The SAGE Handbook of Nature

Edited by
Terry Marsden

Industrial Symbiosis – a bottom-up business response to nexus challenges

By Teresa Domenech

Extraction and consumption of resources have achieved historical heights during the last decade. This has allowed for the rapid industrialization of emerging economies but has also aggravated global problems such as growing volumes of waste, climate change and lost of biodiversity. Commodity markets have also experienced profound changes as increased demand has led to higher volatility (e.g. between 2000-2010 metal prices increased by 250% (ECORYS, 2012), followed by important price drops after 2011). Concerns have also been raised about scarcity and geopolitical implications for a number of raw materials that are critical in modern technologies (ECORYS, 2014). These changes have sparked the attention of the business community around issues of resource efficiency and supply security and have created receptivity for alternative ways to manage resources, with an emphasis on efficiency and better use of underutilized resources.

Industrial symbiosis has been defined as a system approach in which "*traditionally separate industries [engage] in a collective approach to competitive advantage involving physical exchange of materials, energy, water and by-products*" (Chertow, 2000). Although examples of resource exchanges between companies can be traced back to the industrial revolution and have been a common practice in sectors such as the chemical industry, the key innovative element of what has been called 'industrial symbiosis' lies in its *inter-sectoral* dimension to use waste streams as a resource across different sectors and categories of resources. Building on the wider framework of industrial ecology, industrial symbiosis provides a systemic approach for the understanding of resource flows in the economy and for identifying areas of inefficiency and potential for enhanced efficiency. This encompasses all types of resources, including energy, water, land and materials, and all human activities, primarily the manufacturing sector but also the service and household sectors. Perhaps the most well-known example of industrial symbiosis is the industrial symbiosis network in Kalundborg (Denmark), where industries from sectors as different as oil refining, chemical, production of construction materials and power generation, among others, have created a web of physical exchanges that have proven beneficial not only in environmental terms (reduction of environmental impacts, including water savings, reduction of emissions and waste) but also in economic terms (through important cost savings and new revenue sources).

From the resource nexus perspective, industrial areas and industrial estates provide a clear example of resource nexus 'in action' and industrial symbiosis offers a complementary approach to the inter-linkages of resources with a focus on the output side. This chapter explores 'resource nexus' in the manufacturing sector and the relevance of industrial symbiosis, as a bottom-up business approach to find alternative productive uses of underutilized resources through industry collaboration. Building on a review of case studies in Europe and China, the chapter provides an overview of inter-industry resource management practices with an emphasis on those with potential to reduce environmental impacts of manufacturing activities, preserve resources and create value. The chapter also discusses critical aspects for successful deployment of industrial symbiosis such as improvements on the data/ knowledge base of material flows and resource uses, organizational aspects of networks and entrepreneurial culture shifts. The chapter concludes with lessons for the 'resource nexus' perspective from industrial symbiosis practice.

1. Introduction

Manufacturing accounts globally for approximately 16% of global GDP and 14% of employment (McKinsey, 2012). However, the size of the sector varies greatly between countries, depending on their stage of development. Manufacturing has undergone a process of profound change over the last decades and has been a motor of development for emergent economies. Moreover, the sector has played a pivotal role in value creation and innovation (McKinsey, 2012). Industrial and manufacturing activities, however, have also been a major contributor to resource consumption and generation of waste and emissions. Emergent countries have experienced an unprecedented pace of development that has led to rapid increases in consumption of resources and generation of waste. While volumes of waste streams have grown, so has their complexity and hazardousness, as primary industries account for a large part of the industrial activity in emerging countries (UNEP, 2014). This is specifically problematic, as in many cases these countries still lag behind in terms of recycling and waste processing technologies (UNEP, 2014), leading to environmental and health threats. In terms of resource and energy efficiency, the sector has also experienced a deep transformation. Traditionally resource intensive sectors such as steel production have managed to reduce their energy consumption and emissions significantly. For example, the energy required to produce a tonne of steel has been reduced by 60% since 1960 (World Steel Association, 2015).

The resource nexus perspective is especially relevant for the industrial sector where different types of resources, materials, water, land and energy are employed to transform raw materials into intermediary and finished products. Industrial symbiosis fits perfectly well into this perspective as it provides a system approach to the understanding of resource flows between different activities and unveils opportunities to increase the efficiency of the system by identifying underused resources and waste flows that can be reutilized by other sectors and activities.

This chapter introduces the concept of industrial symbiosis from the perspective of resource nexus and provides some insights into the potential benefits and challenges of such approach. Next section presents the concept of industrial symbiosis, typologies and summarizes its key characteristics. Section 3 reviews some practical experiences of IS implementations and discusses main drivers and barriers. Section 4 concludes with lessons learnt from the practical application of IS for the resource nexus approach.

2. Definition of industrial symbiosis

Industrial symbiosis is a sub-field of industrial ecology. The concept of industrial ecology (IE) emerged as a system approach to understand the interaction between man-made systems and natural systems. A comprehensive definition of IE is given by Graedel and Allenby (2010):

"*Industrial ecology is the means by which humanity can deliberately approach and maintain sustainability, given continued economic, cultural, and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems view in which one seeks to optimize the total materials cycle from virgin material, to finished material, to component, to product, to obsolete product, and to ultimate disposal*." (Graedel and Allenby, 2010)

Within industrial ecology, industrial symbiosis is principally concerned with the "*cyclical flow of resources through networks of businesses as a means of cooperatively approaching ecologically sustainable industrial activity*" (Chertow, 2000). Therefore, the emphasis of industrial symbiosis is on the interfirm interface of IE, focusing on ways of resource optimisation based on collaboration among different industries and activities. It aims to overcome the traditional boundary of the organisation to achieve better environmental collective performance offered by a more global approach to material and energy flows.

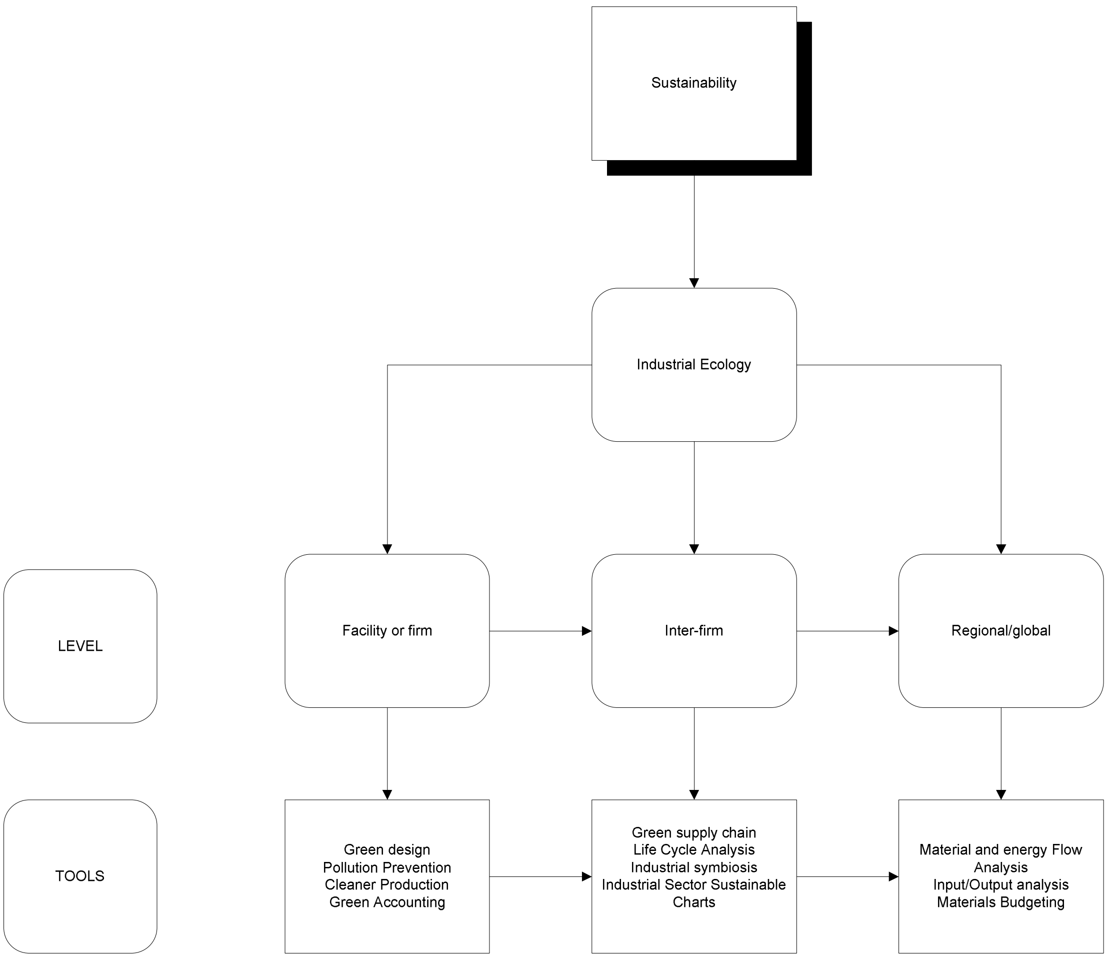


Figure 1: Dimensions of Industrial Ecology; Source: adapted from Chertow, 2000.

A well-established definition of industrial symbiosis is that offered by Chertow (2007):

> *"Industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchanges of materials, energy, water and/or by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity".*

In 2012, Lombardi and Laybourn proposed a redefinition of the concept that emphasised its innovative component and economic dimension, where IS not is only seen as a way to better use reuses but to also contribute to eco-innovation and value creation:

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

One of the practical representations of industrial symbiosis is an eco-industrial park. The term eco-industrial park generally refers to eco-industrial projects taking place within the narrower geographical scope of an industrial estate. The definition proposed by Indigo Development has wide acceptance in the literature. Indigo Development defines Eco-Industrial Park as (Lowe, 2002):

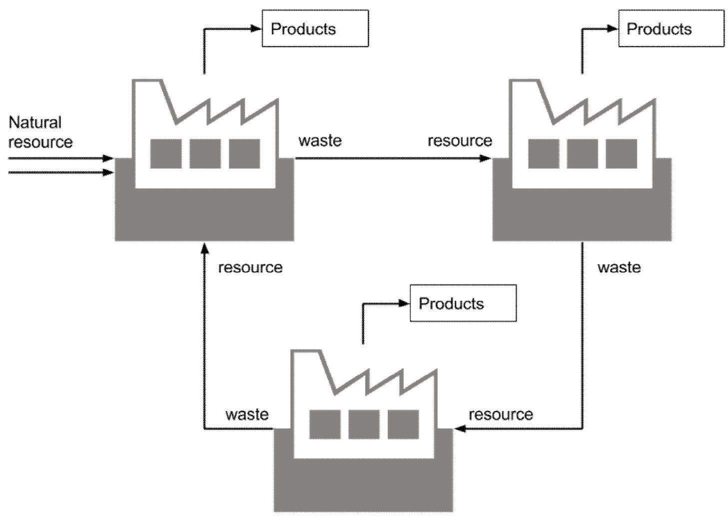
> *"a community of manufacturing and service businesses located together on a common property. Member businesses seek enhanced environmental, economic, social performance through collaboration in managing environmental and resource issues. By working together, the community of businesses seeks a collective benefit that is greater than the sum of individual benefits each company would realise by only optimizing its individual performance".*

Although in many instances industrial symbiosis happen to material and energy exchanges "*among co-located firms*", within the boundaries of a park or an industrial area, IS networks can happen at different spatial levels and include collaborative interactions of companies that are not necessarily co-located, operating on a regional or even national scale to optimize resource use and utilize resources previously wasted or downgraded. Another key characteristic of IS projects is that they may generate concrete economic and environmental benefits both for the companies involved as well as for the wider society.

From the perspective of resource nexus, IS is an exemplification of how resource nexus happens in the praxis as it systemically considers all different types of resources, including materials, water, energy and even knowledge and space as the basis for the interorganisational collaboration and system optimization. Although physical exchanges, including material, energy and water, tend to be at the core of IS networks, aspects such as exchange of knowledge, know-how, facilities and logistics are also important contributors to the economic and environmental advantages of IS networks. It is also important to note that transactions of one type of resources may trigger collaboration in other areas, involving other types of resources, as learning and transactions costs may be reduced and further opportunities identified (Bleischwitz 2007). Chertow (2007) identifies three primary opportunities for resource exchange: 1) by-product reuse; 2) utility sharing and 3) joint provision of services.

IS differs from traditional waste management practices as it involves the unveiling of innovative ways to identify underutilized resources and find alternative optimal uses for them. Chertow (2007) proposes the "3-2 heuristics" rule to distinguish IS from other types of waste/ by-product exchanges. According to this, IS networks would involve at least three different entities, none of which is primarily a recycling company, exchanging at least two different resources. Chertow also refers to "kernels" or "precursor" to describe those situations where the 3-2 criterion is not met yet but there is a potential to evolve to a full IS. Some authors have also emphasized the innovative dimensions of IS networks that go beyond standard waste management practices.

In conclusion, industrial symbiosis is characterized by complex networks formed by different industrial actors belonging to different sectors of activity that, by collaboration and networking, achieve a better system optimisation in the use of resources, energy, water, technology and knowledge, resulting in better environmental and economic outcomes, from a sustainability perspective.



Core characteristics of industrial symbiosis developments relevant for the resource nexus are listed below:

- It implies different industrial actors, belonging to different sectors of activity
- It involves more than one by-product exchange or resource sharing
- It involves different types of resources including water, land, energy and materials and interactions among them. These resources are optimised through collaboration
- They generally transcend mere market exchanges and involve different degree of cooperation, collaboration and innovation
- collaboration takes place through networking
- the environmental and economic outcomes should surpass the outcomes that the individual organisations would obtain by acting individually

By focusing on inter-company exchanges, aspects less intrinsic to the company level such as pollution reduction targets and eco-design of products, or aspects that move beyond the supply side such as promotion of sustainable consumption are generally outside the scope of industrial symbiosis. Having said this, involvement in industrial symbiosis projects generally creates changes in the company culture and mindset that can contribute to internal change and promote further commitment in other areas.

In recent years, the concept of IS has been associated to that of the Circular Economy (CE). The CE refers to an alternative system to the linear economy of extracting, consuming and disposing, where resources are kept in productive circles for longer, value is maximized. The Ellen McArthur Foundation (EMF, n.d.) affirms that *"the CE is one that is restorative and regenerative by design, and which aims to keep products, components and materials at their highest utility and value at all times, distinguishing between technical and biological cycles".* While industrial symbiosis optimizes existing systems and aims to restore natural capital by reducing intake of virgin raw materials and minimizing the generation of waste, the circular economy notion is more prescriptive. It generally implies changes of processes and systems so that resources are used more efficiently and flows become circular with less wastage of resources and consumption of energy. Applications of this still happen very much in niches but they show potential for scaling up. Industrial symbiosis is at the core of the circular economy through the promotion of opportunities to optimize the use of resources. In most cases, innovation in industrial symbiosis is demand-led, that is, driven by the need to clean-up or restore a residual by-product to become a raw material. The circular economy concept also includes the dimension of process design and evolutive optimization and thus adds a dynamic perspective to the concept of IS.

Both IS and CE are inspired by "the ecological metaphor" (Ehrenfeld, 2004), which compares the efficient operation of ecosystems where resources and materials are continuously reprocessed and reused, assimilating waste to resources, as waste from one process or organism is a resource for another process or organism, to the wasteful and inefficient operation of industrial systems, where the conversion of wastes into resources is far from being achieved. The basic idea behind the captivating image of the "ecological metaphor" is that, the functioning of natural systems, with an efficient biological cycling of material flows throughout the system, maintained by the self-coordinated activity of producers (plants), consumers (animals) and decomposers (fungi and bacteria), can serve as a model for the reorganisation of the societal systems of production and consumption. Graedel (1996) explored the biological characteristics of an organism and discussed the degree to which they can be extrapolated to industrial or social "organisms". From the comparison between industrial and biological systems, he concluded that the main differences were: 1) the role of the decomposer is undertaken in industrial system by the recycler, b) the industrial system has an additional actor, which is the disassembler and, finally and fundamentally, c) whereas high efficiency in the use of resources is achieved in natural systems, industrial systems generated great losses of resources throughout the process. Other differences are the divergence in the time scales when comparing biological processes and industrial systems (Ayres and Ayres, 2002) and the physical proximity and "functional matching between producers and consumers" in natural systems, in comparison to the displacement between production and consumption in industrial activities. The "ecological metaphor" thus aims at inspiring the transformation of industrial systems by mimicking the efficient energy and material flows in natural ecosystems.

The ecological metaphor identifies a core of features in biological systems that "should" be mimicked by industrial systems (Boons and Baas, 1997):

- Energy requirements, consumption of scarce materials and waste generation should be minimized.
- Waste flows should be used as raw materials for industrial processes, mimicking the cycling of nutrients in biological systems
- The system should be "diverse and resilient", so that it can recover easily from shocks.

3. Industrial symbiosis in the praxis

The theoretical development of the field has run in parallel to attempts of practical implementation of its principles to real world settings. In fact, the main model of industrial symbiosis systems is based on the case of Kalundborg, a small Danish town that has developed an IS network over the last four decades creating a complex web of synergies and exchanges that have proven both economically and environmentally beneficial (Jacobsen, 2006). Following the inspiration of Kalundborg a number of initiatives have emerged in different parts of the world. Some of these developments have happened spontaneously as a response to the contextual conditions while, in other cases, IS initiatives have been the result of planning and policy intervention.

Different institutional frameworks and conditions have also given rise to different types of developments, ranging from industrial estate-focused strategies, such as in South Korea to nation-wide initiatives such as the former UK National Industrial Symbiosis Programme (NISP). In the next section, we briefly review the paradigmatic case of Kalundborg and current developments in Europe and latest developments in China, one of the areas that has concentrated much of the action in IS in the last decade.

3.1 The IS symbiosis network of Kalundborg

Kalundborg is situated in the West Zealand County, on the west coast of the island of Zealand (Sjælland), in Denmark. Retrospectively, the symbiosis in Kalundborg can be described as a process of development of collaborative linkages between different industries located in near proximity to each other. This process has been the result of the material and social conditions that characterise the area. From bilateral exchanges, the collaboration gained in complexity, leading to a dense network of IS exchanges. The process of cooperation has had an impact on the structure of relative costs of the companies and global environmental impact of the industrial area.

The first "symbiotic" projects emerged in the 1960s just after some of the major players of the network located in the area. In the beginning, the projects were not framed as environmental solutions; they were initiated by the companies, in a combination of alliances and commercial agreements. The institutionalisation of the symbiosis only came after. The projects included in the symbiosis comply with three main criteria: a) allow the reutilisation of waste flows as inputs for other processes; b) entail both environmental and economic benefits compared to the business as usual scenario and c) require companies to work "across the fence".

Figure 2 below provides a graphical representation of the IS ties developed in the network of Kalundborg.

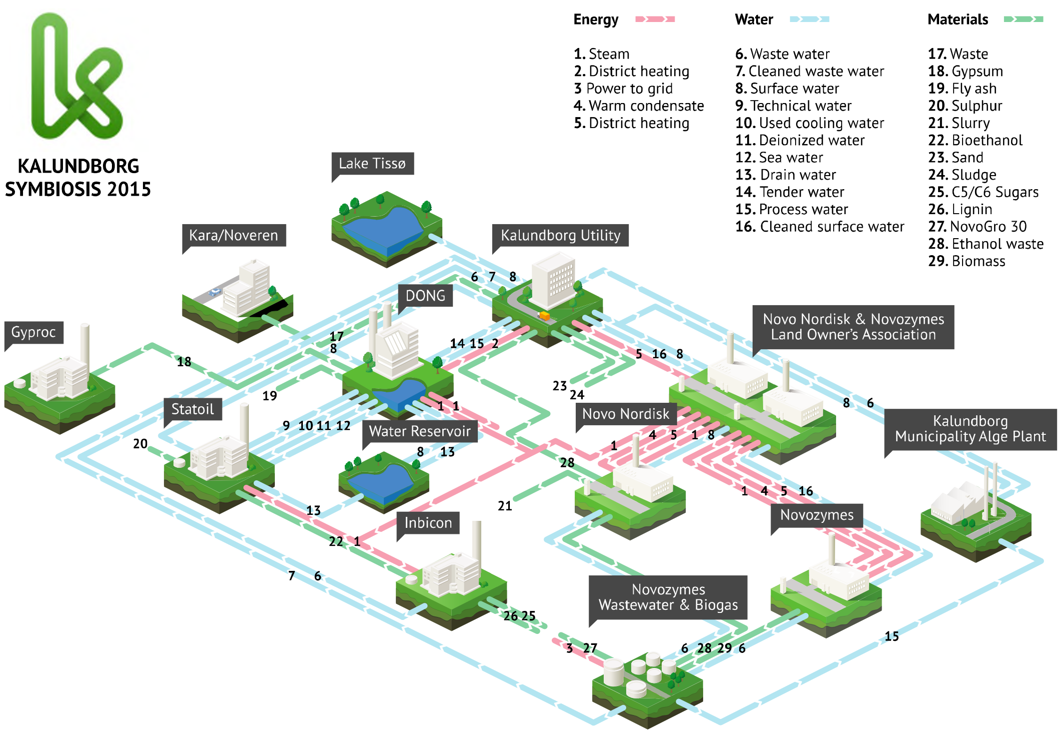


Figure 2: Industrial Symbiosis Network at Kalundborg (Denmark); Source: www.symbiosis.dk

The IS network has developed gradually over the years. The genesis of the IS network can be traced back to 1960, with the commissioning of the power plant (1959) and the refinery (1961). The refinery's processes had a large requirement for cooling water and the municipal water supply was insufficient to cover this demand. The solution found was to source the water from lake Tisso by running a pipeline about 13 km long. The cost of the investment could not be assumed by the municipality, so the refinery financed the project. If considered in isolation, this can hardly be considered an IS project; however, it represents the beginning of the process of cooperation that resulted in a complex IS network. The next project developed as a result of the location of a plasterboard manufacturer, Gyproc, in the area. In the production of plasterboard, gypsum has to be burned, decalcinated, suspended in water and then drained so that excess water can evaporate. The drying process requires a lot of energy and an agreement was signed between Gyproc and the refinery to use the excess gas from the refinery. This project eventually died as the refinery found a more efficient use of the gas and Gyproc changed to alternative sources (butane and then, natural gas).

The expansion of the power station in 1973 increased its water requirement, which was sourced from lake Tisso by using the existing pipeline. As a consequence of the strengthening of environmental regulations, introduced in the early 1970s in Denmark, Novo industry was forced to separate the effluents and find a solution for the waste biomass generated in the enzyme production process. The most cost-efficient alternative was in this case to apply a heat treatment to kill potential microorganisms, so that it could be used as fertiliser and be distributed free of charge among adjacent farms (around 80,000 tonnes a year), through a network of pipelines and trucks.

The next IS project developed within the network, involved the use of fly ash, from the power station, in different cement companies in Jutland. Other IS linkages were generated in order to reuse lost heat from the power station. The power station used sea water as cooling water. This water is re-circulated and returned to sea, although at a higher temperature. This proved to be an excellent medium to grow fish and it spawned an entrepreneurial project generated by the IS network (first as part of Asnaes and later as a small private company).
Also changes in the regulatory framework this time affecting energy production favoured the development of another IS project. The new regulation stated that power stations became not only

suppliers of electricity but also suppliers of energy, such as heat for district heating. This fostered the introduction of a cogeneration system in the power station, generating three additional flows: 1) heat to be used for district heating, 2) steam to be used in Novo industry (covering all its demand) and 3) steam to cover part of the requirements of the refinery (around 15% of total needs).

The scarcity of water in the area was again the origin of two new IS projects. Novo industry replaced ground water for surface water for cooling purposes. The other project consisted in reusing the cooling water from the refinery as raw boiler feed water for Asnaes. As some of the biomass generated by Novo was yeast slurry, a valuable by-product from the insulin production, the company separated this fraction and sold it for animal feed (in the pig industry). In 1990, the refinery built a desulphurisation unit to remove the sulphur from the gas and transform it into liquid sulphur that was sold and shipped to a company in Jutland for the production of sulphuric acid. However, as the market value of sulphur dropped, the refinery decided to produce ammonium thiosulphate that could be sold directly as fertiliser, and generated better revenue.

The construction of a waste water treatment plant for the refinery also allowed reuse of the treated water by the power station as second or third-class water, to be used in less demanding processes. The next project also involved the refinery and the power station. The refinery piped excess gas, once desulphurised, to be used as supplementary fuel by the power station. Regulatory requirements also forced the power station to desulphurise its emissions. Among the alternative methods, they selected a sulphur dioxide scrubber that generated calcium sulphate, or gypsum, as a by-product. This by-product could be used as an input material by Gyproc, covering most of the gypsum needs. In 1995, also the power station constructed a water basin, to reuse the drain water and use it as third-class water.

In 1996 the Symbiosis Institute was formed. This can be considered another IS project, although of a different nature. Among the aims of the institute was: a) favouring interaction between companies, b) generating new ideas and projects for the IS network and c) to publicise and give information about Kalundborg IS network so that it could be used as a referent for further developments somewhere else.

At the end of the 1990s, a new company located in the area and joined the symbiosis network. Former Soilrem (now called Jordrens), a soil remediation company, started to use the sludge from the municipal wastewater plant to speed up the process of aerobic digestion of contaminated soil.

For some years, the power station used ori-emulsion as fuel. The fly ash generated by this fuel was of a different composition and had important concentrations of oxides of nickel and vanadium. This made the fly ash unsuitable for the cement industry, but it was possible to recover and reuse the content of nickel and vanadium, so it was sent to a company in England that recovered those metals. This, thus, generated a new exchange, in this case with an external actor. The ori-emulsion is not used anymore and therefore this tie has been stopped. The power station requires a fraction of water of high quality for the boilers. This water needs to be treated by decarbonisation and osmosis to make it suitable for this purpose. The refinery also requires a small fraction of pure water for some of its processes. Instead of investing in the equipment for the purification of the water, they reached an agreement with the power station and run a pipeline to use some of its high quality water.

In 2004, another project to save ground water was undertaken by Novozymes and the municipality. To reduce the pressure over ground water resources, which are scarce in the area, Novozymes decided to treat surface water up to drinking standards, so that it could replace ground water in some technical processes. A water works was built together with the municipality for this purpose, allowing Novozymes to use one extra million m3 of surface water.

Another synergy consists of a bilateral collaboration between the power station and the refinery. As a result of the extension of the refinery they required more cooling water. They studied the possibility to use sea water for cooling, but this required a high investment. The power station already had one sea water installation and therefore, they reached an agreement to share the use of the installation at the power station and construct a pipeline to the refinery.

More recently, a number of new synergies within the field of bioenergy have emerged. Since 2009, the Inbicon Biomass refinery uses local straw for the production of bioethanol and lignin pellets and Molasses. Dong energy has also a demonstration plan to gasify local biomass (Chertow, 2015). These new developments open up new opportunities to diversify energy production and demonstrate the ability of the system to innovate.

Kalundborg proves that IS is truly based on the resource nexus and that the optimization of some resources have developed further opportunities to reuse, reutilize other resources. For example, water optimization led to exploration of other synergies such as reuse of waste steam and heat from the power station. In most cases, key industrial actors deal with a wide range of resources, including water, materials and energy. The ways one type of resource is optimized have impact on the management of the other resources. Knowledge and innovation happening in the management of one type of resource permeates to other resources. In Kalundborg water scarcity was the main driver for companies to engage in collaborative activities in the first place. Know-how in collaboration soon promoted collaboration in the optimization of other underutilized resource streams. Kalundborg has demonstrated over the years a high degree of resilience. While some scholars have pointed at the risk of industrial symbiosis to create interdependencies between industrial units that could increase vulnerability to external shocks (reuter et al., 2005; Sagar and Frosch, 1997), Kalundborg has demonstrated high adaptability and, in an era of outsourcing of industrial activities to China, Kalundborg has remained quite stable. In fact, IS may have been one of the elements contributing to the stability of industry in the area over the years.

3.2 Industrial symbiosis in China

While kalundborg is a clear example of bottom up IS development, China exemplifies the top-down approach to IS. Industrial areas have experienced an exponential increase in China in parallel to the growth of its economic power. The very rapid pace of IS activities is a result of: 1) the rapid process of industrialization and large volume of waste/underutilised resources available; 2) the introduction of ad-hoc policies that target resource efficiency through industrial symbiosis and the circular economy to foster efficient use of industrial resources and reduce resource depletion and pollution concerns. In 2011, there were at least 1568 industrial areas, producing about 30% of the Gross Domestic Product (Yu et al., 2015). China now produces about 50% of world aluminum and 60% of cement and consumes some 25.2 billion tonnes of resources (Mathews and Tan, 2016). Even though steep improvements have been achieved in recent years, resource efficiency is still an area that needs addressing. In 2014 China generated 3.2 billion tonnes of industrial waste, of which only 2 billion were recovered (Mathews and Tan, 2016). Industrial symbiosis and the opportunities of the Circular Economy (CE) have attracted increased attention in this large country. Already in the 11th five year plan covering the period 2006-2010 there was a whole chapter on the opportunities of the circular economy. The need to reduce consumption of resources and find solutions for pollution problems led the Chinese government to introduce stringent reduction targets for energy consumption and emissions in their 12th five-year plan covering the period 2011-2015 and the circular economy acquired the status of a national development strategy This was based on the achievement of previous plans. In fact, the 11th five-year plan included ambitious mechanisms to promote the circular economy, including the Circular Economy Law introduced in 2008 and city and industrial park demonstration programmes. Targets have been set to reduce CO2, NOx and SOx among others. Most of these targets have been extended in the new 13th five-year plan (Matthews and Tan, 2016). Also specific sectors have to meet stringent targets in waste reutilization, e.g. 75% of chemical waste has to be reutilized and 100% has to be effectively treated (Ding and Hua, 2012) or 72% of industrial solid waste needs to be recovered and resource productivity should increase by 15%. This has been accompanied with province regulation to resource and waste reutilization. In fact, since beginning of 2000, Eco-industrial parks have been seen a viable way to reduce emissions, preserve resources and increase efficiency and diverse actions have been implemented to fully exploit the opportunities of industrial symbiosis applied to industrial areas (Shi et al., 2010). In fact the plan defined a "10-100-1000" strategy (Matthew and Tan, 2016), which includes 10 major programmes to increase recycling of industrial waste, reconvert industrial estates, develop of sort of recycling and waste management system; 100 demonstration cities and 1000 demonstration projects of businesses or industrial parks. These huge efforts have started to give fruits and an increasing number of research papers have been published discussing the learning outcomes of these initiatives (Zhang et al., 2010; Shi et al., 2010; Liu et al, 2012; Geng et al, 2010). National level parks of Cao-Jing (Shanghai) and Nanjing and Tianjin (TEDA) have been accompanied by regional/ province initiatives in Shanxi, Zhejian, Guangxi and Shandong among many others (Ding and Hua, 2012).

The IS experiences in China have resulted in outstanding environmental and economic benefits. For example, Ding and Hua (2012) report a complex network of IS synergies in the Shanxi Province around the coal industry. Coalmines and power plants have created a complex web of synergies that reutilize waste streams such as slags, off-gases, coal sludge and tars and fly ash to produce silica, alumina, cement and other products (Ding and Hua, 2012). In parallel to this, the eco-industrial park has created a regenerative network whereby land restoration projects have brought mined land into cultivation and plantation (Ding and Hua, 2012).

Yu et al. (2015) report growing IS activity in the Rizhao Economic and Technology Development Area (REDA), which has become a Circular Economy demonstration project. The area concentrates a variety of industrial sectors including cereal oil production, pulp papers, machinery, food and chemical sectors among others. Based on a number of relatively simple initial exchanges around food by-products and waste textiles, the area has evolved into more complex synergies including the reuse of coal ash and slag for cement production and by-products from oil and fat industries to be used as fertilizers. More recently waste molasses are sent to the alcohol plant, waste CO_2 from the alcohol plant to the beverage producers, scrap metals to metallurgical plants and wood chips and sludge to produce charcoal and fertilizer. While initial synergies were fuelled purely by economic drivers, dedicated regulations, guidance and financial support from government and the park management committee have helped in the identification of further opportunities. By-product exchanges have also been complemented with synergies based on infrastructure sharing focused on co-generation and waste-water treatment and other forms of symbiotic exchanges. IS has contributed to achieve a 98% re-utilization of solid waste, water conservation and energy optimization. Among key reductions Yu et al (2015) recorded a 71,446 of white sludge from the pulp and paper plant to replace calcium carbonate in the citric acid plant and cement factories or 66,000 tons of fly ash for the cement industry.

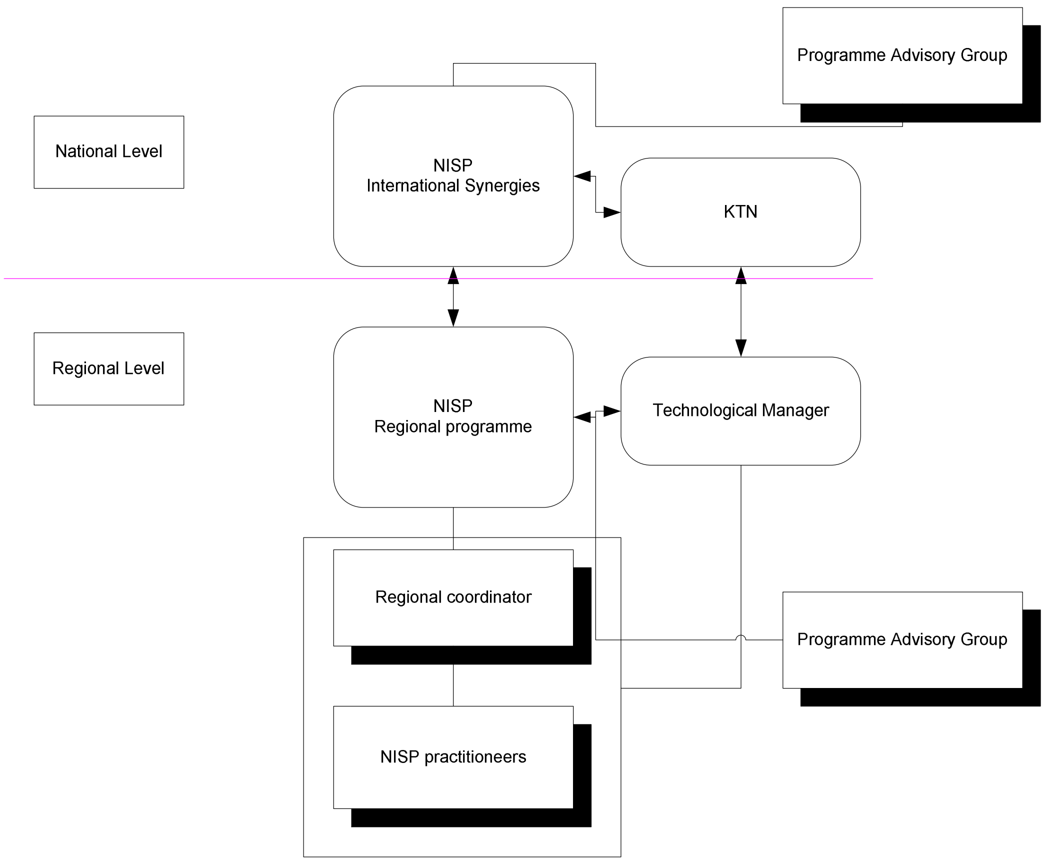
Matthew and Tan (2016) report the achievements of the Suzhou New District (SND), one of the national demonstration sites in 2008. The park comprises 16,000 firms and over 4,000 manufacturing firms in the area of electric and electronics, medical devices and bio technology. IS projects have promoted the recovery of high value materials such as precious metals from printed circuit boards and other metals. A kaolin producer turns mining waste streams into construction materials and necessary inputs for the production of sulfuric acid. Important benefits have been reported as a results of exploiting IS opportunities. Matthew and Tan, 2016) report a decrease in energy intensity by 20% for the period 2005-2010, to levels almost three times lower compared to the national average. Emissions of sulfur dioxide also reduced significantly by 38% for the period while oxidazable organic pollutants decreased by almost half (47%). Industrial symbiosis also contributed to increasing the rate of recovery of industrial waste and recycling and cycling of water, reaching 96% and 91% respectively, well above the national averages of 69% and 86%.

Unlike the case of Kalundborg where industrial symbiosis has spontaneous developed over the years driven by economic incentives that have also provided important environmental incentives; in most cases, experiences in China have been driven by dedicated policies and financial support. In both cases, though, IS initiatives have resulted in important resource efficient opportunities boosting economic and environmental benefits. IS synergies have covered as in the case of Kalundborg solid waste, but also water and energy. Facilities and infrastructure sharing have also been pursued in Eco-industrial parks resulting in cost-saving opportunities for businesses to improve their environmental performance.

3.3 Developments in Europe

While industrial symbiosis has experienced a boom in China and other parks of Asia (e.g. in 2005 South Korea launched a 15 year programme to transform industrial parks into eco-industrial parks which commenced with 5 pilot projects) developments in Europe have been slower. This is partly explained by the progressive relocalisation of primary industries to third countries but also to the lack of dedicated mechanisms to promote IS. An exception to this was the UK that in 2005 was the first country to introduce a nation-wide IS programme for the promotion of industrial symbiosis. The UK National Industrial Symbiosis Programme's (NISP) main goals were to foster the exchange of by-products, materials and other assets among companies, so that they can be reused and recycled, serving as inputs for new processes. The programme promoted the adoption of "a collective approach to competitive advantage involving physical exchange of materials, energy, water and/or by-products together with the shared use of assets, logistics and expertise" (NISP, 2012). To achieve this goal the programme focused on (a) building up of information channels that favour the exchange of information and data concerning the inputs and outputs required by companies, (b) analysing the potential synergies and exchanges that could lead to economic and environmental benefits and (c) the promotion and undertaking of pilot projects that show new potentialities and possibilities of reuse, recycling or adding value to waste in different sectors or processes. Since the start of the programme, the members of NISP steadily grew, achieving more than 15,000 members at the height of the programme in 2012. NISP relied on a two-level structure (national/regional), organised as shown in the Figure 3.

Figure 3: NISP structure



Source: author generated

There were 12 regional programmes covering all UK regions. At the national level, targets were defined for the different regions, covering following areas:

- Landfill diversion

- Water saving
- CO_2 reductions
- Additional revenues
- Cost savings for industry
- Inward investment
- Creation and safeguarding of jobs
- Creation of new companies
- Savings in virgin raw materials

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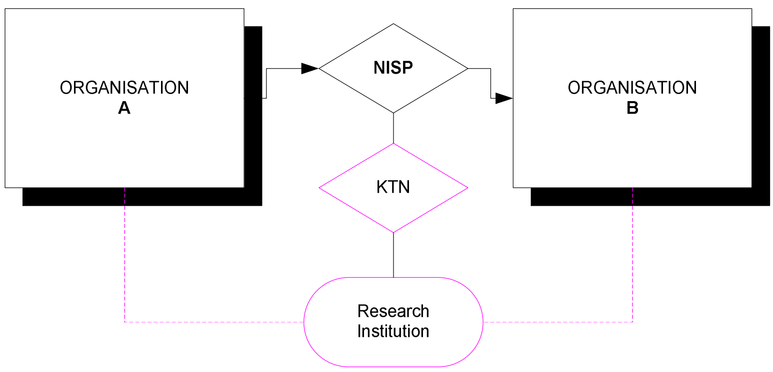
The methodological approach adopted by NISP comprised: a) identifying key sectors in the region; b) Developing connections with key actors (companies, entrepreneurial associations, business networks...) within the sectors and c) tracing potential IS opportunities between sectors. The programme was partly funded by DEFRA through the Business Resource Efficiency and Waste Programme (BREW) and selected regional development agencies in England and by the Scottish Executive, in the case of the Scottish Industrial Symbiosis Programme (SISP), The Welsh Assembly, for NISP Wales and Invest Northern Ireland, in the case of Northern Ireland. Changes in the availability of public funding since 2008 and the disappearance of BREW significantly affected the programme. Under the umbrella of WRAP the programme was funded for another four years until public funding stopped and forced the commercialisation of the programme from October 2012. Since then the programme is only available for paying members, which has significantly reduced its capacity and ability to generate synergies.

As a large, geographically distributed network, NISP played the role of a coordinating node, that centralized knowledge about resource flow between different actors and regions and helped in the identification of potential matches (between resources needs and resource outflows or waste streams) and realization of synergies, as shown in figure 4.

Figure 4: NISP as facilitator of innovation



Source: author generated

The innovative character of IS exchanges meant that in most some sort of innovation or technological developments were required for the successful implementation of the synergy. This includes the development of technologies/ processes to clean up waste streams, so that they can be used and/or recycled in other processes or sectors or the development and testing of new products that use waste as raw material. According to information provided by NISP, over 70% of the completed synergies through the programme required some sort of process of technology innovation while over 50% involved the introduction of best practices and knowledge.

Facilitated IS networks, such as the one developed in the UK (NISP), have reported excellent results in terms of CO_2 reduction and landfill diversion, but also in terms of job generation, and private investment, with a modest public investment of just €40 million investment over the course of 7 years (since 2005), as shown in the tables below. A study for the European Commission (COWI, 2011) estimated that scaling up IS programmes across the EU could generate more than €3,000,000,000 in sales and cost savings and 45 million tonnes of CO2 reduction (5% of Europe's annual reduction target for 2020).

Table 1: NISP reported accumulated benefits 2005-2012

Areas	Accumulated results
Landfill diversion (tonnes)	9,074,493
Carbon savings (tonnes)	7,869,473
Virgin raw materials saved (tonnes)	11,679,029
Hazardous waste avoided (tonnes)	420,739
Water conservation (tonnes)	14,114,161
Cost savings to business (£)	205,648,184
Increased sales for business (£)	198,520,840
Jobs created & jobs saved	10,000+
People trained	6,296
Private investment (£)	316,610,204

Source: NISP (2012)

Table 2: Industry benefit realised through NISP

Industry benefit realised	In year spend	Lifetime spend
€1 new income generated for industry	€0.02	€0.005
€1 saved by UK industry	€0.02	€0.005
1 tonne of virgin raw material saved	€0.48	€0.100
1 tonne of water saved	€0.40	€0.080
1 tonne of CO_2 reduced	€0.73	€0.150
1 tonne of waste diverted from landfill	€0.64	€0.130
1 tonne of hazardous waste eliminated	€13.74	€2.740
Cost savings	€243 million	€1.21 million
Additional sales	€234 million	€1.71 million
OTHER BEENFITS		**TOTAL SINCE 2005**
Jobs		+10,000

Source: NISP (2012)
*All reported has been externally audited and verified by third parties.

From the perspective of the member organisations, although the commercial driver seemed to dominate the participation in the programme, a broader perception of the benefits in terms of improvement of the bottom line was also generally valued. These wider set of benefit included promotion of cultural and organizational change and identification of new areas or business and revenues. Participation in successful synergies was an eye opening experience for companies that proved that resources previously discarded were valuable to other companies and could be traded, providing cost-savings and even new areas of revenues for the company. The fact that participation in NISP was free (while it was publicly funded) reduced significantly the risks and perceived costs of the programme. However this and other experiences have contributed to demonstrate that while public and private benefits can be realized through promotion of facilitated programmes, their continuity as commercial programme may be compromised, as companies may be reluctant to pay for services such as the ones provided by NISP. This can be explained by a number of factors or barriers, including, risk associated to IS exchanges, difficulty to calculate a priory the benefits of IS exchanges and reluctance to invest in an area (waste and by products) that is not part of the core business.

Earlier industrial symbiosis in Northern Europe also include the Kemi-Tornio region on Laplan (Finland), focused around forestry products, steel and minerals, the Handelo IS, in Ostergotland (Sweden), around ethanol and biogas production, or the EYDE network in Vest_Agder (Norway), with a focus on metals and chemicals (Johnsen et al., 2015). The success of NISP, but also the lessons learnt from it, have contributed to recent attempts to promote IS using similar approaches to the ones used in the UK to other parts of Europe. Recently, Denmark have introduced a nation-wide IS programme with a similar structure to the former NISP and other regions in Europe have attempted similar projects, supported by a diversity of funding mechanisms including Life, FP7 and, more recently, Horizon 2020. Progress though has been uneven across regions and countries due to a variety of factors including the disparity of institutional frameworks, industrial structures and organizational culture and lack of support from public actors. Table XX provides an overview of main IS initiatives in Europe.

Industrial symbiosis venture/ region	**Country**	**Coordination**	**Key IS opportunities**
Kalundborg	Denmark	Self-organised	Transactions of waste heat, water and materials (gypsum, slag, fertiliser, etc.) with substantial economic and environmental benefits.
Kemi-Tornio region (lapland)	Finland	Mixed model with anchor tenant	An area dominated by large scale industrial operations from a variety of sectors including steel and metals, pulp and paper, cardboard, fertiliser producers and chemical sector. In 2013-2014 they produced a material flow mapping to identify key potential streams for IS.
Händelö Industrial Symbiosis	Sweden	Self-organised	This area combines IS focused on renewable energy projects with a Nature 2000 conservation area. The key player is an EON CHP plant with linkages to a biogas and an ethanol plant. They use a fuel mix with 95% renewable resources sourced from local waste streams including household waste, rubber and wood waste.
EYDE network	Norway	Facilitated	The network's main focus is eco-innovation with consideration of opportunities to use waste as a resource and utilise waste heat, among other areas.
Svartsengi Resource Park	Iceland	Planned	Established around a geothermal Combined Heat and Power plant, the park, the main focus of the park is to promote symbiotic relationships that utilise all resources derived from the plant and adjacent activities.
NISP-Hungary and	Kozep-Magyarorszag	Facilitated	Promote landfill diversion through innovation IS transactions engaging

REPROWIS	(Budapest) Hungary		SMEs
Styrian recycling network	Austria	Self-organised	A complex network of IS exchanges among over 50 facilities belonging to sectors such as agriculture, food processing, wood, metals, paper, textiles, energy, plastics, etc
Essenscia- Brussels	Belgium	Facilitated	Promote valorisation of side-streams and by-products of the chemical sector
ECOREG - Suceava	Romania	Facilitated	The initial development of the network was funded by Life+. For the period 2009-2012 more than 194 were completed, with more than 530,000tons of waste diverted from landfill.
Bratislavsky Kraj/ ERDF	Slovakia	Facilitated	Identification of waste minimisation opportunities through industrial symbiosis
Werecylce.be	Belgium	Web-based facilitated network	Opportunities for the recycling of post-consumer and post-production plastics
EUR-IS Wroklaw	Poland	Facilitated	Funded by Climate-Kic pathfinder programme, the project main focus was to identify innovative solutions and technologies for diverting from landfill waste that has traditionally been difficult to recycle.
PNSI	France	Facilitated	The programme is active in 4 Provinces and is funded by a combination of Government (ADEME) and the provincial regional governments.
SILVER project	The Netherlands	Facilitated	Funded by the province of Limburg, started in 2013 and has over 70 industrial members. Benefits realised are over €5 mill. Strong emphasis on innovation and SME involvement.
Rotterdam harbour, INES project	The Netherlands	Facilitated	The Europort business association has developed an intermediary role fostering the realisation of IS. Over 80industrial partners and strong presence of chemical and energy sectors. The key flows are heat and water.
Finnish Industrial Symbiosis system (FISS)	Finland	Facilitated	Started after a pilot programme led by Motiva and Sitra. The idea is to use the methodological approach develop by NISP in the UK.
ENEA Italian network for industrial symbiosis- Sicilian Region		Facilitated	Still at an early stage of development, the network has used NISP methodology to promote IS in the region of Sicily with the view to expand it to other regions. It has a

			strong presence of SMEs from a variety of industries and waste streams including WEEE, plastics and waste linked to tourism.
Industrial park of Rieti-Cittaducale	Rieti (Italy)	Facilitated network in an established industrial estate	A number of synergies have been implemented in the areas of biomass-wood and packaging
Green Industrial symbiosis Denmark	Denmark	Facilitated network	This national programmes was established in 2012 by the Danish Business Authority to exploit the untapped potential of moving waste up the waste hierarchy. It is organised around a task force of experts in different region that provide advice through "resource checks" and facilitate matchmaking.
EUR-ISA European Industrial Symbiosis Associatiom	EU	Platform of networks	It brings together organisations from 10 established IS programmes, including Belgium, Denmark, England, Finland, Hungary, Ireland, the Netherlands, Northern Ireland, Poland and Turkey. It is mainly about knowledge sharing, including sharing of data, best practices, expertise and innovation.

Source: compiled by author

Also recently, the European Union have recognized IS as a way to increase resource efficiency and decouple economic growth, wellbeing from resource consumption and emissions. In 2012, the European Resource Efficiency Platform (EREP), a high level advisory platform to the European Commission, recognized IS as one of key focus areas for promoting resource efficiency. In its final set of recommendations, published in April 2014, pointed to the potential of IS networks for optimizing resource use in Europe, divert waste from landfill, moving waste up the waste hierarchy as well as its positive contribution to jobs and growth. References to the potential of IS were also included in the Roadmap for a Resource efficient Europe, published in 2011 and more recently in the Circular Economy package "Towards a Circular Economy: Zero waste programme for Europe" released in 2014. The package was then withdrawn and a new package was published in December 2015. The new package also refers to industrial symbiosis and commits to the revision of waste directives to include further clarity on by-product exchange to tackle some of the regulatory barriers to industrial symbiosis. Following the recommendations from the EREP, a pan-European networks of IS programmes was formed in 2014, the European Industrial Symbiosis Association, EU-ISA, although at this stage the association remains inactive given the lack of support. Main partners include programmes in ETC (as in table above). However, the association has been dormant to date due to the lack of support.

4. Conclusions and main lessons from a nexus perspective

Practical experiences of IS seem to prove that resource nexus approaches focused on inter-company transactions can contribute to achieve win-win-win opportunities through better use of resources and utilization of previously discarded valuable resources. IS is intrinsically a resource nexus approach as several types of resources are considered simultaneously to identify ways to use them in a more optimal way. The following points summarise key areas where resource nexus can profit from IS lessons.

IS shares with the resource nexus a holistic perspective on resources, which considers dynamically all types of resources used and traded in an area and identifies opportunities for optimising their use. IS's main aim is to maximize synergies and reduce trade-offs in the use of resources. Thus it overcomes the traditional facility focus of businesses and the single resource perspective of policy-making to provide an integrated approach to resource use. Network collaboration and system-thinking are thus at the core of both IS and resource nexus.

From an applied perspective, IS can also contribute to the creation of complex networks of reutilization of a variety of underutilized resources including materials, energy, water, land and knowledge through the systematic identification of synergies or matches (where a waste can become a resource). Main techniques and methodologies for the identification of synergies and approaches to collaboration applied in IS could be useful from the resource nexus approach. The key methodological framework for the systematic analysis of opportunities for resource utilization relies on material flow analysis for the defined industrial boundary. Material flow analysis helps to identify and track the flow of materials through a system. From a IS perspective, inputs and outputs for business units are analysed and cross-compared to identify areas where the by-products from an activity or process can be used as an input or raw material for another process. Generally, material flow analysis is combined with GIS to identify opportunities at the local/ regional/ national level.

Both resource nexus and industrial symbiosis rely on a complex knowledge system that tracks all flows of resources in a system and identifies areas of wastage, opportunities of reuse, substitution and combined use. A nexus perspective might perhaps shed additional light on risks of temporary or future shortages such as water stress. IS exchanges or transactions need to be supported by complex knowledge networks that help to identify potential synergies (were a waste streams has the potential to become an input) as well as technological, geographical and socio-economic implications (Is there a technology to clean-up/ adapt the resource in order to be reused? can the resource be transported over long distances? How does it compare economically to traditional use of virgin raw materials?)

Innovation in IS is generally demand-led and may include novel applications of different resource types to fulfil a business needs and new uses of previously discarded resources. Involvement in IS projects also generates learning spill overs that may reduce transaction costs of future projects and induce new IS opportunities.

One key difference between the IS and resource nexus approaches is that while the focus of IS is on the output side (waste and underutilized resources), for the resource nexus the focus lies on the input side. Combining both approaches could yield important benefits for the integrated management of resources covering simultaneously input and output sides.

Lessons regarding the mechanisms by which IS emerges and evolves into networks can also be useful for the resource nexus approach. Building on Domenech (2010) it is possible to point to a set of pre-conditions for the enabling of resource nexus and IS synergies:

1) Both approaches require of a comprehensive knowledge base that tracks resources in the economy in order to identify: 1) inter-linkages between different types of resources; 2) synergies and areas with potential for reducing resource pressures and 3) areas of potential trade-offs between different resources (i.e the reduction in the consumption of a resource can trigger demand/ consumption of another type of resource) and resource constraints that can have an effect on supply chains.

2) There are generally transaction costs and learning costs associated to exploitation of synergies, both on the input and output sides. A diverse material base of by-products, waste streams and other underutilized resources to be exchanged has proven key in the emergence of IS networks. For bulky, low-value waste streams, a minimum critical mass may be needed to make the exchange viable. One-off exchanges may occur when the benefits generated by the exchange exceed the transaction and negotiation costs assigned to the transaction. Similarly, a diverse base of resources may enhance the potential to increase the overall efficiency of the system and identify potential synergies, from the input, resource nexus point of view.

3) One element highlighted by IS is the need to consider the feasibility of synergies within the socio-economic system they are embedded. This calls for IS transactions to be commercially viable and thus, has implications on resource prices. Internalization of externalities has a positive effect on IS as it affects the viability of IS solution when compared to consumption of virgin raw materials. The viability of a transaction is thus closely dependent on the framework conditions that define the relative prices of different use/ treatment alternatives. The resource nexus approach may also benefit from framework conditions that promote prices of resource that more truly reveal their scarcity both from the input side and from the output side (i.e. environmental effects associated to resource extraction).

4) Both approaches tend to consider all five-resource dimensions, including water, energy carriers, minerals, biomass and land in an integrated manner. This allows for the identification of areas of synergies, within and across categories and thus improving the efficiency of the overall system.

Resource nexus and industrial symbiosis may be considered as complimentary approaches for the transition towards more efficient socio-economic systems that work within the planetary limits covering both the input and output side and offering an integrated view across different resource types and sectors of activity. Industrial symbiosis provides bottom-up, industry-led examples of the resource nexus in the practice covering all five-node resource dimensions and may provide lessons for the practical implementation of resource nexus both from a business and policy perspective.

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