

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 national, regional, and local levels, including city level as well as 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 participatory form of research for studying complex real-world problems by drawing upon the different perspectives and understandings of 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.

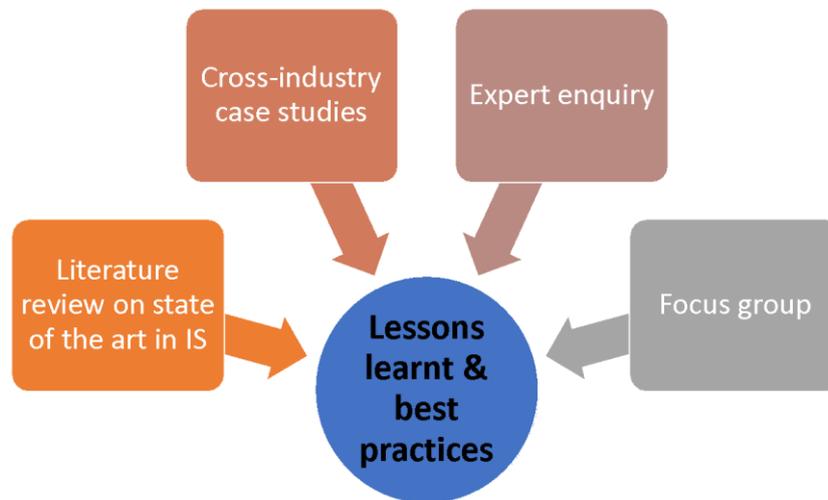


Figure 1 - Mixed-method approach

2. State of the art on industrial symbiosis

In Circular Economy literature, studies follow three main lines of action; the first aims to change the social and economic dynamics at macro and administrative level; the second to support firms in circular processes implementation at micro level to spread new forms of consumption and product design; the third, developed at meso level, discusses IS experiences and eco-industrial parks (Merli, Preziosi, & Acampora, 2018). Thus, IS is firmly nested within the Circular Economy field.

To understand IS more specifically, Yap & Devlin (2017) argued for and outlined a mixed-level (society, network, and enterprise) analytical framework for analysing IS emergence, development, and disruption. This argument emerged from two patterns observed in the post-1990s IS literature — that enablers and barriers exist at national, regional, network, enterprise, and personal levels and that the processes involved in IS emergence and development are fluid, with the boundaries of the different stages porous. The framework does not assume that the evolution of IS networks is one-way, linear, or caused by a single combination of factors. The development of each IS network is path dependent and contingent because it is dependent on a broad range of conditions. Different networks may achieve IS as a result of quite different combinations of factors (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 (GHG) emissions by 40% below the 1990 level in 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, Schöggel and Posch (2017) suggest that the search for waste recycling possibilities represents a completely new trigger in the classic innovation process.

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).

In a study of 'live' and 'dead' industrial ecosystems (Ashton, Chopra, & Kashyap, 2017), the following factors were noted that spur collaborative developments: the presence of industries that can serve as anchors (providing materials to diverse actors, e.g. power plant providing steam or waste heat) or scavengers (receiving materials from diverse actors, e.g. recyclers receiving diverse waste); facilitative government policies, such as waste disposal pricing or preferences, rather than direct intervention or planning; natural resource abundance or scarcity; favourable firm-level economic rationale (e.g. cost reduction, efficiency, revenue streams); and social, cultural and/or institutional pressures on firms (to cooperate, conserve resources, etc.).

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 their study of the largest integrated EU steel mill located in the city of Taranto in Southern Italy, Renzulli, Notarnicola, Tassielli, Arcese, and Di Capua (2016) look further and identify several specific environmental issues alongside the economic crisis in the area. These issues have forced the steelworks' managers to reduce its productive capacity by nearly 50% over four years. As a consequence, the industrial complex was striving for innovation, both at technical and managerial levels, in order to reduce the environmental impacts to acceptable levels.

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) offer 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.

As a result, the Guitang Group grew from 2 internal to 11 internal and external symbiotic exchanges and is now a conglomeration with more than 3000 employees generating more than 1 billion RMB (150 million USD) in revenue annually. The driving forces of the Guitang Group's evolution continuously reinforced the IS message as part of the Guitang Group's business model and competitive strategy, helping to create, disseminate and share information. In addition, state-level policies such as establishing the Guigang (the city where Guitang is located) Eco-Industrial Park enabled IS in Guitang (Shi & Chertow, 2017).

Globally, profits and environmental benefits are the key factors driving eco-industrial networking and its development into Eco-Industrial Parks (Yedla & Park, 2017). In their study of a Flemish (Belgian) eco-industrial greenhouse park development, Verguts, Dessein, Dewulf, and Lauwers (2016) suggest that the economic and energy crises and environmental considerations have been increasing awareness about reorganisation needs and technological changes, but somehow these triggers seem not to be strong enough to make change really happen. Only after municipal land-planning decisions were made was the Koekhoven greenhouse park development kicked-off.

Many IS clusters do arise from a deliberate effort to create symbiotic or "sustainable" systems (Boons, Chertow, Park, Spekkink, & Shi, 2017) as in the Koekhoven greenhouse park development. Others, however, organically emerge as a reaction to resource restraints, resource pricing, environmental regulations or other external signals, which drive innovation and partnership (Boons 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

The following social conditions in establishing and nurturing a thriving system are important according to Ashton, Chopra, and Kashyap (2017):

- Trust, openness and cooperation among firm(s) personnel
- Strong social network ties or social capital
- Knowledge creation and sharing
- Embeddedness (cognitive and social)

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).

Park, Park, & Park (2016) identify how regional eco-industrial park (EIP) centres help participating firms provide fair project benefits and recognise the personnel and department within each firm who are in charge of the work and achievements for the project. To mobilise the participation of various stakeholders in addition to business actors, regional EIP centres organise stakeholders from businesses, universities, research institutes, and local governments as a way to promote communication, information sharing, and cooperation among them. If necessary, the EIP centres help create a new unit for resource recovery and circulation so that the role of the unit aligns with the goal of the EIP projects without the loss of jobs.

Where participation was particularly difficult in the early phase of the Korean EIP program due to behavioural barriers, 51 local experts (including business retirees and professors who had local tacit knowledge) were co-opted to act as coordinators to help in the project development and implementation. This resulted in the Ulsan EIP centre developing the first successful project as a model: a steam-sharing network between a city waste-to-energy incinerator and a chemical company (Park et al., 2016).

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). Prozman, Wæhrens and 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: 1) the education and support of purchasing managers about the cost structure of IS, 2) increasing the understanding of the supplier's processes and its effect on the waste quality, and 3) increasing the quality of communication with the supplier, hence increasing the supplier's understanding of the buyer's needs.

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 in dealing with environmental issues (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, on-site guidance, policy tours 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). This includes developing an interface between industries and local communities for the long-term sustainability of eco-industrial development. Additionally, the communications should promote green consumerism in order to enhance the marketability of 'green products' for 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 that have varied and sometimes contrasting interests — 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 institutes (Sun et al., 2017a; Yedla & Park, 2017).

Synergistic relationships are further supported by partnership building and the balancing of the playing field between the primary and recycling sectors, in addition to the development of new business models and harnessing of key knowledge and innovations (Aid et al., 2017). Luciano et al. (2016) identify the following components:

- Increasing the biodiversity of the firms within the productive sectors and a consequent solicitation and involvement of underrepresented companies.
- Providing companies that are technologically able to reuse residues in their production processes in a sustainable way with the technical information that can be found for the potential use of available resources.
- Increase the presence and participation of local stakeholders and control authorities during operative meetings in order to ensure greater confidence in the symbiosis approach to companies, as well as a greater awareness of the same stakeholders of the real potential of the approach and of the future issues to solve.
- Encouragement of paths that are not so financially attractive but can have a strong positive impact on the environment, e.g., agriculture residues management.

Other 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, & Morgante (2017) note that these government-sponsored consortia offer a new model of development. IPs are created within EU programs, with the objective of stimulating innovation within a network of organizations and helping promote the competitiveness in specific industries or value-chains at a local or regional level. The positive role that IPs play in the development and diffusion of IS in a given territory is related both to their institutional activity of production and dissemination of knowledge and innovation, and mostly (if considered as applicative contexts for IS) to the promotion of the establishment of symbiotic relations among their members. In respect of this, some aspects of IPs have emerged as relevant, i.e., the sectoral specialization, the spatial scales, the existence of social relations and trust, the role of stakeholders and the regulatory issues.

Siskos and Wassenhove (2017) propose a new coordination approach for the development of IS synergies within industrial parks, based purely on market forces, and introduce the concept of a synergy management services company (SMSCO), a synergy contractor and third-party financing model, where a synergy contractor undertakes the financing, construction, operation, and maintenance of synergistic projects on behalf of collaborating firms.

At a more granular level intermediaries and other knowledge agents help advance IS networks and enhance eco-efficiency through eco-efficiency reviews, eco-efficiency opportunity assessments, eco-efficiency implementation assessments, and pollution prevention workshops (Liu et al., 2018a). Comprehensive assessments of co-benefits help to integrate eco-industrial development with climate protection strategies (Yedla & Park, 2017). 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.

Desrochers and Szurmak (2017) offer a simpler view and suggest the main factors usually deemed necessary for the development of IS can be observed at a much larger geographical scale. These could be: i) a high volume of potentially valuable (in terms of physical and chemical components) but otherwise problematic (high disposal costs) residuals, and ii) an economically diverse industrial structure that allowed for the development over time of inter-industrial linkages.

Other authors suggest that industrial diversity in a location is a key factor to create 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. In general, areas of higher diversity, whether measured by industry type richness or relative community evenness, do possess greater instances of companies involved in local IS. By definition, these areas of high IS also possess higher rates of localised resource recycling and reuse and thus system productivity.

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), as tax incentives can encourage stakeholders to become genuinely and actively involved (Liu et al., 2017). 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.

With a national need to enhance the performance and competitiveness of an aged industrial base, the Korean government invested in the establishment a three-stage, 15-year EIP program. During the first five years of pilot experimentation, between 2005 and 2010, the program produced significant economic and environmental benefits by developing and implementing 47 IS projects at five pilot sites. The first-phase of the program successfully implemented IS projects by examining technical, economic, legal/regulatory, and social factors to expose important drivers for further IS development in Korea and elsewhere (Park et al., 2016).

In the Korean EIP approach, the government did not intend for its financial support to provide all necessary investments to realize IS. Instead, government funds were intended to help businesses examine potential economic benefits at the feasibility study phase. That support motivated industries to conduct feasibility studies and drew private investments later when businesses realized the scale of the economic benefits offered by a project. A positive way to use government financial support is as leverage to draw private investment and scale-up IS projects (Park et al., 2016). Governments can give further assistance by stimulating investments in the private sector related to waste reuse and recycling; and

through the provision of subsidies for the development of waste exchange networks and projects (Ceglia et al., 2017).

Governments 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” (connecting sustainability with competitiveness) 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:

- Produce a long-term vision encapsulating the concepts of sustainable development and IS.
- Develop an integrated approach to policy making that complements resources conservation and the promotion of eco-industrial development.
- Involve the business community in planning to achieve eco-industrial development.
- Enact institutions that promote environmentally friendly infrastructure.
- Introduce policies towards enhancing the participation of industries in environmental management.
- Develop policies towards enhancing the use of “eco-friendliness” of products as a market driver.
- Undertake feasibility studies and the development of a national-level master plan to facilitate the development of networking among various industries within a complex and among coexisting industrial complexes.
- Complement policy making in other allied sectors.
- Improve overall capacity to conduct material flow analysis in industrial R&D.
- Institutionalize, internationally, eco-industrial networking initiatives so as to avoid international trade distortions.
- Adopt multipronged awareness-raising initiatives.

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).

For some time, China has engaged in durable governmental facilitation of the development of Sustainable Industrial Parks (SIPs). This has materialized through two policy programs: one stimulating EIPs and one advancing Circular Economy Industrial Parks (CEIPs) (Jiao, Boons, Teisman, & Li, 2018). More innovative policies should however be raised in China, such as increasing the costs of natural resources and charging resource tax (Guo, Geng, Sterr, Dong, & Liu, 2016), which links to the section on government instruments above.

Ceglia et al., (2017) describe how the development of national and state solid waste policy, and the more specific establishment of policy and undertaking by governments to guide symbiosis development help stimulate activity. These authors note that in tandem is the increase in enforcement mechanisms to support national and state (regional) solid waste policies. Regulatory issues such as conflicting rules of hazardous waste management also need to be addressed and aligned to complement eco-industrial networking (Yedla & Park, 2017). In so doing barriers that are commonly cited at an industrial park and firm level can be alleviated.

Certain waste legislation and policies strongly promote reuse of waste materials and recycling targets but meeting the demands of a “recycling society” may require further development of the legal definition of waste and product-based legislation and standards. New legal thinking is therefore 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 from the beginning of the program, there was an intensive focus on establishing appropriate legal and regulatory systems to support and promote EIP projects. As a basis of the EIP program, the Transition to Environment-friendly Industrial Structure Act was amended in 2006 to provide an overarching legal framework for the activities of the regional EIP centres. In particular, it empowered the regional EIP centres to compile the necessary statistics from central and local government bodies and to collect industry data through facility visits and surveys (Park et al., 2016).

In August 2009, an amendment to the Industrial Cluster Development and Factory Establishment Act allowed environmental industries that process and recycle by-products and residual heat (i.e., scavengers and decomposers) to be located within an industrial complex. Before that amendment, those industries were classified as service or ancillary facilities and had limited ability to move into industrial complexes, which was hindering the development of resource sharing networks (Park et al., 2016).

2.2.2.6 Regional/local authorities

Horvath and Harazin (2016) explore the changing duties 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 in closing open material flow loops, resulting in mutual benefits. Under the traditional approach to industrial ecology, the realignment of processes or the closing of loops occurs between businesses, located at sufficient geographic proximity, enabling them to engage in an exchange or shared use of resources, by-products and waste. However, these authors recognise that there are certain processes where loops may be closed not by other businesses, but by regional/local governments. 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 the establishment of an orientation plan for eco-industrial park development (Ceglia et al., 2017), and the provision of an institutional setting locally (Sun et al., 2017a). Measures such as developing preferential policies to attract companies, and actively recruiting companies to IS are helpful. Furthermore, authorities can help facilitate firms' settlement in IS, provide by-product and utility synergies 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 workshops and training seminars, and disseminate information through newspapers, pamphlets and other 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:

- Intra-estate (park) and interstate coordination channel towards an EID (this reinforces the part played by intermediaries/ knowledge brokers described above).

- Institutionalise potential bilateral and multilateral agreements dealing with recycling of resources, by-product, and waste streams.
- Apply regulations that could avert the risk of an industry running short of input stock that comes from multiple sources of resource recycling.
- Carry out site assessments of individual parks.
- Develop a comprehensive material flow matrix at 'park-level'.
- Facilitate the development of infrastructure needed for the exchange of resources, by-product, and waste streams among industries.
- Employ public-private partnerships to provide much needed support for the initial costs of infrastructure development (this aligns with the findings at the national and regional/local government levels).

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) the 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. 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, as well as support from banks and other financial institutions with amended guidelines for inclusion in eco industrial networking activities.

Political support, i.e. with specific goals for lowering emission levels and promoting closed-loop systems (Sacchi & Ramsheva, 2017) and the renegotiation of regulations that restricts recycling of waste and by-products within firms and with other firms act as other incentives (Yedla & Park, 2017). Similar benefits are derived by embarking on EPR and EIs, which can act as an interface between eco-efficient industries and ecologically efficient consumption patterns (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).

Priority strategies for firms such as the conduct of seminars, focus group discussions and other forms of information dissemination activities, which highlight the benefits of IS, are essential for the implementation of IS. Involving the top management and executives of firms is a key strategy to ensue innovative action (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.

Contracts

Specific attention needs be devoted to the design of contractual mechanisms, which, if properly defined, can be a facilitator for establishing symbiotic relationships. In particular, a contract based on a transfer payment which re-aligns firm incentives to IS, is easy to design and particularly beneficial when demand uncertainty is not high, while turbulence is high. Such a contract would improve the number of IS stable relationships as well as to assure win-win conditions, i.e. the economic benefit of all firms is increased in the case of IS compared with its absence (Albino et al., 2016).

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) – 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 research and development for process redesign, reorganisation and the establishment of the 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

Efforts should be made to supplement individual company level R&D investment in technologies by encouraging broader collaboration among different organizations (Guo et al., 2016). Stimulation should occur at all points through the value chain (Hodgson et al., 2016), and international collaboration is crucial so that advanced technologies and management practices can be transferred from other countries (Guo et al., 2016).

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. Innovative PPPs, joint ventures, and cluster platforms could be some of the tactics for promoting long-term partnerships (Aid et al., 2017). 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).

Measurement

Conventional resource productivity (RP) evaluation methods for industrial parks (IPs) are usually limited in scope, as they do not differentiate between the different types of resources. The real resource consumption and environmental impact are usually hidden. In response to this limitation, the Adjusted Raw Material Consumption (ARMC) method was introduced. The method took upstream production efficiency and resource grades into consideration. The development of RP using the ARMC method helps to connect the assessment of regional material flows to the broader macro-level issue (Hu, Wen, Lee, & Luo, 2017).

Another key area is the quantitative assessment of various production processes, including carbon reduction from substitution of virgin materials, improvement of production technique and equipment (energy efficiency), reuse and recycle of some by-products, and reduction of total wastes, so that more valuable policy insights can be provided to industrial companies and industrial park managers (Albino et al., 2016). Assessment links into the three sections below.

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. Many different tools have indeed been developed over recent years to facilitate IS. In a recent literature survey of information systems facilitating the identification of IS Capelleveen et al. (2018) for example identified multiple existing tools, which were categorised into six different types based on their facilitation approach. These included:

1. Open online waste markets — digital environments for firms to find and establish partnerships for waste-to-resource exchanges.
2. Facilitated synergy identification systems — intermediaries to actively identify and connect firms to establish waste-to-resource exchanges.
3. Industry sector synergy identification — tools to determine potential waste-to-resource exchanges at the industry sector-level.
4. Social network platforms and communities — platforms to foster the sharing and exchange of IS knowledge through formation of online common interest groups and communities.
5. IS repositories — central knowledge management systems that organises and enables the sharing of IS knowledge.
6. Region identification systems for IS — tools for urban planners or policy makers to determine the potential of areas for IS development (Low et al., 2018).

The SymbioSys Tool for example corresponds to type 3 as it helps promote the efficient use of resources and new business models through the detection of the main synergies among companies based on the substitution of raw materials from waste, sub-products or recycled materials, and the possibility of new opportunities for collaboration in the sharing of infrastructure and services (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.

Building on the previous point, at the level of an industrial park, in order to prepare sustainable management policies, it is critical to have effective evaluation methods so that decision-makers can identify the key problems and prepare appropriate development strategies. Appropriate evaluation methods allow park managers to self-check their problems and prepare feasible development targets by considering their own realities (Zhe, Yong, Hung-Suck, Huijuan, Liang, & Tsuyoshi, 2016). Yet, there has been no agreed indicator system for an eco-industrial park around the world (Liu et al., 2018b).

Zhe et al. (2016) have however developed an emergy-based hybrid method for assessing IS of an industrial park. Others have investigated the comparison between direct benefits and co-benefits using an emergy-based co-benefits accounting for the implementation of eco-industrial development strategies in the scale of industrial park (Liu et al., 2018b). 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 improve CE related technologies. Advanced recycling technologies for example can create new synergy opportunities (Guo et al., 2016). 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.

Technology was deployed in the Korean EIP program to establish 17,600 databases for materials, 4000 databases for industrial sites, and 7100 databases for relevant organizations and human and infrastructure resources. These elements provided a solid foundational resource platform, which enabled IS projects especially during the first phase of the initiative (Park et al., 2016).

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	PURPOSE
Afshari, Jaber, & Searcy (2018)	Multi-objective mixed integer linear programming (MILP) model to optimise energy exchange flows between energy suppliers and users	A multi-objective mixed integer linear programming model for non-industrial purposes. Model is used to determine optimal energy partners in an industrial area and residential neighbourhoods in a Western European industrial park.
Albino et al. (2016)	Agent-based simulation model for symbiotic exchange networks	Agent-based simulation model to study spontaneous emergence of IS relationships coupled with quantitative approach based on enterprise input-output to model network of symbiotic exchanges.
Dong et al. (2017)	Hybrid evaluation model integrating process-based life cycle assessment (LCA) and input-output (IO) model	Hybrid evaluation model integrating process-based life cycle assessment (LCA) and input-output (IO) model to assess environmental benefits in whole supply chain. Based on local conditions, innovative urban IS is designed and analysed.
Leurent, Da Costa, Sylvestre, & Berthelemy (2018)	Techno-economic model to assess feasibility of transferring steam to industrial users	Assesses technical and economic feasibility of transferring steam sourced from nuclear plants to factories in France based on detailed spatial analysis.
Liu, Hao, Zhou, Yang, Zhang, & Su (2016)	Logarithmic Mean Divisia Index (LMDI) Model	Assess China's low-carbon industrial transformation.
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	Supports companies and network facilitators to integrate and analyse jointly economic and environmental issues. Enables decision-makers to analyse, through sensitivity analysis, the selling price



		of a waste, or minimal processing capacity of piece of equipment they wish to acquire.
Pan, Sikorski, Akroyd, Mosbach, Lau, & Kraft (2016)	Multilevel modelling and optimisation in EIPs	Series of systematic approaches for multilevel modelling and optimisation in EIPs which include building four-level modelling framework (from unit level to process level, plant level and industrial network level) for EIP research, applying advanced mathematical modelling methods to describe each level operation, developing efficient methodologies for solving optimisation problems at different EIP levels, and considering symbiotic relations amongst three networks (material, water and energy networks) at top EIP level with boundary conditions of economic, social and legal requirements.
Ramaswami et al. (2017)	Multi-scale modelling of linkages across intra-city, hinterland, provincial, grid region and national scales	Assesses local health and national CO2 benefits of urban–industrial symbiosis.
Ren, Liang, Dong, Sun, & Gao (2016)	Model for sustainable design of integrated industrial system	Model for sustainable design of integrated industrial system with objective to maximize profit and integrated energy index of sustainability of integrated industrial system simultaneously. PSO algorithm is proposed to solve the model and multiple Pareto solutions can be obtained for decision-makers.
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	Helps to understand current levels of sustainability of steelworks, which should be used as starting point for development both of pollution control measures and of symbiotic waste reutilization scenarios needed to maintain competitiveness of an industrial plant.

Røyne, Hackl, Ringström, & Berlin (2017)	Life Cycle Assessment (LCA) for environmental evaluation of industry cluster strategies	Assesses upstream and on-site consequences and estimates the reduction in fossil CO2 emissions in downstream processes.
Sun et al. (2017b)	Integrated material flows analysis (MFA) and emergy evaluation model	Integrated material flows analysis (MFA) and emergy evaluation model to investigate environmental and ecological benefits of urban IS implementation in one typical industrial city in China.
Wang, Wang, & Song (2017)	Integrated stability analysis	Promotes and manages stability of IS networks.

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, including both the demand and supply sides, is not sufficiently developed, and there is an insufficient amount of wastes to substitute for all fuels and materials used in production processes (Ohnishi, Dong, Geng, Fujii, & Fujita, 2017). Too little or too much diversity (i.e., the inability to match material flows) 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 issue for EIP development in Korea. The uses of industrial by-products are regulated and limited by the “Waste Control Act” (amended in 2007), even when recycling technologies are available and potential users are specified. In one project, the Waste Control Act limited the use of wastewater sludge (e.g., as a complementary fuel at a coal-fired power plant, soil amendment, land cover, or input material for plastic production), though this was later deregulated (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. Different stakeholder objectives can also create conflicts between locators, which result in limited sharing of resources, e.g., information (Bacudio et al., 2016).

2.2.3.6 Coordination and management and leadership support

A lack of clear coordination has been identified as a prohibitive problem by several authors (Horvath & Harazin, 2016). Institutional support is imperative; where this is lacking there is little integration, coordination and communication. Improper management is a major cause of this problem, for example with an uneven distribution of resources and benefits, 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. Current management practices in many industrial plants, as a consequence, have yet to include an IS approach as part of their policy (Bacudio et al., 2016). A cascade of other problems comes from unengaged leaders, which includes a lack of willingness to collaborate. 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 players, 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. Adopting IS requires knowledge in multiple aspects such as technical and organisational expertise. Many people do not have awareness of IS concepts or sufficient understanding of IS terminologies due to a lack of mechanisms to educate potential stakeholders (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).

Other authors identify that one of the main challenges to the emergence of IS lies in the inherent conflicts of interest among potential partners. 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 — therefore the challenge is to determine a rational and equitable allocation of the benefits among the partners. Power or status asymmetries (i.e.,

who wants to partner with whom) 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. From many standpoints, including technical ones, IS is already a viable option for most industries to adopt. In fact, for almost any waste, there are available technologies to convert (recycle) it into a resource. However, there are significant barriers which are often of non-technical nature, such as, a lack of trust (Low et al., 2018). Trust is a prerequisite of collaboration since most stakeholders have minimal or no prior cooperative mechanism in the form that is required for IS. (Bacudio et al., 2016). 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 as follows. Firstly, 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. Secondly, the case studies review results are presented, beginning with the triggers, then the enablers and finally the barriers. 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).

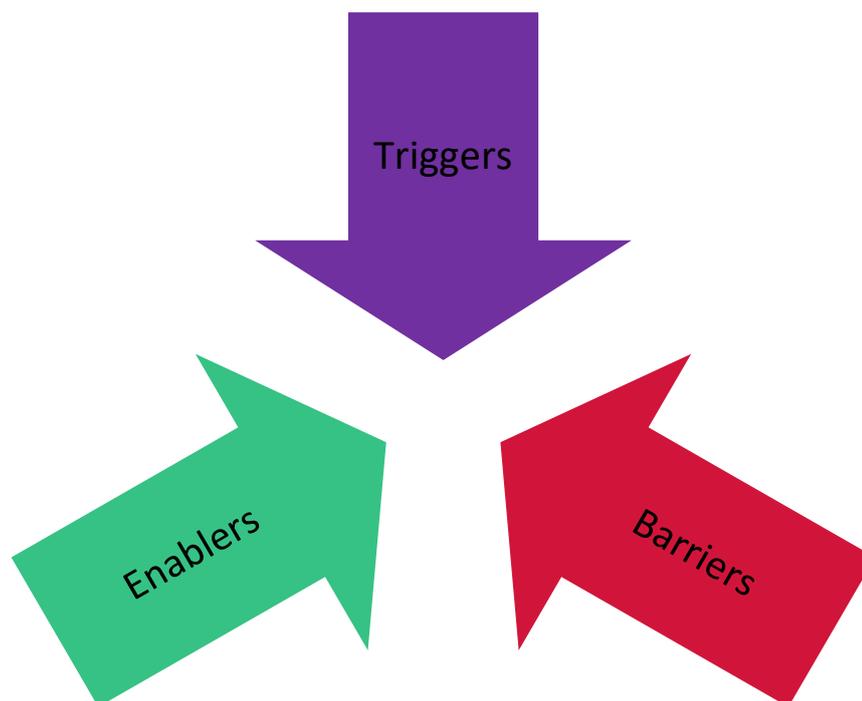


Figure 2 - Analytical framework

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.

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 creation of a large integrated recovery, treatment and elimination centre for 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. The Taranto district in Italy was declared an area with a high risk of environmental crisis due to alterations to the ecological conditions of the ground, water and air surrounding the district posed a severe risk that was not only environmental but also social due to the negative

impact on the local population's health. 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.

After 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 set up 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 in support of collaborative business strategies in resource management. 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 set up 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 high-ranking managers in the local companies. 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 has played an important role 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 avenues for waste streams as feedstocks for others, acting as an information barrier (many possible waste uses are not known to firms). 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 human resources and capital 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

Difficulties in acquiring permits for industrial development emerged in CS 2, where Chamusca is controlled by Lisbon and Tagus Valley Regional Development Agency (CCDR-LVT). 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)
 - How would you describe the relationship between the partners in the resource synergy?
11. How would you describe the **relationship** between the partners in the resource synergy?
- Transactional (one-off, mutually beneficial agreements that do not substantially integrate operations or share assets)
 - Contractual (two parties begin to work together to select non-critical activities)
 - Relational (companies come together to each share the risks and rewards in more critical tasks)
 - Integrated (complex and interdependent relationship built on trust and encompassing critical tasks)
 - 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.

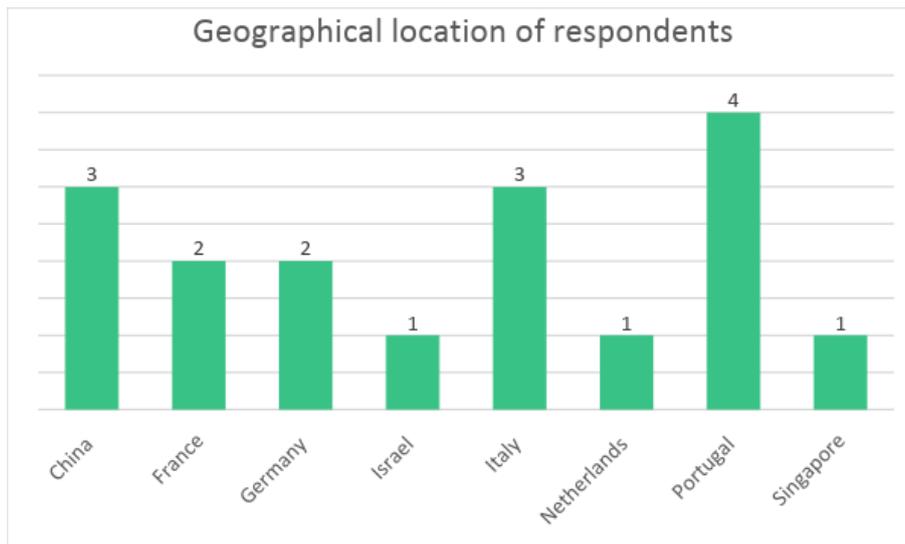


Figure 3 - Geographical representation of survey respondents

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.

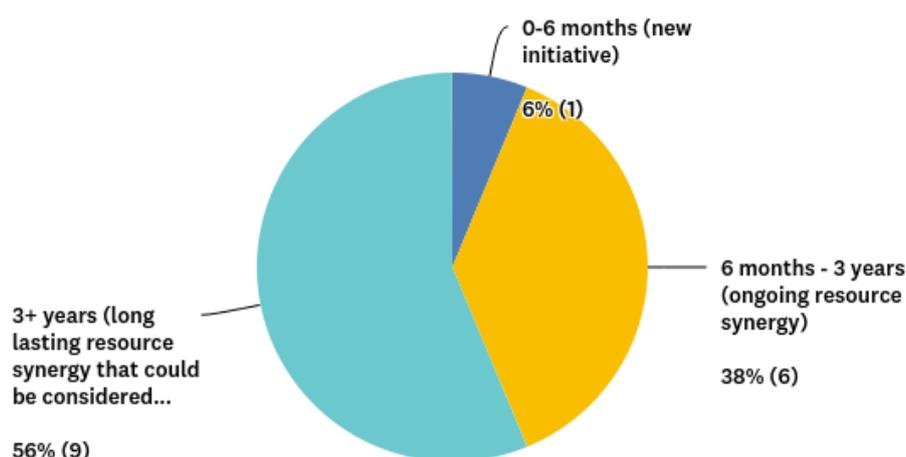


Figure 4 - IS maturity of respondents

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.

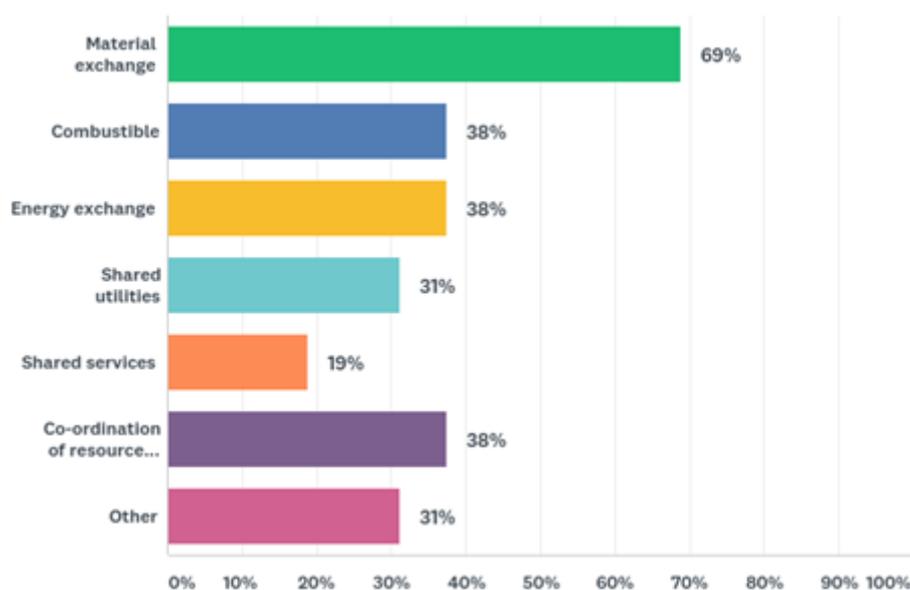


Figure 5 - Resource synergy initiatives

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
<p>More efficient use of materials and energy streams leading to lower overall costs.</p> <p>Less wasted resources.</p> <p>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.)</p>	<p>Reduction or avoidance of raw materials consumption.</p> <p>Reduced consumption of energy.</p> <p>Reduced waste.</p> <p>Alternatives to raw materials.</p> <p>Address water scarcity and preserve organic matter.</p> <p>Reduced impacts of disposal residues and raw materials supply.</p>	<p>Less road occupation.</p> <p>Less pollution, leading to a better quality of life.</p> <p>Waste management improvements. (A waste management plan introduced for municipal garbage for nearby villages.)</p> <p>Low water services cost due to low operation costs.</p> <p>Residues can be valorised in the same territory in which the product is used and the raw materials are bought.</p>

<p>Reduced management costs for residues disposal and raw materials supply.</p> <p>Raw material sourced at a lower cost.</p> <p>Cost sharing.</p> <p>Company compliance with environmental protection policy (becomes an "environmental protection" enterprise) means production can continue.</p> <p>Highly efficient circular economy business development.</p>	<p>Reduced pollution, including less emissions from incineration.</p> <p>Less transport leading to less fuel being required leading to lower CO2 emissions.</p> <p>Landfill is avoided.</p> <p>Largely reduced municipal garbage in nearby rural areas.</p> <p>Can guarantee that the waste produced by industries is totally recovered and well treated.</p> <p>Align industry with sustainability and circular economy goals including reduction of CO2 emissions.</p>	<p>New supply chains (residues treatment and transportation, for example) can provide new occupation and more jobs.</p> <p>Existing jobs maintained, and new jobs and employment created.</p> <p>Cooperation of companies generating a positive vibe in a region.</p> <p>Catalysation of the circular economy.</p>
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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.

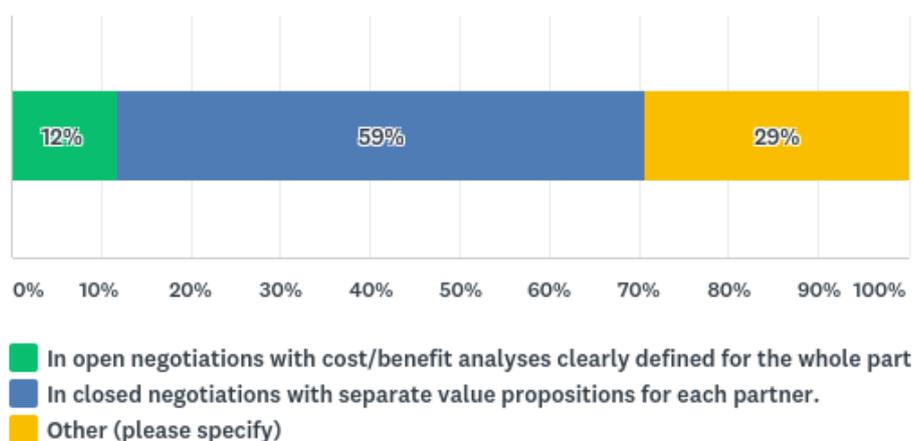


Figure 6 - Defining the business model of the resource synergy

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 (one-off, mutually beneficial agreements that do not substantially integrate operations or share assets), contractual (two parties begin to work together to select non-critical activities), relational (companies come together to each share the risks and rewards in more critical tasks), integrated (complex and interdependent relationship built on trust and encompassing critical tasks) or a combination of several types of relationships.

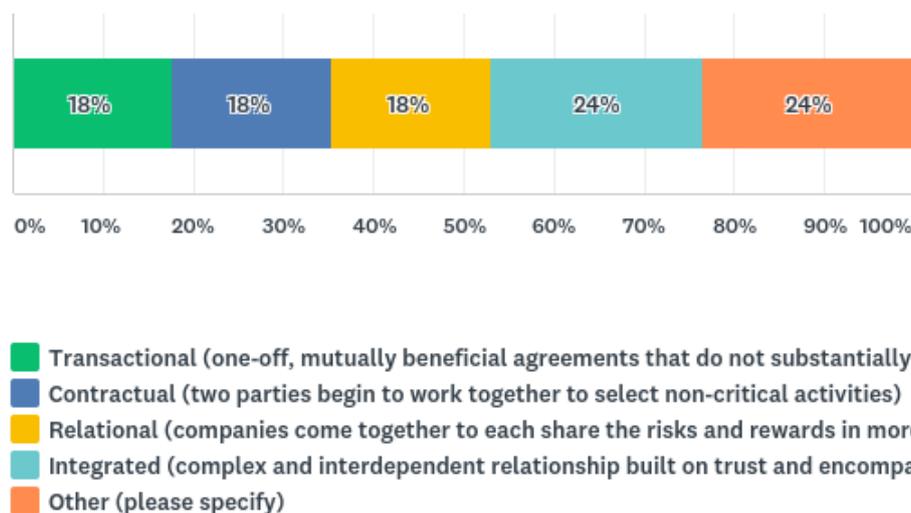


Figure 7 - Relationships between partners

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 CO2 emissions reduction targets.

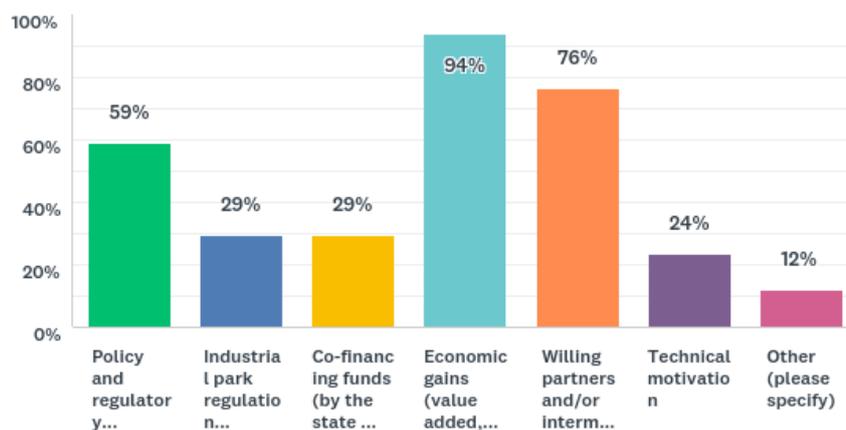


Figure 9 - Incentives

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.

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