Governance of material and energy flows

The dynamics of industrial symbiosis:

A proposal for a conceptual framework based upon a comprehensive literature review

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Pre-publication draft
Published in:
Journal of Cleaner Production 2011
19: 905-911

Abstract

There is increasing evidence that throughout the world, firms, governmental agencies and NGOs are seeking to stimulate industrial symbiosis. This concept and its application have also been the topic of extensive research. Up till now, this work lacks a more comprehensive theoretical framework, and this paper fills this gap. We provide a theoretical basis for understanding the dynamics through which regional industrial systems change their connectiveness in an attempt to reduce their ecological impact. We position our framework within the field of industrial symbiosis based on a comprehensive literature search in the ISI Web of Science database for publications that listed 'industrial symbiosis', 'eco-industrial park', or a combination of 'industrial-ecology' and regional' as a topic.

The framework conceptualizes industrial symbiosis as a process at two levels: (1) the level of the regional industrial system (RIS), and (2) the societal level where the concept and routines of industrial symbiosis diffuse. We link the dynamics at these levels to changes in ecological impact and increase in institutional capacity. We conclude with a research agenda based on the variables and their basic relationships specified in our framework. The main line of research we propose is to systematically investigate how institutional capacity evolves over time in regional industrial systems and how it affects the ecological impact of such systems. We also propose to investigate how insights from existing literature about stimulating and impeding factors to industrial symbiosis can be understood in terms of mechanisms of transmission and how these mechanisms interact to create nationally distinct patterns of diffusion of industrial symbiosis.

Keywords: industrial symbiosis, institutional capacity, industrial networks, concept diffusion

1. Introduction

While it has become fashionable to talk about the globalization of economic activities and the corresponding rise in importance of the *space of flows*, such activities require a specific place where they are performed (Castells, 1996). Within the field of industrial ecology, this *space of place* has been coined industrial symbiosis. Chertow has defined industrial symbiosis as "engaging traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity" (Chertow, 2007). Removing the intentionality from this definition, industrial symbiosis concerns the material and energy flows and transformations that are generated by economic actors within a geographically bound system. Chertow's definition points to the fact that in several countries, firms, NGOs and governmental agencies have sought to make such flows and transformations more sustainable (for overviews see Mouzakitis et al., 2003; Sakr et al., 2009).The aim of this article is to provide a missing link in the literature: an adequate theoretical underpinning of the process through which industrial symbiosis comes about. In our view, industrial symbiosis can be usefully conceptualized as a process rather than a state of affairs. This also provides a basis for the longitudinal analysis of industrial symbiosis; a necessary quality given the finding that it takes years to develop.

We start with a characterisation of the existing literature on industrial symbiosis, assessing the concepts and theoretical insights that have been proposed to aid understanding of this phenomenon (section 2). We then propose our theoretical framework, which addresses two levels of analysis: the societal level and the level of regionally bounded clusters of firms (section 3). In section 4 we then take another look at the literature to see the extent to which evidence is available

that corroborates the relevance of our framework. We conclude with an agenda for future research.

2. Conceptual approaches in the literature

For our literature research we have used the ISI Web of Science database and searched for publications that listed 'industrial symbiosis', 'eco-industrial park', or the combination of 'industrial ecology' and 'regional' as a topic. From the resulting 347 items we removed all entries that dealt with topics unrelated to material and energy flows among firms in regional industrial systems. We also excluded conference proceedings for reasons of accessibility. This procedure resulted in a list of 102 publications (see Table 1) that were analyzed first for their conceptual background.

Included	Explanatory conceptual frameworks and theories	13
	Typologies	2
	Methodologies	2
Not included	Descriptions	38
	Models	27
	Normative conceptual frameworks and theories	11
	Quantitative evaluations	6
	Epistemological discussions	3

Table 1. Number of ISI listed publications in eight categories. The first three categories are included in the discussion of the literature in section 2. ANNEX 1 provides the full list of items included in the review.

Based on our assessment we categorised publications in eight categories. Five categories are excluded from our discussion of the literature, because they do not address our primary interest: to develop a theoretical underpinning of the process through which industrial symbiosis comes about. The first category we excluded covers descriptive publications. This includes case studies, descriptions of policy developments and historical overviews. In some of these publications findings are generalised post hoc by identifying drivers, barriers, strengths or weaknesses to industrial symbiosis. However, these factors fall short of a theoretical framework because their connections remain unexplored. The second excluded category covers the publications which present a model. These are usually developed to aid in the design and evaluation of eco-industrial parks. Although some of the models also attempt to develop an understanding of the coming about of industrial symbiosis, they are predominantly prescriptive and necessarily limited to only a few parameters and variables (Ostrom, 2007). A third category we excluded from our discussion covers publications that offer conceptual frameworks or theories of a normative nature. These are designed and applied to prescribe how industrial symbiosis should develop but they do not analyse and explain empirical cases of industrial symbiosis developments. The fourth category we excluded covers quantitative analyses of the outcomes of industrial symbiosis developments. Although these are very useful in understanding the outcomes of industrial symbiosis they do not offer an understanding of the process through which industrial symbiosis comes about. The last category we excluded is that of publications that provide epistemological discussions about the use of nature as an analogy, model or metaphor.

The remaining publications relate to the purpose of developing a theoretical framework for analysing and explaining the process through which industrial symbiosis comes about. The first category covers publications that offer conceptual frameworks or theories for understanding empirical cases of industrial symbiosis. Korhonen and Snäkin (2005) build their conceptual framework on a model of

natural ecosystems. They analyse and explain the evolution of an industrial park from a type I ecosystem into a type III ecosystem using the concepts of roundput, diversity, and connectance. They argue that increased diversity (of the actors involved) enhances connectance and opens up new possibilities for cooperation, although increasing the number of actors can also lead to conflicting interests, thereby preventing connectance and interdependency.

Mirata and Emtairah (2005) discuss industrial symbiosis networks from the perspective of innovation studies. The authors argue that industrial symbiosis networks can contribute to fostering environmental innovation at the local or regional level by stimulating the collective definition of problems, providing inter-sectoral interfaces, and promoting a culture of inter-organisational collaboration oriented towards environmental challenges.

Lyons (2007) examines the relationship between geographical scale and loop closing for heterogeneous wastes. He finds that there is no preferable spatial scale at which loop closing should be organised. According to Lyons, loop closing is dominated by the spatial economic logic of the transactions of the involved firms.

Ashton (2009) builds a framework for the analysis of the structure, function and evolution of regional industrial ecosystems by combining perspectives from economic geography and industrial ecology with Holling's theoretical framework of complex systems. The emphasis in Ashton's framework is on successional changes observable in regional industrial ecosystems (exploitation, conservation, release, and mobilization). Patterns of change in regional industrial ecosystems are described for multiple levels of analysis, using the metaphor of ecosystem development and concepts borrowed from literature on economic geography and industrial ecology. The link between industrial ecology and concepts of economic geography has also been explored by Deutz and Lyons (2008), Deutz and Gibbs (2008) and Chertow, Ashton and Espinosa (2008).

There are several publications that draw more attention to the social aspects of industrial symbiosis. Lambert and Boons (2002) describe the sustainable development (including industrial symbiosis) of industrial parks as a social process based on ecological, social, and economic aspects and emphasise the importance of learning processes among social actors. The authors describe two main difficulties in the development toward sustainability. First, it is relatively easy to achieve superficial, short-term social changes, but social actors have a tendency to fall back into their old patterns of behaviour on the long term due to their embeddedness in an institutional context. Second, to ensure system change rather than system optimisation, it needs to emerge from the existing system. Thus all system actors need to be involved in the change process. In addition, Lambert and Boons suggest that in practice, change toward sustainability is particularly difficult to achieve in mixed industrial parks due to divergent interests of the involved actors, a lack of collective organisations, and minimal experience with cooperation. Baas and Boons (2004) develop a social science framework for investigating regional industrial ecology. Central to their analytical framework is a three-phased learning process that can be used to analyse the evolution of industrial ecology initiatives. The phases are called regional efficiency, regional learning, and sustainable industrial district. Each phase is associated with different governance mechanisms through which different types of collective competitive goods are produced. Hewes and Lyons (2008) investigate the role of champions of industrial symbiosis in the establishment of humanistic connections in industrial symbiosis developments. The main focus of the authors is on the concepts of trust and its relation to the concepts of community embeddedness and proximity. Posch (2010) investigates whether industrial recycling networks or industrial symbiosis projects can be used as a starting point for broader inter-company cooperation for sustainable development. In his conceptual discussion Posch defines sustainable development as an outcome of sustainability-oriented cooperation between human actors and stakeholders. According to Posch sustainable development revolves around the decisions made by

particular people in particular organisations and social settings. "How such individuals perceive their concrete situation, their possibilities and their responsibilities, determines whether sustainability networks emerge."

Costa, Massard and Agarwal (2010) argue that industrial symbiosis depends on an enabling context which can be described in terms of cognitive, structural, cultural, political, spatial and temporal embeddedness. The authors consider self-organisation a more feasible strategy for the development of industrial symbiosis but building on the findings of Mirata (2004) in his assessment of the (National Industrial Symbiosis Programme) NISP in the United Kingdom they argue that coordinating bodies and governmental policies can foster (or pose barriers to) the development of industrial symbiosis by influencing some of the factors that shape the enabling context of industrial symbiosis. The authors focus on the influence of policy development at the supra-national, national, and sub-national level. Similarly, Costa and Ferrão (2010) suggest that a context favourable to the development of industrial symbiosis "can be shaped through an interactive process wherein the government, industries and other institutions are guided towards aligning their strategies in support of collaborative business strategies in resource management". The authors refer to this process as the middle-out approach.

Another category we include in our discussion covers two publications that offer a typology of different shapes of industrial symbiosis. Based on a taxonomy of eco-industrial parks Chertow (2000) distinguishes 5 material exchange types of which the inter-firm exchanges are identified as industrial symbiosis: those among firms co-located in a defined eco-industrial park, those among local firms that are not co-located, and those among firms organized 'virtually' across a broader region. In addition, Chertow discusses several tools and approaches for developing eco-industrial parks. She argues that evolutionary approaches are key to the development of eco-industrial parks because cooperation develops over time. Three possible variants are suggested: (1) building on existing types of material or energy

exchange, (2) building on pre-existing organisational relationships and networks, and (3) the anchor tenant model. In another publication Chertow (2007) distinguishes between a planned model and a self-organising model of industrial symbiosis. The former refers to conscious efforts to identify firms from different industries and co-locate them so they can share resources across and among them. The latter refers to industrial ecosystems that emerge from the decisions by private actors motivated to exchange resources for economic reasons. Chertow argues that policy initiatives should be focused on the identification of industrial symbiosis and aid in their further development.

The last category we include in our discussion covers two publications that develop methodologies for analysing empirical cases of industrial symbiosis. Ashton (2008) discusses the increasing attention given to the social aspects of industrial symbiosis and introduces social network analysis as a methodology to study the patterns of relationships, interactions, and social structure that are often emphasized in social theories. She demonstrates the relevance of this methodology in the context of industrial symbiosis by using it to analyze the relation between connectivity among firms and managers in the Barceloneta region of Puerto Rico and the observed industrial symbiosis linkages there. Wright, Côté, Duffy and Brazner (2009) propose a methodology for translating ecological quantitative analysis techniques to an industrial context. The methodology is demonstrated in the case of Burnside industrial park using the concepts of connectance and diversity. The demonstrated techniques can potentially aid in gaining an understanding of industrial symbiosis.

This overview shows the richness of the work that has been done in the field of industrial symbiosis. However, it also reveals that there is only a small amount of publications that attempt to offer a theoretical underpinning for the analysis and explanation of empirical cases of industrial symbiosis. In addition, these publications have a very specific focus, as they take one theoretical approach and

explore industrial symbiosis through that lens. In our view the field of industrial symbiosis would benefit from a conceptual framework that allows for a more encompassing analysis of industrial symbiosis developments. Therefore, we introduce a new framework in the next section.

3. Understanding the dynamics of industrial symbiosis

In our view, industrial symbiosis is best conceptualized as a process. The definition of Chertow, refers to 'traditionally separate' industries, indicating the move towards increased connectiveness in terms of material, energy, and information flows. Also, the work that analyses empirical evidence continuously stresses the factors that hinder or stimulate the process through which industrial symbiosis comes about. Thus, we aim to provide a theoretical basis for understanding the dynamics through which regional industrial systems change their connectiveness in their pursuit of reduced ecological impact.

For this, we distinguish two levels of analysis. First we have the level of the *regional industrial system* (RIS), a more or less stable collection of firms located in proximity to one another, where firms in principle can develop social and material/energy connections as a result of that proximity. At this level we also find local governments and other actors (consumers, citizens, educational organizations, NGOs) that may become involved in efforts to increase the sustainability of the RIS. In the literature, this level is addressed with various labels such as (eco-)industrial park and industrial cluster. We abstract from such labels for two reasons. First, the geographical scale of a regional system varies a lot among countries: a region in China is of a different size then one in the Netherlands. Secondly, the label used is sometimes linked to policy initiatives to stimulate industrial symbiosis. For these reasons, we use the more neutral label of RIS, stressing that its precise meaning is an empirical variable.

As a result of the increased popularity of industrial symbiosis and the related philosophy of reducing ecological impact through increasing connectiveness of material, energy and information flows, actors beyond the regional level have sought to stimulate its practice. We will call this the *societal level*. Here we are not interested in the dynamics that directly produce linkages among firms, but instead in the ways through which industrial symbiosis, and its associated philosophy, diffuses through society.

As a general approach we adopt the view that understanding of social phenomena is best advanced through the study of mechanisms (Elster, 2007; Gross, 2009; Hedström and Swedberg, 1998; Stinchcombe, 1991). Rather than developing an overarching theory, we are currently able to specify mechanisms: "frequently occurring and easily recognizable causal patterns that are triggered under generally unknown conditions or with indeterminate consequences." (Elster, 2007). Empirical research aims to further specify the conditions and consequences under which certain mechanisms occur. Our theoretical framework thus consists of a number of such mechanisms which we expect to occur (2). It is completed by: (1) a set of conditions which we derive from the literature as relevant antecedents affecting the operation of these mechanisms, and (3) the outcomes of these mechanisms in terms of ecological impact, social networks, and concept diffusion (see Figure 1). We are also interested in investigating the assumption that increased connectiveness leads to a reduced ecological impact. There are still few studies that aptly address this aspect of industrial symbiosis.

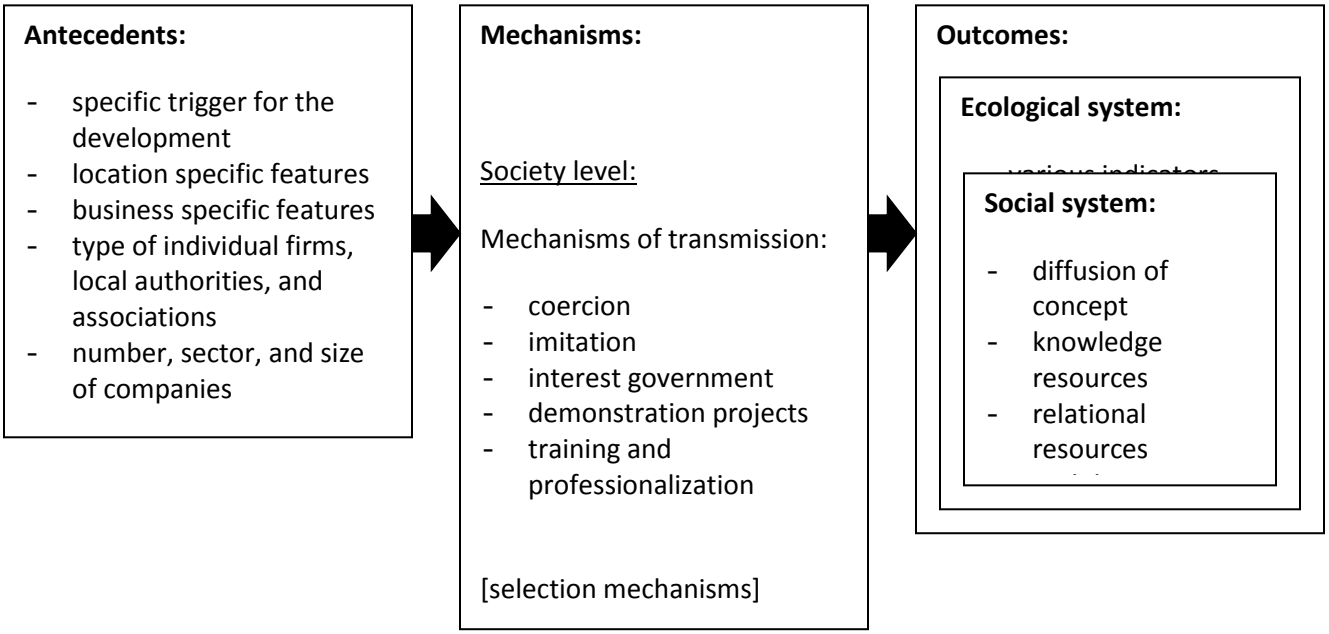

Figure 1. Conceptual framework for analysing the dynamics of industrial symbiosis

3.1. Regional industrial system level

This level has been central in the existing literature on industrial symbiosis (Heeres et al., 2004; Van Leeuwen et al., 2003). Much of the industrial symbiosis literature describes, compares and analyses cases where regional industrial systems of varying geographical sizes are shown to develop increased connectiveness, or plan to do so. To theorize at this level, we draw on a body of literature that comes out of the field of community development. We build on the idea that the ability of communities to deal with collective problems depends upon the extend to which they have built up institutional capacity (Healey et al., 2003; Innes and Booher, 1999). This approach resonates with many of the conclusions on successful cases of industrial symbiosis that stress the crucial role of trust and social networks.

Institutional capacity building is the process through which different forms of institutional capital are formed, *"an array of practices in which stakeholders, selected to represent different interests, come together for face-to-face, long-term dialogue to address a policy issue of common concern"* (Innes and Booher, 1999). Innes and Booher show that this process can produce both tangible and intangible results. To further specify the results of this process we will make use of the analytical distinction between three forms of institutional capital by Healey et al. (2003):

- knowledge resources: the availability and structural sharing of explicit and tacit knowledge;
- relational resources: the embeddedness of agents in social networks;
- mobilisation capacity: the structure and means by which knowledge resources and relational resources are formed and mobilized.

The overarching hypothesis here is that the coming about of industrial symbiosis is aided by a high level of institutional capacity. It depends on specific knowledge that actors acquire through experience and learning of the specific potential for industrial symbiosis in their system, as well as about the process of realizing that potential. In addition, they need to develop the linkages among actors whose activities need to be coordinated to make it actually happen. These actors include firms, as well as local governments and communities, knowledge institutes, and NGOs. We also draw attention to the capabilities of individual actors to build and maintain the linkages between them (Boons, 2004). Finally, the system needs to be able to mobilize resources that are currently not part of the system. These may include local actors and resources, but it may extend also to the wider political and economic context, such as national governments, or the headquarters of local production plants.

Increased institutional capacity can be linked to more specific lines of inquiry. Baas and Boons (2004) have proposed that the long term development at

industrial parks is constituted by three distinct phases of regional industrial ecology. These phases combine an increase in institutional capacity with two dependent variables: (1) increased scope of the sustainability themes that are addressed by the system, and (2) the move from win-win projects to projects where the pay-off structure to participants can be win-lose.

A second line of inquiry can be derived from Ashton's (2009) application of Holling's (2001) adaptive cycle to the evolution of industrial symbiosis. The cycle gives an abstract representation of the different phases through which complex adaptive systems go: growth, conservation, release, and reorganization. These phases are defined in part by the level of connectedness, and thus relate to institutional capacity. An important question would be to assess the consequences of the phases of release and reorganization for the institutional capacity of the system. This can be linked to the dual quality of social networks: they can act as the context for innovation creativity, but they can also be a source of inertia (Boons, 1998).

3.2. Societal level

At the societal level actors may be involved in the diffusion of industrial symbiosis, including the underlying philosophy and rationale. To address this level and its linkage to the level of RIS's we base ourselves in *institutional theory* (Czarniawska-Joerges and Sevón, 1996; DiMaggio and Powell, 1983). This theory deals with the mechanisms that are responsible for the diffusion of a concept, innovation, or idea among a set of organizations. This is indicated by the adoption of the concept in language (corporate newsletters and internal memoranda, annual reports, descriptions towards stakeholders) and in practice, through the adoption of certain organisational routines. Diffusion can be a result of transmission of a concept from one organization/individual to another, or by a process of selection through which

organizations that do not use the concept are eliminated (Boons, 2009). Here we will focus on the process of transmission, which is most relevant to the diffusion of industrial symbiosis.

DiMaggio and Powell (1983) distinguish a number of mechanisms of transmission which can lead to the diffusion of organizational characteristics in an organizational field. A field is defined by the interaction among its members as a result of the fact that they mutually acknowledge to be involved in similar/related activities. The boundaries of the field are thus an empirical variable. Boons et al., (2000) adapted this approach and used it to assess the diffusion of environmental routines in Dutch industry. Building on this, the following list of mechanisms of transmission can be proposed:

- *coercion:* an organization is forced to adopt a certain concept or routine by another organization that holds power over it, such as the government issuing a rule;
- *imitation:* organizations may adopt routines and concepts they see from similar organizations for reasons of status or because it provides a way of dealing with uncertain situations;
- *private interest government*; a group of organizations may choose to collectively adopt a concept or routine voluntarily, because of the threat of legislation if they remain inactive;
- *demonstration projects*; policy actors may initiate experiments with new concepts and routines, and actively spread the results of these under a label like 'best practice' to accelerate its diffusion;
- *training and professionalisation*; individuals may learn about new concepts and routines through education, and subsequently start to apply these in their work environment;
- *altering boundary conditions*; actions to stimulate actors within regional industrial systems to self-organize (Boons, 2008).

These mechanisms may all play a role in the diffusion of industrial symbiosis concepts and routines throughout a society. A major initial condition is the way in which actors are linked at this level, that is, through what ways can firms, and coordinating actors in regional industrial clusters, acquire information in the larger society about industrial symbiosis, and have access to the resources to start implementing them? Here we may find considerable differences. These differences combine into approaches that are distinct for societies, as research on national developments in the UK (NISP) the Netherlands (sustainable industrial parks), the US (Presidential Council on sustainable Development, 1996), China (circular economy) and Japan (urban symbiosis) indicate.

3.3. Analysing (changes in) outcomes

In the industrial symbiosis literature there seems to be an underlying assumption that increased connectiveness leads to reduced ecological impact. Surprisingly, the ecological impact that results from increased linkages among firms is one of the neglected outcome variables in the same literature (see Chertow and Lombardi, 2005; Jacobsen, 2006; Laybourn and Lombardi, 2007; Mattila et al., 2010; Van Berkel et al., 2009 for exceptions). In this study, *ecological impact* refers to the effect of human activities (or of a natural phenomenon) on living organisms and their non-living (abiotic) environment. Actors at the two analytical levels (regional industrial system and society) distinguished above may define ecological impact, and the reduction of it, in various ways (March and Olsen, 1989). Ideally, we want to be able to take into account both actor definitions of ecological impact as well as ecological impact defined through our own perspective. We should notice that in the context of this paper, we do not propose new methods for ecological impact measurement or provide a critical review of the existing ones. In the next paragraphs, we seek to give

an indicative example of how existing approaches of the related literature can be connected to a basic dimension of our conceptual framework.

To be more specific, we draw on *Life Cycle Assessment* (LCA), which is a methodological tool used to quantitatively analyse the ecological impact of products/activities in four distinct phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation. The first two phases of LCA cannot by definition raise meaningful methodological disputes, but one may find several LCIA methods with different assumptions and stages. Since there is no single 'gold standard' method applicable in all situations, it is usually recommended to deploy alternative LCIA methods in order to have a more robust decision-making basis. Broadly speaking, two main categories of approaches may be identified: those which seek to convert the emissions of hazardous substances and extractions of natural resources into impact category indicators at the midpoint level (such as ecotoxicity, land occupation, climate change etc.) and those which employ impact category at the endpoint level (such as damage to human health, ecosystem diversity and resource availability). A group of Dutch universities and consultancies, working under the umbrella of the Dutch Ministry of Environment has developed an integrative method called RECIPE 2008[1] which combines the above approaches and comprises two sets of impact categories at both midpoints and endpoints levels (see Figure 2).

[1] The report has been published in January 2009 and describes all the technical details (including units of measurement) in all different categories [see http://www.lcia-recipe.net/]

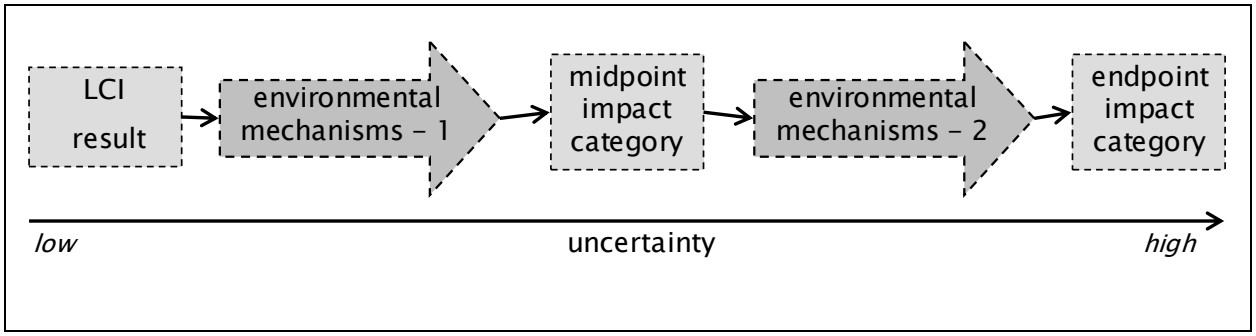

***Figure 2**: the RECIPE 2008: Relationship between LCI parameters, environmental mechanisms and midpoint/endpoint indicators (the report comprises details for each one of these categories). A basic remark is that as we move to the right side, the uncertainty is increasing.*

Life Cycle Assessment encounters a number of unresolved problems (Reap et al., 2008) which come into play when we seek to explore the outcomes of an industrial symbiosis with respect to its host ecological impact. To be more specific, when assessing the ecological impact of a symbiosis, it is difficult to move beyond the boundaries of the very left side of figure 2. We should remark that a basic task is the evaluation of a symbiosis through the comparison of its ecological impact (at both individual firm and regional industrial system levels) with and without eco-industrial cooperative activities between the participants of the cluster. In addition to changed ecological impact, outcome variables include the diffusion of concepts and routines of industrial symbiosis at the society level, and changes in the institutional capacity of regional industrial systems.

4. Empirical support for our framework

In many studies empirical evidence of the mechanisms described above are touched upon. Policy programs from governmental agencies are usually referred to as a

major conditioning factor. In China the influence of policies is probably most evident as a coercive mechanism. The Chinese policy on circular economy is one of the central factors of influence on Chinese industrial symbiosis development (Geng and Doberstein, 2008; Geng et al., 2008; Geng et al., 2009; Yuan et al., 2006). In the United Kingdom the influence of public policies is also evident, as a result of the NISP and policy waste management (Mirata, 2004; Phillips et al., 2006), but there it acts more as a facilitator, funding the activities of NISP. Van Beers et al. (2009) argue that the Australian legislative framework poses special challenges for industrial symbiosis developments in Australia. Elabras Veiga and Magrini (2009) state that public policies on eco-industrial developments were a strength at first, but that this turned out to be weakness on the long run, after some changes in the public and political system. Van Berkel et al. (2009) show how the Japanese government established a comprehensive legal framework in order to move towards a recycling-based society and how the Eco-Town Program was made possible through this framework. Here the approach seems to fit with the private interest government mechanism, as societal actors are involved in shaping the initiatives.

At the level of regional industrial systems, the importance of institutional capacity and institutional capacity building is even more evident in empirical studies. Several studies have revealed the importance of the commitment of and collaboration among stakeholders (Gibbs and Deutz, 2007; Heeres et al., 2004; Kim, 2007; Lowitt, 2008; Zhu and Côté, 2004; Zhu et al., 2007). There are also some studies that emphasise the importance of a key player, anchor firm or coordination body (Mirata, 2004; Yang and Feng, 2008; Zhu et al., 2007). Hewes and Lyons (2008) bring forward some interesting evidence for the important role of advocates or champions of industrial symbiosis in developments in Devens, Massachusetts and the towns of Komsomolske and Cherkassey in Ukraine. Korhonen and Snäkin (2005) have shown the influence of participant diversity on possibilities for initiating industrial symbiosis developments. These elements are often addressed in isolation,

but the specific results in several ways go beyond the general findings in the literature on institutional capacity.

5. Research agenda

We find that our conceptual framework connects well to the existing conceptual and empirical literature on symbiosis. In addition, it provides a way to further develop the field by building on theoretical insights that help to understand the dynamics through which regional industrial systems change their connectiveness and consequently their ecological impact. The framework specifies basic relationships between variables. Further research is required to define variables more precisely, and establish in more detail the relationships among them. For this, we propose the following lines of research:

1. *How does institutional capacity building take place in regional industrial systems, and in what way does it affect the ecological impact of such systems?*

This question relates the general literature on institutional capacity building to research on industrial symbiosis. Here there is a potential for cross-fertilization. Concepts such as champions and anchor tenants have corollaries in that literature. On the other hand, the literature on community development is often silent on the technical processes that occur within the systems they study, and consequently they ignore possible impacts of capacity building.

2. *Is there something like an optimal level of institutional capacity, and does this vary with phases of development as distinguished in Holling's adaptive cycle?*

The implicit hypothesis in much of the literature is that an increase in connectiveness is good for industrial symbiosis. It is important to test this hypothesis explicitly. There has been criticism that industrial symbiosis may lead to lock-in into wasteful practices (Oldenburg and Geiser, 1997), and maybe specific features of social networks may allow for flexibility to identify and then remedy these.

3. *What is the role of antecedent conditions in shaping the process of institutional capacity building?*

We have not discussed in detail the role of antecedent conditions such as the size of the regional industrial system (in terms of geographical scale, number of firms), nor of its diversity. With more precise measurements of institutional capacity we may be able to find systematic differences among RIS's with specific antecedent conditions.

4. *How can existing insights about stimulating and impeding factors be understood in terms of mechanisms of transmission?*

There have been a number of attempts to generalize findings about the process of industrial symbiosis in terms of factors. As discussed in section 4, factors such as 'governmental policy' need to be dissected to identify the actual mechanism that is used by government which aids or hinders the diffusion of industrial symbiosis. Also, the list of mechanisms seems to cover aspects that have hardly been used as research variables, such as imitation or training and professionalisation.

5. *How do mechanisms interact to create nationally distinct patterns of diffusion of industrial symbiosis?*

From the literature it is clear that there are specific ways in which industrial symbiosis is interpreted and implemented in different countries. In our view, this can be usefully analysed by looking at this not only in terms of different characteristics of regional industrial systems, but also in terms of specific combinations of mechanisms of transmission. The field of comparative capitalism is an example of a field of research that connects well to this perspective, and it allows to better understand differences among countries, and be cautious about transplanting best practices too easily from one context to another. This may go a long way in explaining the difficulties of creating new Kalundborgs all over the world.

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ANNEX 1

Included	Explanatory conceptual frameworks and theories	13 [1-13]
	Typologies	2 [14,15]
	Methodologies	2 [16,17]
Not included	Descriptions	38 [18-55]
	Models	27 [56-82]
	Normative conceptual frameworks and theories	11 [83-93]
	Quantitative evaluations	6 [94-99]
	Epistemological discussions	3 [100-102]

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