Methodological Aspects of Applying Life Cycle Assessment to Industrial Symbioses

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Summary

In view of recent studies of the historical development and current status of industrial symbiosis (IS), life cycle assessment (LCA) is proposed as a general framework for quantifying the environmental performance of by-product exchange. Recent guidelines for LCA (International Reference Life Cycle Data System [ILCD] guidelines) are applied to answer the main research questions in the IS literature reviewed. A typology of five main research questions is proposed: (1) analysis, (2) improvement, and (3) expansion of existing systems; (4) design of new eco-industrial parks, and (5) restructuring of circular economies. The LCA guidelines were found useful in framing the question and choosing an appropriate reference case for comparison. The selection of a correct reference case reduces the risk of overestimating the benefits of by-product exchange. In the analysis of existing systems, environmentally extended input-output analysis (EEIOA) can be used to streamline the analysis and provide an industry average baseline for comparison. However, when large-scale changes are applied to the system, more sophisticated tools are necessary for assessment of the consequences, from market analysis to general equilibrium modeling and future scenario work. Such a rigorous application of systems analysis was not found in the current IS literature, but would benefit the field substantially, especially when the environmental impact of large-scale economic changes is analyzed.

Introduction

Industrial symbiosis (IS) can be described as waste or by-product exchange and utility-sharing networks among colocated firms (Chertow 2000). Resource consumption and costs are reduced through utilization of materials that would otherwise be classified as by-products or waste and jointly providing energy, water, and waste treatment services for associated partners.[1] Most symbioses have self-organized in order to improve economic profits and comply with stricter environmental permit requirements (Chertow 2007), but also some policy instruments can promote their development (Lehtoranta et al. 2011). The practical applications of IS include expanding existing symbioses (Chertow 2007), planning new eco-industrial parks (EIPs) (Baas and Huisingh 2008; Gibbs and Deutz 2005; Heeres et al. 2004; Mirata 2004; Van Leeuwen et al. 2003; Veiga and Magrini 2009; Zhang et al. 2010), and even restructuring the whole nation into a circular economy (Geng et al. 2009; Yuan et al. 2006).

Central to IS is the biological analogy (Hardy and Graedel 2002): in natural ecosystems, nutrients are cycled and energy is cascaded between the actors of the systems in a mutually beneficial way. Local emissions have been found to be lower in symbioses than in hypothetical stand-alone reference cases (Chertow and Lombardi 2005). However, a significant amount of the emissions caused by an industrial symbiosis occurs

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outside the boundaries of the local industrial area (Mattila et al. 2010; Sokka et al. 2011a). These supply chain impacts are usually excluded from the analysis of industrial symbioses, which introduces a risk of transferring emissions from the local symbiosis to elsewhere in the supply chain.

Recently the usefulness of the biological analogy as a goal in itself has been questioned, prompting transparent assessment of the net environmental impacts (conversion, substitution, and avoidance) and the comparability to a hypothetical reference state (Van Berkel 2010). There is a risk of reinventing the wheel in this process, since by-product substitution, system boundary selection, and reference states have long been research questions in life cycle assessment (LCA). LCA is a method for analyzing the multidimensional environmental impacts of an individual product, process, company, city, or country. It has clear and accepted standards (ISO 14040, 14044) and guidelines (Guinee et al. 2002; ILCD 2010), as well as good acceptance by the scientific community. Capturing environmental impacts throughout the life cycle helps to avoid problems in shifting between contexts: life cycle phases, regions, and also environmental issues (Finnveden et al. 2009). In addition, LCA has undergone a two-decade development process. The main developments have been in solving problems in coproduct allocation, recycling, reference states, and separation of static and change-oriented analyses (Finnveden et al. 2009). These issues are encountered in some form in almost all sustainability assessments; therefore, lessons learned in LCA may prove useful in the analysis of the environmental performance of IS as well (Boons et al. 2011).

The aim of this article is to explore the methodological issues encountered in the application of LCA to the various research questions arising from IS studies. Research questions from existing studies were classified according to whether they refer to analysis, improvement, or expansion of existing systems; development of new EIPs; or macroeconomic changes. The research questions were then considered in view of the guidelines for applying LCA in different decision contexts (ILCD 2010). The main methodological issues were identified and compared with the results and methodology of existing studies. Finally, recommendations for the application of LCAs were given, especially in relation to the selection of an appropriate reference state and the use of static (attributional) or dynamic (consequential) modeling approaches.

A Typology of Industrial Symbiosis Research Questions

Industrial symbiosis has been studied for various purposes, from identification of improvement options to generalization of the results to the macroeconomic level. The overall environmental performance of the individual contexts differs greatly, as do the methods required for their analysis. For the purposes of this study, the research questions reviewed were classified into five basic groups: analysis (accounting), improvement, expansion, design, and circular economy (see table 1). The first three groups aid in analysis of an existing system, although each with a different focus. The last two groups are for study of hypothetical future systems on two different scales: the EIP level and the macroeconomic level. (For this study, it is assumed that the boundaries of the foreground system under study are well defined. Defining the boundaries of a symbiosis is a difficult task in itself, but is best considered as a separate question from the problem of quantifying the environmental implications of a defined system, which is the focus of this article.)

Studies classified as analysis assess the environmental impacts of an existing IS. Usually the goal is to quantify the benefits of by-product exchange. The range of environmental impacts and spatial extent included in the analysis varies considerably between studies, but the main focus is on the local level and on the resources saved through by-product use. A few studies (Eckelman and Chertow 2009; Mattila et al. 2010; Sendra et al. 2007; Sokka et al. 2011a; 2011b) have extended the system boundaries to include the supply chain.

Some studies were aimed at improving existing symbioses. Of these, many do not quantify the environmental impacts at all, but look at the improvement from an industrial ecosystem vantage point and suggest improvements to organization to facilitate more by-product exchange (Gibbs and Deutz 2007). A related question is that of IS expansion over time. One study of the historical development of an eco-industrial area concluded that during expansion the total impacts increased but the emissions per unit produced decreased (Pakarinen et al. 2010). Other studies have found that industrial complexes offer many unused by-products, which offer a possibility of including new processes in the system, such as biodiesel for a pulp mill (Andersson et al. 2006).

A group of literature has focused on providing guidelines for implementation of symbioses in industrial parks (Côte and Cohen-Rosenthal 1998). Issues encountered in these studies include how to measure the performance of a symbiosis type of operation and how to determine whether a certain type of waste management is representative of IS (Zhang et al. 2010). Another group of research questions is related to study of the concept of the circular economy. In a circular economy, material flows are closed loops and resources are used in cascading series (Yuan et al. 2006). Curiously, very little has been presented so far in the scientific literature about the environmental impacts or pathways toward such a system.

Classifying Research Questions by Decision Context

The main difference in the research questions is the extent of change assumed in the system studied. In pure analysis (accounting), nothing is changed and an existing system is studied retrospectively. The system is usually compared to a hypothetical situation where by-product exchange would not take place. In improvement and expansion studies, an existing system is changed, which will also change the surrounding economy (through increased demand for by-products and

Table 1 Research questions addressed in industrial symbiosis studies, assigned to five main groups

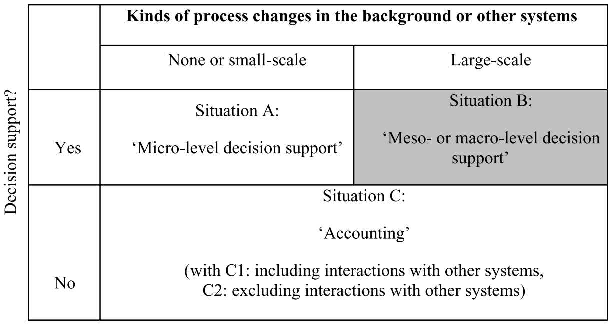
Group	*Research questions addressed*	*Examples*
1. Analysis (accounting)	What are the impacts of an existing symbiosis? Are there any benefits from the cooperation, in the form of lower environmental impacts than for stand-alone plants? What are the relevant boundaries of the symbiosis in different analyses?	Albino et al. 2003; Ashton 2009; Chertow and Lombardi 2005; Jacobsen 2006; Karlsson and Wolf 2008; Korhonen and Niutanen 2003; Lambert and Boons 2002; Sendra et al. 2007; Sokka et al. 2011b
2. Improvement	Which parts of the system should be improved, and how?	Geng et al. 2007; Gibbs and Deutz 2007; Kim et al. 2010; Kincaid and Overcrash 2001; Mirata and Emtairah 2005; Shi et al. 2010; Sokka et al. 2011b; Sterr and Ott 2004; Van Berkel et al. 2009; Wolf et al. 2007; Yuan and Shi 2009
3. Expansion	What happens to the environmental impacts of the system when it expands? Should new processes be included?	Andersson et al. 2006; Pakarinen et al. 2010; Park et al. 2008; Wolf et al. 2007
4. Design (eco-industrial parks)	Does the industrial symbiosis approach provide benefits over other design options?	Chiu and Yong 2004; Côte and Cohen-Rosenthal 1998; Fang et al. 2007; Gibbs and Deutz 2005; Heeres et al. 2004; Kincaid and Overcrash 2001; Lowe and Evans 1995; Mirata and Emtairah 2005; Roberts 2004; Sterr and Ott 2004; Van Leeuwen et al. 2003; Wright et al. 2009; Zhang et al. 2010
5. Circular economy	What are the environmental impacts of a circular economy? What kinds of systemic changes would this shift cause?	Fang et al. 2007; Geng et al. 2009; Liu et al. 2009; Park et al. 2010; Yuan et al. 2006; Zhu et al. 2010

possibly increased supply of other products). The design of EIPs and new economic structures influences the surrounding economy considerably.

The recent International Reference Life Cycle Data System Guidelines for Life Cycle Assessment (ILCD 2010) use the extent of change to the surrounding economy as a criterion for categorization of LCA studies by decision context. The context will then influence the methods that should be used to collect the inventory (static vs. dynamic, scenarios vs. equilibrium modeling) and to set the system boundaries of the supply chain. In the following, we divide the groups of research questions according to decision context and then apply the guidelines on this basis.

The three decision contexts of the ILCD guidelines are presented in figure 1. In situation A, the LCA will be used to support a decision with only minor influence on the surrounding economy. In situation B, the decision to be supported may have significant impact on the regional economy, through, for example, increased or decreased production capacity. In situation C, no decisions are supported, but the focus is on static analysis of either an existing site or a hypothetical scenario.

In the field of LCA, two different methods have emerged for inventory collection: attributional and consequential analysis. The former looks at existing systems and allocates environmental impacts to a certain production chain using accounting rules. The latter analyzes the changes (consequences) caused by decisions. Since the analysis of potential changes includes so many uncertainties and assumptions, some researchers recommend using attributional approaches, which at least are based on measurable data (Heijungs and Guinee 2007). Others, however, view avoiding the uncertainties as providing a false sense of security (Weidema 2009). In real-life application, the difference in methods is very apparent in the assessment of liquid biofuels. While many biofuels have lower greenhouse gas emissions when compared to their fossil counterparts, the increased demand for biomass results in indirect land use change and possibly in a reduction of carbon stocks (Cherubini et al. 2009; Kløverpris 2009).



<table>
<tr><td rowspan="2" colspan="2"></td><td colspan="2">Kinds of process changes in the background or other systems</td></tr>
<tr><td>None or small-scale</td><td>Large-scale</td></tr>
<tr><td rowspan="2">Decision support?</td><td>Yes</td><td>Situation A:
‘Micro-level decision support’</td><td>Situation B:
‘Meso- or macro-level decision support’</td></tr>
<tr><td>No</td><td colspan="2">Situation C:
‘Accounting’
(with C1: including interactions with other systems,
C2: excluding interactions with other systems)</td></tr>
</table>

Figure 1 Combination of two main aspects of the decision context: decision orientation and kinds of process changes in the background or other systems (modified from ILCD 2010).

Table 2 Combining the industrial symbiosis (IS) research questions with decision context from life cycle assessment (LCA)

IS research questions type/group	*Change beyond local system boundaries*	*LCA decision context*	*Measurable data available?*
1. Analysis	None	Situation C: accounting	Yes
2. Improvement	Small	Situation A: micro-level decision support	Some
3. Expansion	Small/moderate	Situation A: micro-level decision support	Some
4. Design (eco-industrial parks)	Moderate/large	Situation B: meso- or macro-level decision support	No
5. Circular economy	Large	Situation B: meso- or macro-level decision support	No

Note: See figure 1 for more details on situations A, B, and C.

The ILCD guidelines (ILCD 2010) take a middle position in the debate on whether consequential or attributional methods should be used. Generally they recommend attributional modeling, but they do point to cases in which the change is so significant that consequential methods need to be applied. The separation between consequential and attributional methods is based on the decision context (see figure 1). Overall, consequential modeling is applied if the study is used for decision support and if the decision influences the background economy considerably (i.e., in situation B). These criteria can be used to classify the IS research questions by decision context (see table 2), and context-specific guidance can be proposed.

Very few studies in the literature survey considered the influence of the IS studied on the surrounding system(s). While system analysis tools have been used to quantify the consequences of system change (Karlsson and Wolf 2008), the focus has been on the changes caused in the local system, not in the supply chain. In comparison, the few studies that consider the supply chain do so statically, looking at the life cycle impacts caused in a certain year (Mattila et al. 2010; Sokka et al. 2011a, 2011b). Thus far, no consideration has been given in IS research to the decision context or the effect of changes, and the field could benefit from the LCA guidelines.

Life Cycle Assessment Guidelines for Industrial Symbiosis Assessment

Analysis of Existing Symbioses

Allocation of By-products

In some cases, it can be beneficial to assess the environmental performance of the symbiosis in producing a certain type of commodity. Because industrial symbioses, by definition, produce and utilize by-products, the question of *allocation* is crucial in the separation of the emissions of a single product system from the whole complex. In LCA, two approaches to by-product allocation are presented: partitioning and system expansion (Guinee et al. 2002; ILCD 2010). In partitioning, the emissions and raw material usage are partitioned among the main products and by-products by means of an allocation key, such as mass, energy, or economic value. The system expansion approach considers what production is replaced by the use or supply of the by-product, and this replacement is credited to the system studied. Two approaches for identifying system expansion have been presented: attributional and consequential, referred to above. In the attributional approach, current industry average values are used to estimate the credits of using or supplying by-products. For example, if a symbiosis uses biodegradable waste, it has replaced the collection and composting of that waste. In the consequential system expansion, market effects and marginal technologies are considered (Ekvall and Weidema 2004). In the biowaste case, if a symbiosis would no longer accept the biowaste, what would happen? Would the regional composting and waste treatment systems be able to cope with the increase in demand? Would the biowaste be incinerated? What would this change do at the incinerator? The ILCD handbook (ILCD 2010) recommends that if the purpose of the study is to account for historical emissions and not to consider process changes, system expansion should be done attributionally, using actual historical average technologies.

Definition of a Reference Case

A common issue faced in analysis of existing systems is quantification of the environmental performance of the system in comparison to a reference system. In LCA, this is related to the definition of the functional unit, as only systems with the same functional unit can be compared. Functional units quantify the products and services the system provides, which are of interest in the comparison. If the functional unit of the symbiosis is the total annual production of the symbiosis (as in Sokka et al. 2011a, 2011b), it should be compared to a system that yields the same product mix.

A common practice in IS studies is to have a reference system that is based on the data of the symbiosis under study but that operates without by-product exchanges (Boons et al. 2011; Chertow and Lombardi 2005; Sokka et al. 2011a; Van Berkel 2010). A hypothetical scenario is constructed where all by-products exchanged are sourced from outside the symbiosis boundaries. An example of this is shown in figure 2. In the figure's first pane, a simplified by-product exchange takes place between a power plant and a pulp mill. The power plant utilizes residues from the pulp mill to provide electricity to the national grid and power (heat and electricity) to the pulp mill. Figure 2b shows a reference scenario wherein the by-product exchanges

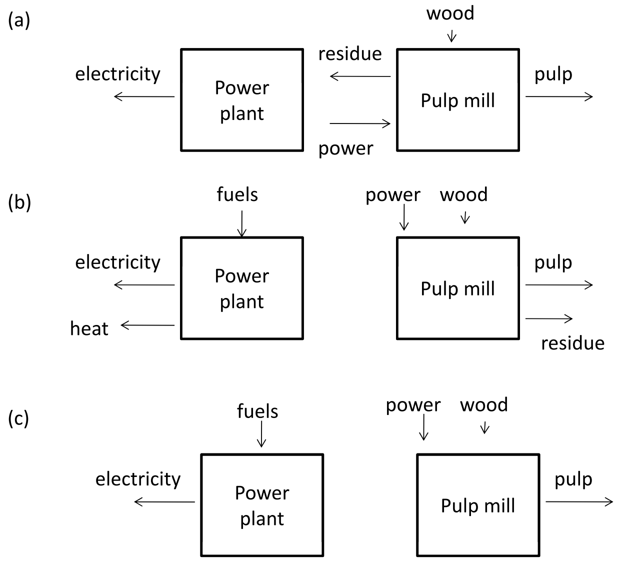


Figure 2 (a) An industrial symbiosis with by-product exchange, supplying electricity and pulp to the outside economy. (b) A disconnected system, with previous by-products replaced by external inputs. (c) A reference case wherein pulp and electricity are produced by means other than in the industrial symbiosis.

are removed. However, in this reference scenario, the production is not changed, although there is clearly no longer local demand for the residues or the heat. The system in figure 2b generates a higher net output than that in figure 2a. In LCA terminology, the functional unit has changed and the systems are no longer comparable.

To enable comparison, the additional net outputs have to be removed from the reference case. This can be done through system expansion, in which emission credits are given from the substitution of alternative production processes (Guinee et al. 2002). For example, if wood residues are used in place of wood chips in landscaping, the emissions of chipping are avoided and are credited to the system (Sokka et al. 2011b). Similarly, the excess heat can be sold to replace coal-fired furnaces in a local district central heating system. After removal of the avoided production from the system, the net output and functional unit are again similar.

However, the system expansion approach has several weaknesses. It requires several assumptions on the potential utilization of the by-products if they are not used in the symbiosis (discussed in more detail in the next section). Also, whether the plants could operate in isolation is debatable, since the by-product exchanges are usually requisite for profitable operation in symbioses. Therefore a more realistic reference scenario could be the one presented in figure 2c, where only the net output is compared to production with sector average technology. The electricity is compared to the grid average, and the pulp is compared to the market mix. This frees the comparison from the technology and feedstocks currently used in the industrial area analyzed.

Environmentally extended input-output (EEIO) tables can be used to estimate the sector average reference case for a variety of products. It should be noted, however, that in many cases the sector average includes several symbioses, so the comparison is no longer between symbiotic and stand-alone modes of operation. Instead, comparison is made between the system analyzed and general practice in production of the basket of products.

Comparing the local symbiosis to the sector average presents a risk of underestimating the local supply chain emissions, because of "cutoff" (Suh et al. 2004). This technical term is used in LCA to describe the flows that have been excluded from the analysis, usually because of lack of data. Since EEIOA captures the whole economy, it has no cutoff. In comparison, in process LCA, services and maintenance are commonly cut off, resulting in ignoring potentially 20% to 80% of the environmental impacts (Mattila et al. 2010; Suh et al. 2004). Comparing symbiosis and the sector average is fair only if the two are assessed with similar system boundaries. The use of hybrid input-output LCA (IO-LCA) methods is therefore recommended to fill the gaps of process LCA before comparison to the sector averages. An example of this is presented by Mattila and colleagues (2010).

As an overall guideline for assessing the environmental performance of IS, we recommend first performing an IO-LCA of the system, using documented purchases and local emission data. This has been found to approximate the more complete results well and can be done fairly swiftly (Mattila et al. 2010). After the IO-LCA, the key issues are identified with contribution (Heijungs and Suh 2002) and structural path analysis (Lenzen 2003). Process LCA data collection can then focus on these main influence pathways (Lenzen and Crawford 2009). The final hybrid LCA results are then compared to the situation where the same net output as in the symbiosis would be produced by sector average technology.

Improvement and Expansion of Symbioses

Calculation of the net environmental impacts of the expansion of an IS network clearly has to take into account the changes caused to the surrounding system: Will the expansion of the network replace other technologies or result in increased total production? If more by-products are used, will this create a market for production of more of those by-products (Chertow 2000)? This applies to both improvement and expansion of IS networks. Improvement is somewhat easier to analyze since the improved system can be compared to the reference of continuing with the unimproved system (Sokka et al. 2011a). In the expansion, no clear reference is available and a market analysis is necessary for identifying what would have happened if the expansion had not occurred (Ekvall and Weidema 2004).

Figure 3 illustrates a few possible consequences of expanding a hypothetical forest industry complex with a biodiesel refinery. If the changes to the whole economy are considered to be small ("situation A: micro-level decision support"), the consequences could be modeled as a replacement of fossil fuels. However, if the plant is sufficiently large, the expansion will affect the market for wood and biodiesel ("situation B: macro-level decision

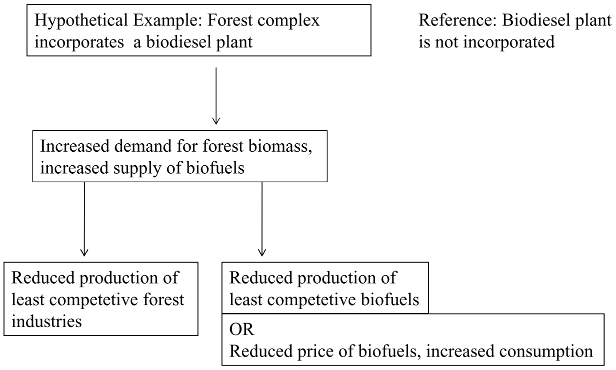


Figure 3 An illustration of the possible consequences of industrial symbiosis network expansion when the changes are sufficiently large to influence economic structures.

support”). In many situations, both are limited markets—wood production is limited by forest area, and biodiesel amounts are limited by the availability of government mandates and subsidies (if only cost is considered, gas-to-liquid clearly outweighs biomass-to-liquid diesel (Van Vliet et al. 2009)). If such a market situation applies, the increased demand for forest products results in reduced production of the least competitive user of forest biomass and reduced production of the least competitive biodiesel process (guidelines for identifying the consequences of changes in different market situations are given by Ekvall and Weidema [2004]). In some cases, it may happen that an increased supply of biodiesel would decrease the average price of fuel and thus result in increased consumption. This is known as the rebound effect.

Applying the guidelines of LCA to IS, we recommend that when improvement or expansion is analyzed either (1) it be demonstrated that the proposed changes do not change the surrounding system or (2) these changes be analyzed with consequential LCA. Since many IS networks operate as waste treatment facilities, and the waste treatment system accounts for a relatively small portion of the economy, relatively small changes in material balances may result in meso- or macro-level structural change in waste management (Ekvall et al. 2007).

Design of Eco-Industrial Parks

The design phase differs from expansion and improvement, since there is no existing reference for the proposed system. In addition, implementing a new EIP will change the local by-product exchange pattern and result in structural change. Therefore a macro-level decision support approach is necessary (figure 1, situation B).

A suggested reference for the EIP is production of the commodities by other means. This could be a new alternative industrial park or the expansion of existing production technology elsewhere in the relevant industries. Also, the waste treatment services provided to the outside economy by the planned EIP should be included as commodities.

In the preliminary planning stage, accounting LCA methods (figure 1, situation C) could be used. Since economic data for planned purchases and sales should be available on the basis of the planned enterprise budgets, EEIO methods could be used to estimate the magnitude of the supply chain effects caused by the proposed system. The hotspots in these indirect effect chains could then be identified via structural path analysis (Lenzen 2003) and the results compared with the sector averages, similar to what was suggested for the analysis of existing symbioses. This approach allows the eco-design of the EIP to consider the whole life cycle and minimize the environmental impact in comparison to the present sector average.

Beyond preliminary planning, however, comparison to existing sector average technology is no longer applicable. Industrial parks can operate for decades, and the decision to build a new EIP will have consequences for the amount and technology of regional production for several years to come. This choice should then be weighed against that of not implementing an EIP. The consequences depend on the market situation, and the LCA guidelines give some archetypal situations for identifying the reference state (ILCD 2010). If the market is expanding, it might be reasonable to assume that the relevant production would replace the most cost-competitive long-term marginal production in the associated industries (ILCD 2010). However, if the market is shrinking or stagnant, the new EIP might only reduce prices further, resulting in replacement of the least competitive alternative, but possibly also increasing consumption. Even if the new EIP would be more efficient than existing technology, there is no guarantee that its implementation would result in the shutting down of existing technology. In the worst case, total emissions would still increase. The risk of such rebound effects should be carefully analyzed before one makes claims about environmental sustainability or implementation of such EIPs on a large scale.

Circular Economy

Long-Term Marginal Development as a Reference Case

The large-scale implementation of IS and EIP would result in a new economic setting known as the circular economy (CE) (Yuan et al. 2006). The idea has recently attracted a lot of attention, especially in China (Zhang et al. 2010), as the concept was accepted as a new development strategy by the central government in 2002 (Yuan et al. 2006). A CE aims for closed-loop material and energy systems in all sectors of industry in order to reduce the use of natural resources and the environmental impact. A CE is implemented through cleaner production, EIP regions, and a national focus on recycling (Li et al. 2010).

The problems of analyzing a proposed CE are similar to those faced in the planning of a new EIP, but arise at a much larger scale. From an accounting point of view, a CE might have significantly smaller material and energy flows than are seen in the current situation. However, what happens when the current situation is changed toward a CE? Is resource consumption decreased, or does total production increase with efficiency and lower costs? What approaches have been lost by focusing on recycling instead of waste prevention?

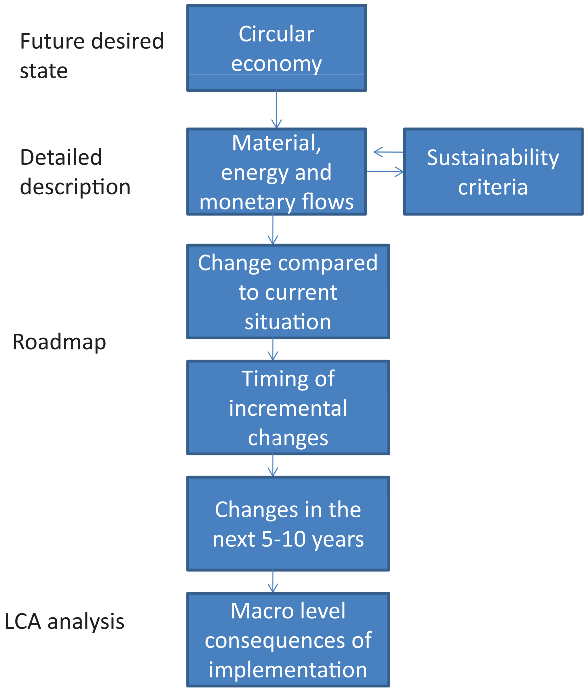


Figure 4 Using a backcasting framework to reduce circular economy plans to units that can be analyzed with life cycle assessment.

Clearly, analyzing the implementation of CEs is macroscale decision support and calls for consequential LCA (situation B in figure 1). According to the guidelines, a CE should be compared to the long-term marginal development that would have occurred without the CE (ILCD 2010), yet identification of the long-term marginal impacts is difficult, since the magnitude of the changes when a whole nation moves to a CE is too great for forecasting. Market equilibrium models commonly used in consequential LCA (Ekvall and Weidema 2004; Kløverpris 2009) rely on historical data on demand and supply elasticity. In a CE situation, the economic structure is purposefully changed on a large scale, historical models no longer apply, and forecasts become largely impossible. Accordingly, other tools are necessary.

Scenario Analysis

In addition, LCA and related tools could be used to analyze systems whose change is too large to be captured even with macroscale decision support as recommended in the current guidelines. Scenario analysis, backcasting, and input-output analysis can be used to bring the large-scale changes closer to the proposed extent of macroscale decision support. In energy analyses, backcasting is typically used to analyze changes that are too large to be forecast from the current situation (Robinson 1982). With the backcasting approach applied to CE (figure 4), the current situation can be described through a national environmentally extended input-output table. Changes would be made to the EEIO until it matches the vision of the CE and possibly meets other sustainability criteria (related to emission levels, employment, the balance of trade, etc.). Further changes would then be made until the proposed system is viewed as a desirable representation of the future CE.

However, investments in construction of infrastructure elements such as production facilities and roads are needed for reaching the desired state, and the environmental impacts of this construction, with all of its energy and material use and emissions, also need to be accounted for. First, a road map is created to link the current situation to the vision through intermediate steps. For the reference case, a corresponding road map is created for production similar to that in the vision, but with the present technology. The environmental impacts of constructing the infrastructure are then added to the yearly environmental impacts in the two cases: “vision” and “reference.”

The intermediate steps on the road map might be small enough to be analyzed with the macro-level LCA tools proposed in the guidelines (ILCD 2010). For example, the indirect market effects of prioritizing the building of new infrastructure and therefore constraining other construction could be captured in a consequential LCA. Full analysis of the consequences of taking the first steps toward a CE could show possible early warning signals and indicate whether undesired indirect effects are to be expected.

Conclusions

Life cycle assessment has been applied in very few IS studies. In addition, LCA has been applied mainly in the quantification of existing systems through environmental accounting. The more decision-oriented consequential LCA has not been applied in the IS field. Our classification of IS research questions indicates that many existing studies fall under micro- or macro-level decision support and would benefit from a fully consequential approach, as recommended by the LCA guidelines. Applying the guidelines to IS would improve the comparison of IS to reference systems and to other development strategies.

Expansion of current EIPs and implementation of new ones may result in changes in the economic structure. This change has not yet been analyzed in the IS literature, even though LCA provides tools for such analysis. Implementation of the more decision-oriented LCA methods could ensure that progress in IS does not result in unexpected indirect effects through market mechanisms. However, the current LCA tools are limited in scope when full-scale IS strategies such as a CE are considered. Backcasting and other scenario tools may be used to reduce them to analyzable units. Overall, LCA can be used as a general framework for measuring the environmental performance of IS.

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Note

1. In this work, both waste and by-products are referred to by the term "by-product." However, it should be noted that these two terms have different regulatory implications. The use of by-products classified as waste is restricted by waste legislation and is therefore not straightforward. Waste management policies may affect the development of industrial symbioses. For further discussion of the role of waste policies in enhancing industrial symbiosis development, see, for example, the work of Costa and colleagues (2010). However, this issue is beyond the scope of the present paper and will not be dealt with further here.

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