. and Posch, A. (2017) 'Early front-end innovation decisions for self-organized industrial symbiosis dynamics: A case study on lignin utilization', *Sustainability (Switzerland)*, 9(4). doi: 10.3390/su9040515.

Ghali, M.R., Frayret, J.M. and Robert, J.M. (2016) 'Green social networking: Concept and potential applications to initiate industrial synergies', *Journal of Cleaner Production*. 115, pp. 23–35. doi: 10.1016/j.jclepro.2015.12.028.

Guo, B., Geng, Y., Sterr, T., Dong, L. and Liu, Y. (2016) 'Evaluation of promoting industrial symbiosis in a chemical industrial park: A case of Midong', *Journal of Cleaner Production*. 135(800), pp. 995–1008. doi: 10.1016/j.jclepro.2016.07.006.

Hashimoto, S., Fujita, T., Geng, Y. and Nagasawa, E. (2010) Realizing CO2 emission reduction through industrial symbiosis: A cement production case study for Kawasaki. *Resources, Conservation and Recycling.* (54), pp.704–710. **doi**:10.1016/j.envpol.2010.10.022.

Hodgson, E., Ruiz-Molina, M.E., Marazza, D., Pogrebnyakova, E., Burns, C., Higson, A., Rehberger, M., Hiete, M., Gyalai-Korpos, M., Lucia, L.D. and Noël, Y. (2016) 'Horizon scanning the European bio- based economy: a novel approach to the identification of barriers and key policy interventions from stakeholders in multiple sectors and regions', *Biofpr: Biofuels, Bioproducts & Biorefining*, 10, 508–522. doi.org/10.1002/bbb.1665.

Holgado, M., Benedetti, M., Evans, S., Baptista, A.J. and Lourenço, E.J. (2018) 'Industrial Symbiosis Implementation by Leveraging on Process Efficiency Methodologies', *Procedia CIRP*. 69, pp. 872–877. doi: 10.1016/j.procir.2017.11.078.

Horváth, G. Á. and Harazin, P. (2016) 'A framework for an industrial ecological decision support system to foster partnerships between businesses and governments for sustainable development', *Journal of Cleaner Production*, 114, pp. 214–223. doi: 10.1016/j.jclepro.2015.05.018.

Hu, Y., Lin, J., Cui, S. and Khanna, N.Z. (2016) 'Measuring Urban Carbon Footprint from Carbon Flows in the Global Supply Chain', *Environmental Science and Technology*, 50(12), pp. 6154–6163. doi: 10.1021/acs.est.6b00985.

Hu, Y., Wen, Z., Lee, J.C. and Luo, E. (2017) 'Assessing resource productivity for industrial parks using adjusted raw material consumption (ARMC)', *Resources, Conservation and Recycling*. 124(December 2016), pp. 42–49. doi: 10.1016/j.resconrec.2017.04.009.

Huang, B., Jiang, P., Wang, S., Zhao, J. and Wu, L. (2016) 'Low carbon innovation and practice in Caohejing High-Tech Industrial Park of Shanghai', *International Journal of Production Economics*. 181, pp. 367–373. doi: 10.1016/j.ijpe.2016.02.006.

Husgafvel, R., Karjalainen, E., Linkosalmi, L. and Dahl, O. (2016) 'Recycling industrial residue streams into a potential new symbiosis product – The case of soil amelioration granules', *Journal of Cleaner Production*. 135, pp. 90–96. doi: 10.1016/j.jclepro.2016.06.092.

Iacobescu, R.I., Angelopoulos, G.N., Jones, P.T., Blanpain, B. and Pontikes, Y. (2016) 'Ladle metallurgy stainless steel slag as a raw material in Ordinary Portland Cement production: A possibility for industrial symbiosis', *Journal of Cleaner Production*. 112, pp. 872–881. doi: 10.1016/j.jclepro.2015.06.006.

Invest Northern Ireland (n.d.) Industrial Symbiosis: Improving productivity through efficient resource management. Available at: https://secure.investni.com/static/library/invest-ni/documents/industrial-symbiosis-guide-for-businesses-in-northern-ireland.pdf.

Jensen, P. D. (2016) 'The role of geospatial industrial diversity in the facilitation of regional industrial symbiosis', *Resources, Conservation and Recycling*. 107, pp. 92–103. doi: 10.1016/j.resconrec.2015.11.018.

Jiao, W., Boons, F., Teisman, G. and Li, C. (2018) 'Durable policy facilitation of Sustainable Industrial Parks in China: A perspective of co-evolution of policy processes', *Journal of Cleaner Production*. doi: 10.1016/j.jclepro.2018.04.226.

Karner, K., Theissing, M. and Kienberger, T. (2017) 'Modeling of energy efficiency increase of urban areas through synergies with industries', *Energy*. 136, pp. 201–209. doi:10.1016/j.energy.2015.12.139.

Kim, H.W., Dong, L., Choi, A.E.S., Fujii, M., Fujita, T. and Park, H.S. (2018) 'Co-benefit potential of industrial and urban symbiosis using waste heat from industrial park in Ulsan, Korea', *Resources, Conservation and Recycling*. 135 (August), pp. 225–234. doi: 10.1016/j.resconrec.2017.09.027.

Kuznetsova, E., Louhichi, R., Zio, E. and Farel, R. (2017) 'Input-output Inoperability Model for the risk analysis of eco-industrial parks', *Journal of Cleaner Production*. 164, pp. 779–792. doi: 10.1016/j.jclepro.2017.06.250.

Laybourn, P. (2013) Opportunities through Industrial Symbiosis: UK NISP and Global Experience Available at: http://www.endustriyelsimbiyoz.org/wp-content/uploads/2013/02/industrial-symbiosis_uk-nisp-and-global-experience_31.01.2013.pdf.

Leong, Y.T., Lee, J.Y., Tan, R.R., Foo, J.J. and Chew, I.M.L. (2017) 'Multi-objective optimization for resource network synthesis in eco-industrial parks using an integrated analytic hierarchy process', *Journal of Cleaner Production*. 143, pp. 1268–1283. doi: 10.1016/j.jclepro.2016.11.147.

Leurent, M., Da Costa, P., Sylvestre, S., Berthelemy, M. (2018) 'Feasibility assessment of the use of steam sourced from nuclear plants for French factories considering spatial configuration', *Journal of Cleaner Production,* 189, pp. 529-538.

Li, B., Xiang, P., Hu, M., Zhang, C. and Dong, L. (2017) 'The vulnerability of industrial symbiosis: A case study of Qijiang Industrial Park, China', *Journal of Cleaner Production*, 157, pp. 267–277. doi: 10.1016/j.jclepro.2017.04.087.

Liu, G., Hao, Y., Zhou, Y., Yang, Z., Zhang, Y. and Su, M. (2016) 'China's low-carbon industrial transformation assessment based on Logarithmic Mean Divisia Index model', *Resources, Conservation and Recycling*. 108, pp. 156–170. doi: 10.1016/j.resconrec.2016.02.002.

Liu, Z., Adams, M., Cote, R.P., Geng, Y., Chen, Q., Liu, W., Sun, L. and Yu, X. (2017) 'Comprehensive development of industrial symbiosis for the response of greenhouse gases emission mitigation: Challenges and opportunities in China', *Energy Policy*. 102, pp. 88–95. doi: 10.1016/j.enpol.2016.12.013.

Liu, Z., Adams, M., Cote, R.P., Geng, Y., Ren, J., Chen, Q., Liu, W. and Zhu, X. (2018b) 'Co-benefits accounting for the implementation of eco-industrial development strategies in the scale of industrial park based on emergy analysis', *Renewable and Sustainable Energy Reviews*. 81(June 2017), pp. 1522–1529. doi: 10.1016/j.rser.2017.05.226.

Liu, Z., Adams, M., Cote, R. P., Geng, Y. and Li, Y. (2018a) 'Comparative study on the pathways of industrial parks towards sustainable development between China and Canada', *Resources, Conservation and Recycling*. 128, pp. 417–425. doi: 10.1016/j.resconrec.2016.06.012.

Low, J.S.C., Tjandra, T.B., Yunus, F., Chung, S.Y., Tan, D.Z.L., Raabe, B., Ting, N.Y., Yeo, Z., Bressan, S., Ramakrishna, S. and Herrmann, C. (2018) 'A Collaboration Platform for Enabling Industrial Symbiosis: Application of the Database Engine for Waste-to-Resource Matching', *25th CIRP Life Cycle Engineering (LCE) Conference*. 69, pp. 849–854. doi: 10.1016/j.procir.2017.11.075.

Maillé, M. and Frayret, J.M. (2016) 'Industrial Waste Reuse and By-product Synergy Optimization', *Journal of Industrial Ecology*, 20(6), pp. 1284–1294. doi: 10.1111/jiec.12403.

Marchi, B., Zanoni, S. and Pasetti, M. (2018) 'Industrial symbiosis for greener horticulture practices: the CO 2 enrichment from energy intensive industrial processes', *Procedia CIRP*. 69(May), pp. 562–567. doi: 10.1016/j.procir.2017.11.117.

Marconi, M., Gregori, F., Germani, M., Papetti, A. and Favi, C. (2018) 'An approach to favor industrial symbiosis: the case of waste electrical and electronic equipment', *Procedia Manufacturing*. 21, pp. 502–509. doi: 10.1016/j.promfg.2018.02.150.

Martin, M. (2015) Quantifying the environmental performance of an industrial symbiosis network of biofuel producers, *Journal of Cleaner Production*. 102, pp.202-212. doi: 10.1016/j.jclepro.2015.04.063.

Mathiassen, L. (2017) 'Designing Engaged Scholarship: From Real-World Problems to Research Publications', *Engaged Management Review.* 1(1), pp.17-28. doi.org/10.28953/2375-8643.1000.

Mathews, J.A and Tan, H. (2011) Progress toward a circular economy in China: The drivers (and inhibitors) of eco-industrial initiative, *Journal of Industrial Ecology.* 15 (3), pp. 435-457. doi: 10.1111/j.1530-9290.2011.00332.

Merli, R., Preziosi, M. and Acampora, A. (2018) 'How do scholars approach the circular economy? A systematic literature review', *Journal of Cleaner Production*. 178, pp. 703–722. doi: 10.1016/j.jclepro.2017.12.112.

Mirata, M. (2004) Experiences fromearly stages of a national industrial symbiosis programme in the UK: Determinants and coordination challenges, Journal of Cleaner Production 12, pp.967–983. doi:10.1016/j.jclepro.2004.02.031.

Mulrow, J.S., Derrible, S., Ashton, W.S. and Chopra, S.S. (2017) 'Industrial Symbiosis at the Facility Scale', *Journal of Industrial Ecology*, 21(3), pp. 559–571. doi: 10.1111/jiec.12592.

Notarnicola, B., Tassielli, G. and Renzulli, P.A. (2016) 'Industrial symbiosis in the Taranto industrial district: Current level, constraints and potential new synergies', *Journal of Cleaner Production*. 122, pp. 133–143. doi: 10.1016/j.jclepro.2016.02.056.

Ohnishi, S., Dong, H., Geng, Y., Fujii, M. and Fujita, T. (2017) 'A comprehensive evaluation on industrial & urban symbiosis by combining MFA, carbon footprint and emergy methods - Case of Kawasaki, Japan', *Ecological Indicators*. 73, pp. 315–324. doi: 10.1016/j.ecolind.2016.10.016.

Organisation for Responsible Business. (n.d.) NISP. Available at: http://www.orbuk.org.uk/article/the-national-industrial-symbiosis-programme-nisp.

Pan, M., Sikorski, J., Akroyd, J. W., Mosbach, S., Lau, R., and Kraft, M. (2016) 'Design technologies for eco-industrial parks: From unit operations to processes, plants and industrial networks', *Applied Energy*. 175, pp. 305–323. doi: 10.1016/j.apenergy.2016.05.019.

Park, J.M., Park, J.Y. and Park, H.S. (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, pp. 33–44. doi: 10.1016/j.jclepro.2015.08.115.

Patricio, J., Angelis-Dimakis, A., Castillo-Castillo, A., Kalmykova, Y. and Rosado, L. (2017) 'Method to identify opportunities for CCU at regional level - Matching sources and receivers', *Journal of CO2 Utilization*, 22, pp. 330–345. doi: 10.1016/j.jcou.2017.10.009.

Prosman, E.J., Wæhrens, B.V. and Liotta, G. (2017) 'Closing Global Material Loops: Initial Insights into Firm-Level Challenges', *Journal of Industrial Ecology*, 21(3), pp. 641–650. doi: 10.1111/jiec.12535.

Raabe, B., Low, J.S.C., Juraschek, M., Herrmann, C., Tjandra, T.B., Ng, Y.T., Kurle, D., Cerdas, F., Lueckenga, J., Yeo, Z. and Tan, Y.S. (2017) 'Collaboration Platform for Enabling Industrial Symbiosis: Application of the By-product Exchange Network Model', *Procedia CIRP*. 61, pp. 263–268. doi: 10.1016/j.procir.2016.11.225.

Ramaswami, A., Tong, K., Fang, A., Lal, R.M., Nagpure, A.S., Li, Y., Yu, H., Jiang, D., Russell, A.G., Shi, L. and Chertow, M. (2017) 'Urban cross-sector actions for carbon mitigation with local health co-benefits in China', *Nature Climate Change*, 7(10), pp. 736–742. doi: 10.1038/nclimate3373.

Ren, J., Liang, H., Dong, L., Sun, L. and Gao, Z. (2016) 'Design for sustainability of industrial symbiosis based on emergy and multi-objective particle swarm optimization', *Science of the Total Environment*. 562, pp. 789–801. doi: 10.1016/j.scitotenv.2016.04.092.

Renzulli, P.A., Notarnicola, B., Tassielli, G., Arcese, G. and Di Capua, R. (2016) 'Life cycle assessment of steel produced in an Italian integrated steel mill', *Sustainability (Switzerland)*, 8(719), pp. 1–15. doi: 10.3390/su8080719.

Røyne, F., Hackl, R., Ringström, E. and Berlin, J. (2017) 'Environmental Evaluation of Industry Cluster Strategies with a Life Cycle Perspective: Replacing Fossil Feedstock with Forest-Based Feedstock and Increasing Thermal Energy Integration', *Journal of Industrial Ecology*. pp. 1–12. doi: 10.1111/jiec.12620.

Sacchi, R. and Ramsheva, Y.K. (2017) 'The effect of price regulation on the performances of industrial symbiosis: a case study on district heating', *International Journal of Sustainable Energy Planning and Management*, 14, pp. 39–56. doi: 10.5278/ijsepm.2017.14.4.

Shi, L. and Chertow, M. (2017) 'Organizational boundary change in industrial symbiosis: Revisiting the Guitang Group in China', *Sustainability (Switzerland)*, 9(7), pp. 1–19. doi: 10.3390/su9071085.

Short, S.W., Bocken, N.M.P., Barlow, C.Y. and Chertow, M.R. (xxxx) From refining sugar to growing tomatoes: Industrial ecology and business model evolution, *Journal of Industrial Ecology,* 18(5), pp. 603-618. doi: 10.1111/jiec.12171.

Song, B., Yeo, Z., Kohls, P. and Herrmann, C. (2017) 'Industrial Symbiosis: Exploring Big-data Approach for Waste Stream Discovery', *Procedia CIRP*. 61, pp. 353–358. doi: 10.1016/j.procir.2016.11.245.

Sun, L., Spekkink, W., Cuppen, E. and Korevaar, G. (2017a) 'Coordination of industrial symbiosis through anchoring', *Sustainability (Switzerland)*, 9(4). doi: 10.3390/su9040549.

Sun, L., Li, H., Dong, L., Fang, K., Ren, J., Geng, Y., Fujii, M., Zhang, W., Zhang, N. and Liu, Z. (2017b) 'Eco-benefits assessment on urban industrial symbiosis based on material flows analysis and emergy evaluation approach: A case of Liuzhou city, China', *Resources, Conservation and Recycling*, 119, pp. 78–88. doi: 10.1016/j.resconrec.2016.06.007.

Taddeo, R. (2016) 'Local industrial systems towards the eco-industrial parks: The model of the ecologically equipped industrial areas', *Journal of Cleaner Production*, 131, pp. 189–197. doi: 10.1016/j.jclepro.2016.05.051.

Taddeo, R., Simboli, A., Ioppolo, G. and Morgante, A. (2017) 'Industrial symbiosis, networking and innovation: The potential role of innovation poles', *Sustainability (Switzerland)*, 9(2), pp. 1–17. doi: 10.3390/su9020169.

Taddeo, R., Simboli, A. and Morgante, A. (2012) Implementing eco-industrial parks in existing clusters. Findings from a historical Italian chemical site, *Journal of Cleaner Production,* 33, pp. 22-29. doi:10.1016/j.jclepro.2012.05.011.

Tan, R.R., Andiappan, V., Wan, Y.K., Ng, R.T. and Ng, D.K. (2016) 'An optimization-based cooperative game approach for systematic allocation of costs and benefits in interplant process integration', *Chemical Engineering Research and Design*. Institution of Chemical Engineers, 106, pp. 43–58. doi: 10.1016/j.cherd.2015.11.009.

Van de Ven, A.H. (2007), Engaged Scholarship: A Guide for Organisational and Social Research, Oxford University Press, New York.

Valentine, S.V. (2016) 'Kalundborg Symbiosis: Fostering progressive innovation in environmental networks', *Journal of Cleaner Production*, 118, pp. 65–77. doi: 10.1016/j.jclepro.2016.01.061.

Velenturf, A.P.M. (2016) Promoting industrial symbiosis: Empirical observations of low-carbon innovations in the Humber region, Journal of Cleaner Production, 128,pp. 116-130. doi: org/10.1016/j.jclepro.2015.06.027.

Verguts, V., Dessein, J., Dewulf, A., Lauwers, L., Werkman, R. and Termeer, C.J. (2016) 'Industrial symbiosis as sustainable development strategy: adding a change perspective', *International Journal of Sustainable Development*, 19(1), p. 15. doi: 10.1504/IJSD.2016.073650.

Vollmeier, T. and Castorini, A. (2015) Case Study Spremberg: RDF-Fueled CHP Plant for a Paper Mill. Available at: http://www.enea.it/it/seguici/pubblicazioni/pdf-volumi/ExperiencesofIndustrialSymbiosisinItaly_Proceedings.pdf.

Wang, D., Li, J., Wang, Y., Wang, K., Song, X., & Liu, Y. (2017) 'Comparing the vulnerability of different coal industrial symbiosis networks under economic fluctuations', *Journal of Cleaner Production*, 149, pp. 636–652. doi: 10.1016/j.jclepro.2017.02.137.

Wang, D., Wang, Y. and Song, X. (2018) 'Evolution model with time lag effects for the coal industrial symbiosis system: A case study of Ordos, China', *Journal of Cleaner Production,* 187, pp. 863–876. doi: https://doi.org/10.1016/j.jclepro.2018.03.231.

Wang, Q., Deutz, P. and Chen, Y. (2017) 'Building institutional capacity for industrial symbiosis development: A case study of an industrial symbiosis coordination network in China', *Journal of Cleaner Production*, 142, pp. 1571–1582. doi: 10.1016/j.jclepro.2016.11.146.

Wu, J., Wang, R., Pu, G., Qi, H. (2016) 'Integrated assessment of exergy, energy and carbon dioxide emissions in an iron and steel industrial network', *Applied Energy*. 183, pp. 430–444. doi: 10.1016/j.apenergy.2016.08.192.

Wu, J., Pu, G., Ma, Q., Qi, H. and Wang, R. (2017) 'Quantitative environmental risk assessment for the iron and steel industrial symbiosis network', *Journal of Cleaner Production*. 157, pp. 106–117. doi: 10.1016/j.jclepro.2017.04.094.

Wu, J., Guo, Y., Li, C. and Qi, H. (2017) 'The redundancy of an industrial symbiosis network: A case study of a hazardous waste symbiosis network', *Journal of Cleaner Production*. 149, pp. 49–59. doi: 10.1016/j.jclepro.2017.02.038.

Wu, J., Qi, H. and Wang, R. (2016) 'Insight into industrial symbiosis and carbon metabolism from the evolution of iron and steel industrial network', *Journal of Cleaner Production*. 135, pp. 251–262. doi: 10.1016/j.jclepro.2016.06.103.

Yang, S. and Feng, N. (2008) A case study of industrial symbiosis: Nanning Sugar Co., Ltd. in China, *Resources, Conservation and Recycling*, 52, pp.813–820. doi:10.1016/j.resconrec.2007.11.008.

Yap, N.T. and Devlin, J.F. (2017) 'Explaining Industrial Symbiosis Emergence, Development, and Disruption: A Multilevel Analytical Framework', *Journal of Industrial Ecology*, 21(1), pp. 6–15. doi: 10.1111/jiec.12398.

Yedla, S. and Park, H.S. (2017) 'Eco-industrial networking for sustainable development: review of issues and development strategies', *Clean Technologies and Environmental Policy*. Springer Berlin Heidelberg, 19(2), pp. 391–402. doi: 10.1007/s10098-016-1224-x.

Yuan, Z. and Shi, L. (2009) Improving enterprise competitive advantage with industrial symbiosis: Case study of a smeltery in China, *Journal of Cleaner Production*, 17, pp. 1295-1302. doi:10.1016/j.jclepro.2009.03.016.

Zhang, C., Romagnoli, A., Zhou, L., and Kraft, M. (2017b) 'Knowledge management of eco-industrial park for efficient energy utilization through ontology-based approach', *Applied Energy*, 204, pp. 1412–1421. doi: 10.1016/j.apenergy.2017.03.130.

Zhang, Y., Duan, S., Li, J., Shao, S., Wang, W., and Zhang, S. (2017a) 'Life cycle assessment of industrial symbiosis in Songmudao chemical industrial park, Dalian, China', *Journal of Cleaner Production*, 158, pp. 192–199. doi: 10.1016/j.jclepro.2017.04.119.

Zhe, L., Yong, G., Hung-Suck, P., Huijuan, D., Liang, D. and Tsuyoshi, F. (2016) 'An emergy-based hybrid method for assessing industrial symbiosis of an industrial park', *Journal of Cleaner Production*, 114, pp. 132–140. doi: 10.1016/j.jclepro.2015.04.132.

APPENDIX 1 - Cross-industry case studies

	Title	Location	Original source	Case narrative	Industry	Insights	
						Non-technological	Technological
1	SCALER CS 1	Taranto industrial district, Puglia region, Italy	http://www.sciencedirect.com/science/article/pii/S095965261600233X	Taranto is centred on the ILVA steelworks and mainly including oil refineries, power plants, and cement and construction companies, but also small agro industries and a large beer factory. The area also includes the municipality of Taranto. The industrial district was founded in 1960s, as a result of the national strategy for the industrial development of Southern Italy. From the 1990s the area has been declared exposed to a high risk of environmental crisis with serious concerns for the safety of the local population, mainly due to high level of air, water and ground pollution.	Steel, oil refining, cement, power generation	Since the foundation of the district, several symbiotic relationships have been spontaneously put in place by the ILVA factory and the cement factory in particular, answering the specific challenge of cutting costs and increasing the competitiveness. Commissioning by the local government of a first explorative study to the researchers of the University of Bari in order to identify existing as well as new potential materials and energy exchanges. The objective was to highlight the potential of IS' contribution to the solution of the environmental issues as well as its positive impacts on firms' costs. At that stage, companies were minimally involved in data gathering and feedback-providing activities as the main aims were to sensibilise them about IS while demonstrating the feasibility and profitability of the solution.	
2	SCALER CS 2	Relvão Eco Industrial Park, Municipality of Chamusca, Portugal	http://www.sciencedirect.com/science/article/pii/S0959652610001071	The Relvão Eco Industrial Park (REIP) in Portugal started in 2006 thanks to the jointed efforts of several different stakeholders, among which were the Portuguese Government, the Chamusca Municipality Government, the Technical University of Lisbon, together with industrial companies and entrepreneurs. Current and planned development for the Industrial Park includes pulp and paper companies, agro industries, several chemical companies (mainly fertiliser producers), and waste treatment facilities.	Urban waste, non hazardous industrial waste landfill, plastics recycling	The setting up of a consortium whose initial objectives have been to find ways to overcome the constraining regulatory environment (e.g. national waste management regulation taking a long time to amend, the need for a special permission to manage) and to influence "contextual factors" so as to facilitate IS exchanges. For example, they used the flexibility given by the national government to companies regarding the implementation of new waste management directives and landfill taxes to start a dialogue with national authorities to assist in shaping more IS-enabling measures. Additionally, the municipality targeted companies who were already licenced as waste management operators so as to aid the emergence of symbiotic exchanges. Finally, the local government sought the help of researchers to disseminate information among companies and the population, organising workshops, seminars and conferences to spread IS knowledge and culture, and to facilitate dialogue between agents.	
3	SCALER CS 3	Kalundborg, Denmark	http://www.sciencedirect.com/science/article/pii/S0959652608000814 http://www.sciencedirect.com/science/article/pii/S0959652610001071 http://www.symbiosis.dk/en/	The Kalundborg industrial cluster in Denmark is one of the most famous examples of IS and it has often been used as a reference case in literature. The initial creation of symbiotic relationships in the area is dated back to the 1960s, when the local refinery set up a project to start using the surface water from a nearby lake, and the cluster has evolved from there. Today, it includes several symbiotic exchanges between power stations, oil refineries, plasterboard producers, biotechnology companies, cement producers, soil remediation firms and the municipality of Kalundborg.	Power generation, oil refining, biotechnology, plasterboard, soil remediation, waste management	The pre-existence of strong relationships between companies and employees operating in mature industrial sectors as well as common infrastructures facilitated the adoption of the long-term perspective needed for IS implementation. The involvement of numerous local stakeholders in the creation of the pipeline bringing water from the lake to the local refinery further fostered the network effect with the pipeline becoming a key component of the network.	
4	SCALER CS 4	Humber region, UK	http://www.sciencedirect.com/science/article/pii/S0959652615007477	The Humber region is one of the largest harbour complexes in the UK, hosting industrial companies from a range of sectors since the 1960s. The industrial district is mainly constituted by food processing, chemicals, furniture, iron and steel and other metals as well as oil and gas production facilities. The case study is well known in literature as one of those originating the idea of the creation of the National Industrial Symbiosis Programme (NISP) in the UK.	Power generation, fuel manufacturing, food processing, chemicals	Role of strong sectoral influences such as in Humber chemical companies. Manufacturing companies in networks have advantages as they are used to collaboration. Networks where HO located close by are more functional than networks where HO is distant (nationally or internationally) due to decision making being more rapid.	
5	SCALER CS 5	Spremberg, Germany	http://www.enea.it/it/pubblicazioni/pdf-volumi/ExperiencesofIndustrialSymbiosisinItaly_Proceedings.pdf	The Hamburger Rieger GmbH paper mill in Spremberg, Germany, has been working since 2005. In 2008, it started a partnership with an energy production company to start reusing waste pulp/paper and sludge for electricity production. A new CHP plant was consequently designed and built in the region. The mill represents the main customer of the CHP plant, which is able to follow its demand fluctuations. Apart from the mill's waste, the CHP plant also uses as input a mix of refuse derived fuels.	Paper and pulp, energy production	The solution rapidly identified as feasible and profitable was to use the mill's wastes as fuel to generate energy, both as electricity and steam. Nevertheless, the company had to face a major implementation barrier, i.e. the lack of suitable facilities in the surrounding area. Hamburger Rieger GmbH decided to find a potential partner from outside the region to jointly undertake the construction of a CHP plant.	
6	SCALER CS 6	Italy and Spain	http://www.enea.it/it/seguici/pubblicazioni/pdf-volumi/ExperiencesofIndustrialSymbiosisinItaly_Proceedings.pdf	Led by the Italian National Agency for New Technologies, Energy and the Environment (ENEA) in collaboration with Italian and Spanish representatives of leather products producers, the PODEBA project was a partnership between industry and research institutes to bring up to date an old production process for leather products — the use of poultry dejections for the bathing phase in the tanning industry. Several agro-industries were also involved in the project as donors of waste materials.	Poultry farming, leather tanning	The discovery process, led by ENEA, involved the identification of several intensive poultry farms that could provide poultry dejections in the right volumes, guaranteeing enough raw material for industrial application as well as a good level of standardisation of the final product's quality. The implementation of IS was also quick-started by the fact that the exchanged material had already been used for the same purpose in the past. Its suitability for the production process was therefore well known.	Finding a suitable technological solution was the objective of the international research project at the core of the PODEBA project. Once the solution was identified, several tests and experiments were conducted so as to define the most appropriate treatment process and use conditions for the raw material. Finally, quality controls were run on treated final products in order to verify their compliance to international standards.
7	SCALER CS 7	Fife, Scotland, UK	http://www.orbuk.org.uk/article/the-national-industrial-symbiosis-programme-nisp	The NISP in the UK acted for several years as a facilitator to create several symbiotic exchanges across the whole country. In this specific case, it helped the implementation of a profitable symbiotic exchange between a manufacturer of alcoholic drinks and a start-up producing firewood out of old whisky barrels, both based in Scotland.	Beverage production, firewood production	The implementation of an IS exchange was made possible thanks to the intervention of the Scottish Environment Agency which re-categorised the hessian sacks as by-products instead of waste. The sacks then became directly tradable by the alcoholic drinks producer. In addition, the high quality of the used sacks was fundamental in making the exchange economically feasible.	
8	SCALER CS 8	Bussi sul Tirino, Abruzzo Region, Italy	http://www.sciencedirect.com/science/article/pii/S095965261200234X	Developed at the beginning of the 20th century, the chemical site located on the river Tirino in Abruzzo is one of the oldest industrial clusters in Italy. It includes basic chemicals producers, pesticides and silicates manufacturers, as well as power stations. The study presented in the article was an attempt to apply principles of industrial ecology to revitalise the site.	Basic chemicals, pesticides, silicates, power generation and distribution	The research project aimed at identifying relevant methodologies for IS implementation in existing industrial clusters. To this regard, Chieti researchers conducted a literature review that they complemented with a study on the history, geography and economy of the area to advance their understanding of the context. They also paid special attention to the stakeholders to involve in the IS implementation and organised a stakeholders' meeting so as to explain the aims and scope of the project. Field activities were then conducted, together with data collection activities including a survey and additional one-to-one meetings with companies' representatives. With the involvement of companies, the hope was to foster some business diversity and identify more potential exchanges. Finally, researchers also had the "Local Observatory for the Chemical Industry" on board. As a local sectorial association, it helped coordinate stakeholders' involvement and organise periodic round-tables to keep them informed and gather feedback.	
9	SCALER CS 9	Humberside, UK	http://www.sciencedirect.com/science/article/pii/S0959652604000848	The plan of a global oil and gas company, already operating in the region and with a previous experience in the creation of an industrial park in Tampico (Mexico), to create a CHP plant in the region acted as a triggering factor for the Humber region Industrial Symbiosis Programme (HISP). Involving from the planning phase neighbouring industrial companies in the project, analysing their energy needs and potential willingness to cooperate, they also proposed that the companies agreed by contracts to channel a certain percentage of the profits gained out of this cooperation for the creation of a coordinating body tasked with developing exchanges in the region. Humberside acted as seedling for IS programmes in West Midlands and Merseyside based on experience of IS in Mexico. Cases explored and presented by RA with emphasis on coordination body — raising awareness and recruiting. Complexity of factors in establishing an effective IS network.	Oil and gas	The Business Council for Sustainable Development-United Kingdom (BCSD-UK) acting as a project coordinator for the HISP with the scientific support of the researchers from the University of Lund, adapted the development process followed in Tampico to the British context. It led to the widening of the scope of symbiosis (including general forms of cooperation among companies) and the adoption of an environmental focus. Role of strong sectoral influences such as in Humber chemical companies. Manufacturing companies in networks have advantages as they are used to collaboration. Networks where HO located close by are more functional than networks where HO is distant (nationally or internationally) due to decision making being more rapid.	Quantitative capture of economic, environmental (e.g. CO2/NOx reduction) and social benefits allows preparation for responses to future policy shifts.
10	SCALER CS 10	West Midlands, UK	http://www.sciencedirect.com/science/article/pii/S0959652604000848	The West Midlands region, situated in the area around Birmingham, has been the focus of an IS implementation project led by the NISP in the UK: the West Midlands Industrial Symbiosis Programme (WISP). In this case, the NISP exploited the interest generated by the previous programme implemented in the Humber region and tried to repeat and improve the experience. The West Midlands is an industrial area that includes, among other industries, automotive, metal production, and plastic and rubber and food processing companies.	Plastics manufacturing, food processing, automotive	The fact that the coordinator of the initiative, MEBC, was well established in the area and had already several connections and other companies' trust allowed them to jump-start IS implementation. MEBC's conducting of a study to identify the main stakeholders (companies, as well as public and research entities) for the programme and organisation of a half-day meeting supported the early identification of potential collaborations. MEBC also set up a project advisory board, chaired by a manager from one of the participating companies, and developed an IT tool in order to enable data gathering, management and sharing. Thanks to this tool and to further interactions among MEBC and local companies, several potential new synergies were identified, and a feasibility study was conducted for each of them. The whole project was planned to be highly interactive, involving participating companies from the very start of the activities, and the leadership of the advisory board guaranteed their full support and an open attitude towards potential collaborations. Thanks to previous experience, the companies were also knowledgeable about materials reuse and recycling. Some extra credibility was gained by the programme since it did not only focus on exchanges identification but also encouraged companies in preventing waste and improving efficiency. Finally, the programme was financially supported by the RDA of the West Midlands (Advantage West Midlands).	
11	SCALER CS 11	Merseyside, UK	http://www.sciencedirect.com/science/article/pii/S0959652604000848	The Mersey river estuary, located in North West England, represents the third attempt of BCSD-UK to implement an IS programme in an industrial district in the UK (the first two were located in the Humber region, see case 4, and in West Midlands, see case 10). This project was framed within the NISP in the UK. Mersey Banks is an industrial area mainly focused on chemical, oil and gas sectors. Other process industries such as pulp and paper companies are located in the area.	Chemicals, oil, gas and service providers/utilities to these.		

	Title	Location	Original source	Case narrative	Industry	Insights	
						Non-technological	Technological
12	SCALER CS 12	Norrköping, Sweden	http://www.sciencedirect.com/science/article/pii/S0959652615004382	The municipality of Norrköping in Sweden is home to a well-established and well-developed IS network. In particular, the urban area and surrounding industrial and agricultural activities have developed a series of exchanges and symbiotic connections over time, showing an ever-increasing attention to environmental and resource scarcity and security issues. Main companies in the network are from the forest industry, agro industry and electricity/gas production sector. A combined heat and power plant is based on the island of Händelö, in front of the city of Norrköping, and a whole industrial symbiotic district focused on energy and fuel production has developed on the island over the years.	Biofuels	Proactive role played by the municipality in building on concerns from the local population to devise and embark upon concrete IS actions. The important presence of farming activities in the region was also an enabler of several existing exchanges, as they provide raw material for biofuel production. Finally, the innovative mindset of most of the companies operating in the area contributed to trigger and speed up the IS development process. Network: strong relationship to taxes, subsidies and environmental performance that is increasingly instigated by policy-makers; and key for communication and both encouragement of new partners into networks and catalysation at the set up stage.	Quantitative modelling approach to understand total and individual benefits distribution for companies in IS network.
13	SCALER CS 13	Trowbridge, UK	http://www.orbuk.org.uk/article/the-national-industrial-symbiosis-programme-nisp	The NISP in the UK acted for several years as a facilitator to create several symbiotic exchanges across the whole country. In this specific case, it helped the implementation of a profitable symbiotic exchange between a supplier of frozen food and an anaerobic digestion plant, both based in the UK.	Food manufacturing and energy generation	The network developed by the NISP was key in assisting the companies in identifying the relevant partners for the symbiotic exchanges they were considering. By contacting NISP representatives, they benefited from guidance and information about how to proceed, and from an established database and network. Able to leverage knowledge/contacts to modify local policy and re-categorise waste streams as in case 7 with hessian sacks. Micro and small businesses make up 90% of network membership.	
14	SCALER CS 14	Province of Foggia, Italy	https://ac.els-cdn.com/S2211464514000888/1-s2.0-S2211464514000888-main.pdf?_tid=9fa204ed-6bb1-4633-98bf-2bf9373dcb0f&acdnat=1533044694_904264267e781193423c0f3eb055e9d9	A small olive-grove farm with an olive mill, located in Southern Italy within the Foggia municipality, has been the focus of a study conducted by the University of Thessaloniki and the University of Foggia in order to evaluate the feasibility to install a pyrolysis reactor on the production site. This would allow the farm to produce energy using agricultural residues while improving the soil quality using the pyrolysis waste (biochar).	Agriculture and energy	A key element for the successful implementation of the IS exchange was the fact that the farm and mill were already integrated on the same production site, resulting in the absence of any transportation costs for both agricultural residues and energy.	Researchers developed a new integrated system using waste heat from the drying treatment in order to pre-heat agricultural residues and make the process more efficient. They also designed the pyrolysis reactor so that its operation parameters could be easily modified and the two agricultural residues could be treated separately during the year. They were therefore addressing the twofold issues around the high moisture content of the agricultural residues, which required a considerable amount of heat to be dried, and the fact that the residues from pruning and pomace were available at different times during the year therefore entailing discontinuous operations. In addition, the technology used to produce biochar and bio-oil by the means of the pyrolysis reactor was already well known and only needed to be customised considering the specific production process.
15	SCALER CS 15	Ballymena, Northern Ireland, UK	http://www.endustriyelsimbiyoz.org/wp-content/uploads/2013/02/industrial-symbiosis_uk-nisp-and-global-experience_31.01.2013.pdf	Michelin is a large corporation with production plants all over the world. There are several waste streams of tyre production and of different natures, such as carbon black, talcum powder, etc. With the help of the NISP, the UK plant in Ballymena (Northern Ireland) approached the waste management issue including an IS perspective.		Through the assistance of NISP, Michelin was able to establish a dialogue with potential partners regarding waste treatment needed and related responsibilities. Benchmarking study in the different Michelin plants complemented by recommendations from external experts to identify alternative solutions to landfill. NISP is national model with international extensions able to leverage learnings/identify new trends and issues. Full facilitator role including helping with negotiations and technical knowledge.	Use of resource mapping and SYNERGie online tool (in 9 countries) to record resources/make matches.
16	SCALER CS 16	Newtownards, Northern Ireland, UK	https://secure.investni.com/static/library/invest-ni/documents/industrial-symbiosis-guide-for-businesses-in-northern-ireland.pdf https://www.thyssenkrupp.com/media/investoren/berichterstattung_publikationen/update_23_11_2017/en_10/neu2_gb_2016_2017_thyssenkrupp_gb_eng_web.pdf	The NISP in the UK acted for several years as a facilitator to create several symbiotic exchanges across the whole country. In this specific case, and in collaboration with the Industrial Symbiosis Service in Northern Ireland, it helped the implementation of a profitable symbiotic exchange between ThyssenKrupp Aerospace Ltd., an aluminium alloy technology solutions provider, and Tedfords Ltd., a manufacturer of bespoke products for the boating, banner and trailer market. Tedfords started to reuse the PVC tarpaulins that were used by ThyssenKrupp to protect the aluminium raw material during transportation and storage for new products creation.	Aerospace, tarpaulin manufacturing	Acting as a facilitator, the local Industrial Symbiosis Service initiated the IS exchange by contacting companies within its network. Moreover, the aluminium alloy technology solutions provider was already aware of the environmental issues while the manufacturer of bespoke products for the boating, banner and trailer market had already the know-how needed for the creation of new, recycled products.	
17	SCALER CS 17	Norfolk, UK	http://onlinelibrary.wiley.com/doi/10.1111/jiec.12171/epdf	British Sugar is one of the biggest sugar producers in the UK, acquired by AB Sugar in 1991. The company has been growing over the years thanks to IS and the increasingly important role played by the trading of its by-products. The company has been exchanging waste materials with several industries, such as landscaping, building construction, animal feed production, agro industries, cosmetics, biofuel and beverages production.	Sugar production	Good practices fostering a supportive environment for IS implementation by British Sugar include the focus of management on business growth and development; the nascent supportive legislation on waste management, renewable energies and fuels; and the good communication and collaboration skills developed over time across the company. The company has implemented an employee suggestion scheme, through which ideas on further improvement actions proposed by operators can be gathered and assessed. Continuous benchmarking activities with other sugar producers all over the world also contribute to the identification of new symbiotic opportunities. Innovation and industrial ecology practices and thinking have been embedded in day to day operations and dedicated innovation teams have also been established in order to periodically identify opportunities.	
18	SCALER CS 18	Helsingborg, Sweden	http://www.industriellekologi.se/symbiosis/helsingborg.html	Sustainability has been considered during the city of Helsingborg's development. The IS network in the city involves synergies between public and private actors. The city's waste collection and sorting system is well known.	Energy, waste treatment	The fact that Helsingborg owns the city's main energy and heat provider and waste treatment facility jump-started the resource exchanges. This leads to a more long-term view of investments, and aids positive relations between firms and authorities Trust between various firms and the City Government of Helsingborg created a strong system of interdependencies. Energy company has sufficient/predictable input for CHP plant due to waste monopoly.	
19	SCALER CS 19	Lidköping, Sweden	http://www.industriellekologi.se/symbiosis/lidkoping.html	The small town of Lidköping has a number of resource exchanges in place in its industrial/harbour area. Bio-based production systems help reduce economic dependence of region on fossil fuels.	Bio-based production	The town's long-term contracts with the department of waste management and monopolies over heating and waste systems aided with the securing of sufficient resources for the CHP plant developments, helped by the fact that the CHP plant was not driven by a desire for profits. The governmental investment programs Lokala investeringsprogram and Klimatinvesteringsprogram have provided some of the funding for developments in Lidköping needed for resource exchanges, e.g., the biogas plant and CHP plant development.	
20	SCALER CS 20	China	https://ac.els-cdn.com/S0959652609001127/1-s2.0-S0959652609001127-main.pdf?_tid=4325d963-5b64-4411-a955-f47b546a4220&acdnat=1533044281_20c3cbfbae0b10198540148aedc124e7	A study on the application of IS to a large state-owned smeltery in South West China, looking into aspects such as the capture and use of materials previously released into the environment and the valorisation of residues.	Smelting	Local government direction of state-owned companies, incentivising innovations in technology, equipment and production techniques. Company managers often have roles in the local government.	
21	SCALER CS 21	Nanning, China	https://ac.els-cdn.com/S0921344907002224/1-s2.0-S0921344907002224-main.pdf?_tid=14641ffe-e2a0-410b-809d-7abb05afdb67&acdnat=1533044022_71301bd5813a85d4d184844e63b1e88	A study on Nanning Sugar Co., Ltd. in China detailing its development into a more sustainable corporation. Factors include raw materials, technology and production systems.	Sugar production	Low profit & high pollution levels because of insufficient investment and decentralised production. Fees on residues.	
22	SCALER CS 22	Kawasaki Eco-town, Japan	https://ac.els-cdn.com/S0921344909002766/1-s2.0-S0921344909002766-main.pdf?_tid=0fabab2e-85b0-4295-807f-f9e14ec5ad9b&acdnat=1533043856_5ff85155d386a5dd88e56c37d792df59	Kawasaki Eco-town contains over 70 companies from various industries. 7 major resource synergies are present, reducing wasted materials and providing economic benefits.	Steel, chemical, cement, nonferrous metal processing and paper making	Low economic performance of companies in the area because of the bubble economy collapse and competition. Subsidies for the development of recycling facilities.	Life cycle analysis provided a benchmark.
23	SCALER CS 23	Liuzhou city, China	https://ac.els-cdn.com/S0301421513005910/1-s2.0-S0301421513005910-main.pdf?_tid=4e00ab17-94a4-4026-bf5c-7797f007f3b&acdnat=1533043523_07d4dd2eceaec57be1a44eed59af46	Resource exchanges are currently within closely related industries, involving blast furnace slag, steel slag and desulfurisation by-products. There is a large volume of industrial solid waste exchanged relative to exchanges in other countries.	Iron/steel, cement	Government pressure.	
24	SCALER CS 24	Ulsan, Korea	https://www.sciencedirect.com/science/article/pii/S0301479707000175	Ulsan was declared a South Korean special industrial park in 1962. There are 700 companies present. IS initially occurred spontaneously — companies within the industrial park made one-to-one negotiations for economically beneficial exchanges, motivated by stringent environmental standards/legislation. The industrial complex was later chosen for a 15 year Eco-industrial Park development plan, beginning in 2006.	Energy generation, water supply and treatment, petrochemicals, chemicals, nonferrous metals	Ulsan being declared a South Korean special industrial park in 1962. Stringent environmental standards/legislation. Eco-industrial Park development plan.	
25	SCALER CS 25	Kwinana Industrial Area, Australia	https://www.sswm.info/sites/default/files/reference_attachments/VAN%20BEERS%20et%20al%202007%20Industrial%20Symbiosis%20in%20the%20Australian%20Mineral%20Industry.pdf	The Kwinana Industrial Area in Western Australia is the largest area for heavy process industries in Australia, established in the 1950s. The Kwinana Industries Council, established in 1991 in response to government and community pressure to manage environmental impacts, initiated studies which identified existing and possible resource exchanges between industries in the area.	Alumina, nickel, iron, oil refinery, alumina and aluminium, pigment, cement, chemicals, fertiliser, power generation, water supply and treatment	Economics: increased revenue through lower operational costs, reduced risks and liability. Information availability: local industry organisation, staff mobility. Corporate citizenship and business strategy: corporate sustainability focus, community engagement and perception. Region-specific issues: new company entering industrial area, geographic isolation.	Technical issues: research and technology developments, technical obsolescence of existing process equipment. Regulation: existing environmental regulations (e.g., air and water quality requirements and reporting) (van Beers, Corder, Bossilkov, & van Berkel, Table 2, p. 67).