Industrial Ecology for Sustainable Development: Six Controversies in Theory Building

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ABSTRACT

This article is building the theory for the scientific *field* of industrial ecology. For this, the industrial ecosystem (IE) *concept* is used. IE uses the model of sustainable ecosystems in unsustainable industrial systems for making progress towards the *vision* of the industrial ecosystem. Six controversies are revealed and identified as research challenges. I invite all those who are interested in industrial ecology to respond to this contribution.

KEYWORDS

Sustainable development, industrial ecology, industrial ecosystem, controversies, theory building

1. INTRODUCTION: SUSTAINABLE DEVELOPMENT AND INDUSTRIAL ECOLOGY

The concept

The emerging field of industrial ecology and the concept of industrial ecosystem (IE) (Frosch and Gallopoulos; 1989; Erkman, 1997; Ehrenfeld, 2000; Korhonen, 2004a; 2004b; Korhonen, von Malmborg, Strachan and Ehrenfeld, 2004; Korhonen and Strachan, 2004; Korhonen, Huisingh and Chiu, 2004) have generated a rapidly developing literature[1] in sustainable development (WCED, 1987) discussion and debate. Two new academic journals,[2] some journal special issues, books, an international society and numerous conferences and seminars have been launched.

The first basic principle of the new IE concept is close to the other recent material and energy flow orientated concept, 'industrial metabolism' (Ayres,

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1994). IE compares the natural ecosystem and the industrial system by tracking the flows of matter and energy (Erkman, 1997). The second principle extends industrial metabolism (Erkman, 1997) and uses the natural ecosystem model in industrial systems (Graedel, 1996). Hence, the provocative term ‘industrial ecosystem’ has been coined. Both physical material and energy flows as well as the more structural and organisational characteristics and properties are studied in a systems perspective (Korhonen, 2004a). The philosophy is to ‘learn from nature’ (see the discussion later on in this paper on this difficult question). But the concept is only rarely presented or classified according to the two categories; flows (1) and structure (2) (Korhonen, 2000a; 2001a). The systems perspective, i.e., that all the industrial system components are studied, is the basis of all IE principles (Erkman, 1997).

In the literature on the IE concept, the natural ecosystem material and energy flows that rely on infinite solar energy, and are materially closed demonstrating advanced recycling and waste energy utilisation (cascading) emitting only waste heat (infrared radiation) to space (figure 1), are seen as the only available example for humans of sustainable or long-lived material and energy flow systems (figure 2) (Jelinski et al, 1992; Graedel and Allenby, 1995; Ehrenfeld, 2000). The more structural and organisational characteristics of ecosystems used in industrial systems include diversity, connectance, interdependency, symbiosis, cooperation, community, adaptation and locality (Allenby and Cooper, 1994; Benyus, 1997; Ehrenfeld, 2000; Korhonen, 2000a; 2001a; 2004a; Hardy and Graedel, 2002; Geng and Cote, 2002).

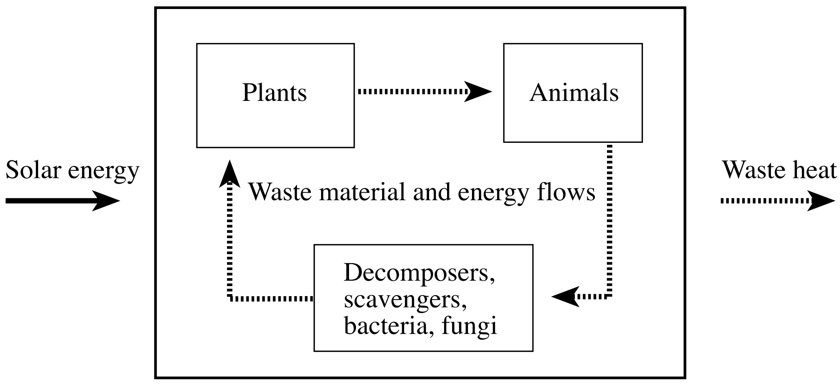

FIGURE 1. Simplified flow of matter and energy in an ecosystem. The flow of matter in a natural ecosystem is cyclic. Plants bind solar energy into chemical form. Plants (producers), animals (consumers) and decomposers, microbes and bacteria (recyclers) are a system in which the actors utilise each other’s waste material flows as a source for energy and as a construction material for organisms. The only external input to the system as a whole is the (infinite) solar energy and the system is materially closed. Eventually, the energy will be released as waste heat into air and into water from which it radiates back to space.

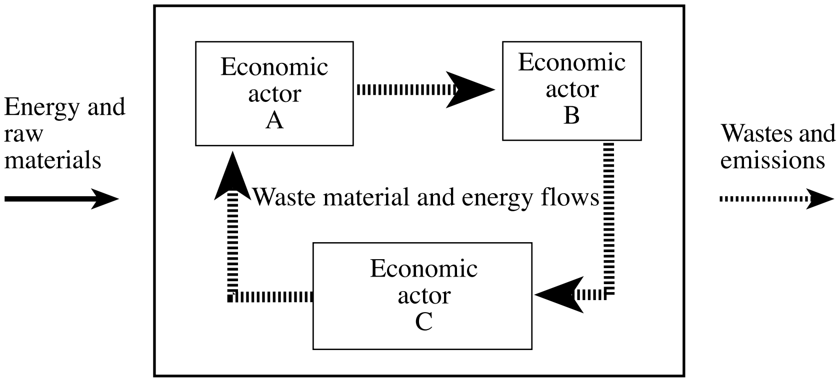

FIGURE 2. Simplified flow of matter and energy in the industrial ecosystem (IE) vision. The flow of matter in an industrial ecosystem is cyclic. Producers, consumers and recyclers are a system in which the actors utilise each other's waste material flows and waste energy flows as well as local/regional renewable natural resources reducing the virgin input to and the waste and emission output from the industrial system as a whole. The system relies on diversity in the actors involved, which sustains the system in case of disturbance, on interdependency in cooperation (e.g., in recycling and energy cascading) and on locality in the system arrangement. The arrows within the system are larger than the arrows to and from the system illustrating the contribution of cooperative recycling and energy cascading. In this vision, it is more important to focus on the local/regional network system as a whole than simply on an individual system component of the system.

Practical applications

The vision of the industrial ecosystem concept in figure 2 is very ambitious. The concept has become popular, because of the natural ecosystem analogy or metaphor as its source. The example of the Kalundborg industrial ecosystem in the Danish city/town, known as the local/regional industrial symbiosis (Ehrenfeld and Gertler, 1997; Gertler and Ehrenfeld, 1996; Tibbs, 1992; Chertow, 2000; Erkman and Ramaswamy, 2003), has also 'aired' the concept.

In the global market economy, the flows of products and their material and energy flows extend over local, regional, national and continental borders. The idea of a 'closed loop' system is, then, very abstract even though one would 'only' try and achieve it in a small local system. I argue that the local/regional application is the only possibility when studying the *concept* of IE, and as noted, also this is very difficult as a focus point (e.g. because of globalisation).

There are practical case studies on regional or local industrial, firm or actor networks, industrial ecosystems or industrial symbiosis (Cote and Hall, 1995; Cote and Cohen-Rosenthal, 1998; Gertler and Ehrenfeld, 1996; Ehrenfeld and Gertler, 1997; Schwarz and Steininger, 1997; Baas, 1998; 2001; Korhonen, 2001b; Korhonen et al., 2002; Chertow, 2000; 2002). In these documented IEs, the cooperative actors within the system boundaries use each other's material and energy flows including by-products and wastes. The vision is to reduce the total input flow and the total output flow to and from the system. Raw material costs, energy and transportation costs on the input side and the emission control, waste management or landfill costs on the output side are reduced and controlled. Green market opportunities are created while costs arising from measures required in environmental legislation are reduced in this highly idealised 'win-win'[3] vision (Korhonen, 2002a). One can argue that the potential contribution of this vision to the common industrial environmental management approaches and tools is the focus on the system as a whole, instead of only on an individual system component (Korhonen, 2002a). Such a focus is relevant for firm network management (Roome, 2001) and for 'inter-organisational environmental management' (Sinding, 2000).

When looking at IE as an emerging scientific *field*, not as a specific concept, we find many practical case studies focusing on physical flows of matter and energy. But these studies are usually other than local industrial ecosystems. This paper argues that they offer very little for the theory building for the young field of industrial ecology. Such studies do not apply the theoretical concept, that is the natural ecosystem analogy or metaphor-derived concept in industrial systems. If one asks what is the specific and unique contribution of the field of industrial ecology to sustainability, I would answer that it is not the focus on material and energy flows. Rather, the systems approach to the material and energy flows derived from the natural ecosystem metaphor or analogy (for discussion on metaphors vs. analogies, see Ehrenfeld, 2003) as in figure 2, in turn, can be the contribution.

For example, environmental life cycle assessment (LCA) forming a large part of the cases published in the field of industrial ecology, has a much longer conceptual history than that of the specific industrial ecosystem concept. The field of industrial ecology has evolved and gathered other environmental science, environmental engineering, industrial environmental technology, management and environmental policy concepts and methods under it and so established itself as an emerging scientific field. I argue that, in this process, the theory building that would help IE to become a field that can offer something unique for making progress in sustainable development and that would help IE to 'stand out' among the many other related fields such as cleaner production (CP), material flow analysis (MFA), life cycle assessment (LCA) and pollution prevention (which all have their own journals and societies), has been ignored to a large extent.

The *Journal of Industrial Ecology* (Yale/MIT) reads on the back cover: 'The field encompasses(:) material and energy flow studies ("industrial metabolism"), dematerialization and decarbonisation, technological change and the environment, life-cycle planning, design and assessment, design for the environment, extended producer responsibility ("product stewardship"), eco-industrial parks ("industrial symbiosis"), product-orientated environmental policy, and eco-efficiency.' LCA, extended producer responsibility, design for the environment or eco-efficiency are usually applied in practice to individual products, processes or firms/organisations, that is, on individual system components. Hence, these tools are usually not applied to entire systems that could be logically analysed against the vision derived from the ecosystem metaphor in figures 1 and 2. The concepts that have been applied to individual system components have either been developed earlier than the concept of the industrial ecosystem or in separation from it.

The objective

I will focus on the industrial ecosystem concept and it is based on figures 1 and 2, on the natural ecosystem metaphor derived concept. The research objective is as follows: *This theoretical paper evaluates the contribution of the industrial ecosystem concept to the ecologically sustainable development of industry.* I believe that this focus on the concept of the industrial ecosystem can contribute to the theory building of the field of industrial ecology, to help the field to stand out from other fields and develop its own unique contribution.

2. METHODOLOGY AND MATERIALS

The literature on IE began with the 1989 *Scientific American* article by Frosch and Gallopoulos (Erkman, 1997; den Hond, 2000; Chertow, 2000, Korhonen, 2001a). But the term has been used before, and even for similar purposes (e.g., Koenig et al., 1972, Koenig et al., 1974; Bennet and Chorley, 1978, see also discussion by Erkman, 1997 and Ehrenfeld and Gertler, 1997).

The search words and terms 'industrial ecology', 'industrial ecosystem', 'industrial symbiosis', 'eco-industrial parks' and 'industrial recycling network'[4] were applied, because these are practically the only terms with which it is possible to find articles in which the specific *concept* of the industrial ecosystem is studied (see the discussion above).

The main literature sources are shown in table 1. Two journals exist: *Journal of Industrial Ecology* (JIE) and *Progress in Industrial Ecology – An International Journal* (PIE). There are two published special issues on IE, *Proceedings of the National Academy of Science* (1992) and the *Journal of Cleaner Production* (JCP) double special issue (1997, JCP 5: 1–2) as well as a roundtable discussion in *California Management Review* (2001, Vol. 43, No.3). Another special issue of JCP is forthcoming (2004) and *Business Strategy and the Environment* (BSE) is also going to publish an IE special issue (2004).

Up to now, JIE and JCP have clearly been the most important sources for IE literature (den Hond, 2000). Although BSE has published only few IE articles so far, it has been included among the main sources, because of the forthcoming special issue and because many IE-related themes are covered in the journal, e.g., the special issue on networks (vol 10, number 2, 2001).[5] Note also that the published call for papers for PIE (and the first issue, which is probably out by now) has a clear business or management focus. *Ecological Economics* covers many themes important for IE, e.g., material and energy flow concepts, analysis and measurement.

The literature analysis is divided into two categories: The physical flows of matter and energy 1) and the structural and organisational characteristics and properties 2).

Books	Journals
Socolow, R., Andrews, C., Berkhout, F. and Thomas, V. (eds.) 1994. *Industrial Ecology and Global Change* Allenby, B. & Richards, D., J. (eds.) 1994. *The Greening of Industrial Ecosystems*. Ayres, R., U. & Simonis, U., E. (eds). 1994. *Industrial Metabolism* Graedel & Allenby, 1995. *Industrial Ecology*. Ayres, R., U. & Ayres, L. 1996. *Industrial Ecology* Richards, D., J. (ed.) 1997. *The Industrial Green Game* Benyus, J. M. 1997. *Biomimicry* Abe et al., 1998. *Business Ecology*. Allenby, 1999a. *Industrial Ecology.* Korhonen, J. 2000a. *Industrial Ecosystem* Chertow, M. (ed.) 2002. *Developing Industrial Ecosystems: Approaches, Cases, and Tools* Ayres, R., U. & Ayres, L., W. 2002. *A Handbook of Industrial Ecology* Erkman, S. & Ramaswamy, R. 2003. *Applied Industrial Ecology – A New Platform for Planning Sustainable Societies*. Bourg, D. & Erkman, S. (eds.) 2003. *Perspectives on Industrial Ecology.* Snäkin, J-P. 2003. *Wood energy and greenhouse gas emissions in the heating energy system of North Karelia, Finland: An industrial ecology approach*. Niutanen, V. 2004. *Industrial ecosystem case studies*. Other related books (the author's opinion)	*Journal of Cleaner Production*. 1992— *Journal of Industrial Ecology*. 1997— *Proceedings of the National Academy of Sciences*, Vol. 89. 1992. *Journal of Cleaner Production* (double) special issue. Vol. 5., No. 1–2. 1997. Articles on IE or on related themes in other journals, 1989–, e.g., *Business Strategy and the Environment* 1992-2003 and *Ecological Economics* 1996–2003.

TABLE 1. The materials of the study.[6]

3. THE INDUSTRIAL ECOSYSTEM CONCEPT FOR ECOLOGICALLY SUSTAINABLE DEVELOPMENT

Flows of matter and energy in IE

In the often-cited Frosch and Gallopoulos (1989) article, the linear industrial material and energy 'throughput' flow was identified as the main challenge of industrial environmental management. Throughput starts from nature and ends up in nature. Industrial systems rely on non-renewable and emission intensive fossil fuels while generating unutilised wastes dumped to nature. Approximately 80% of the world's energy consumption is based on fossil coal, oil or natural gas (Williams, 1994).

The National Academy of Science of USA organised a colloquium on IE in 1991, the first major forum for IE. In the introductory paper, Jelinski et al. (published in 1992) defined three conceptual flow models for IE development/evolution; type I, II and type III ecology. The concepts show an immature (young) linear throughput ecosystem flow model, a semi-cyclical material flow and developing energy cascade and a mature (old) materially closed ecosystem that only emits waste heat to surroundings (or, eventually, infrared radiation to space) after advanced energy cascade structure relying on infinite solar energy. Accordingly, unfortunately, industrial systems are somewhere between I and II.

Ayres and Ayres (1996) continued with this idea showing, e.g., the carbon-oxygen cycle in ecosystems as an example model of the system overall sustainability. Plants use carbon and produce oxygen waste, which is used by animals that produce carbon dioxide (CO_2) as a metabolic waste. Ring (1997) showed how green plants in ecosystems act as decentralised power plants providing the food web with solar energy derived energy cascades securing efficient utilisation. Geng and Cote (2002) highlighted the crucial role of decomposers and scavengers in processing ecosystem waste materials. Korhonen et al. (2001; 2000a) divided the forest ecosystem material and energy flows into categories of matter, base cation (BC) nutrients, energy and carbon comparing these to the same flows in the forest industry arguing that industrial systems should learn[7] from nature to move toward sustainability.

Based on this evidence in the literature on IE, it is straightforward to conclude that the cyclical material flow and the cascading energy flow, the reliance on sustainable use of renewables and waste utilisation constitute the foundation of the IE concept's material and energy flow thesis. Korhonen (2001a; 2000a) termed this flow model as 'roundput' as opposed to the dominant industrial 'throughput'.

What is the contribution of the IE material and energy flow model?

Desrochers (2002a; 2002b; 2001) has presented an insightful and provocative critique arguing that recycling and inter-industry recycling have existed for a long time. Korhonen and Snäkin (2003) showed that their case study, a regional heating energy system, simply had to rely on renewable biomass or wood fuels before fossil fuels were available. It is clear that before the industrial revolution and the fossil fuel era this was more or less the case all over the world: The use of wastes and renewable flows derived fuels was the only available solution to fulfil the societal energy demand. Williams (1994) maintains that biomass was dominant in global energy use and consumption through the middle of the nineteenth century.

The concept or the method of recycling as such contributes little in terms of a new contribution to sustainability. All those who are familiar with thermodynamics or entropy are already familiar with recycling (Korhonen, 2000a). Recycling is much older than the last ten or fifteen years of the 'history of the IE concept'.

The contribution of the IE material and energy flow theory arises out of the systems approach inherent in the concept that uses nature as a model. Biological ecology is a form of systems analysis. It radically departs from the majority of industrial environmental management tools that focus on individual system components, instead of on entire systems that consist of many different system components. Substance flow analysis (SFA) studies the flow of an individual substance, say, cadmium, environmental life cycle assessment, the environmental interventions of an individual product, say, of a newspaper, while environmental management systems (EMS), e.g., EU Eco-Management and Auditing Scheme (EMAS) or the International Standardisation Organisation (ISO) ISO 14001 standard concentrate on an individual firm.

'Problem displacement' or problem shifting from one part of the system to another part may occur if a holistic systems approach is not used (Jänicke, 1990; Jänicke and Weidner, 1995; Ayres, 1994; Rejeski, 1997; Pento, 1998a; 1998b; Anderberg, 1998; Korhonen and Pento, 1999a; Korhonen, 2000b). Consider that production wastes can be shifted to consumption wastes, because of emissions focused instead of product focused environmental policy (Anderberg, 1998; Rejeski, 1997; see Socolow, 1994). Emissions and wastes are 'recycled' between different environmental medium, because of single medium focused legislation and policy, e.g., between air, land and water (Ayres, 1994). Wastes are transformed from one form to another, because the entire life cycle is not measured (Pento, 1998a; 1998b; Korhonen, 2000b).[8] One may transfer the environmental problem from the input side to the output side of industrial production, e.g. note how a shift from non-renewable to renewable fuels in energy production can create a heavy metal containing waste material flow released to the ecosystem as wood waste derived fuel-based energy production produces cadmium containing incineration ash (Ranta et al., 1996).[9]

There is merit in the IE theory, because it looks at entire systems, not simply individual system components. Recycling, in itself, is not a contribution.

The structural and organisational characteristics

The more structural and organisational characteristics and properties of IE theory include diversity,[10] connectance, interdependency, cooperation, community, adaptation, and locality (Allenby and Cooper, 1994; Graedel and Allenby, 1995; Ring, 1997; Benyus, 1997; Pizzocaro, 1998; Hardy and Graedel, 2002; Templet, 1999; Ehrenfeld, 2000; 2003; Korhonen, 2001a; Korhonen, 2001b).

The first textbook on industrial ecology (Graedel and Allenby, 1995) and a 1996 article (Graedel) suggested that the ecosystem material and energy flow evolution from type I to type III also shows the evolution from a system, in which interdependency between organisms is low to a system in which this interdependency or cooperation between ecosystem components is high. Sustainable ecosystems and sustainable regional industrial systems or 'islands of sustainability' (IOS) are systems with more complexity and networking than in unsustainable systems (Wallner, 1999; Wallner et al., 1996). Diversity of the system in terms of the actors, or 'process units' (PUs) involved is higher in sustainable systems than in unsustainable systems.

It can be argued, that the dominant social paradigm (DSP), to a large extent, highlights competition over cooperation (Ehrenfeld, 2000; 1997). Traditionally, the only corporate social responsibility in neoclassical economics-based business paradigm has been to make profits and compete in the markets (Hussain, 1999; Ahmed, 1998; see Friedman, 1962). Ehrenfeld maintains that organisms in ecosystems compete, but not in a way firms in an industrial system do. The overall condition of cooperation prevails in ecosystems. Accordingly, IEs should also be cooperative. Hardy and Graedel (2002) analysed food web connectance values against data gathered from several eco-industrial park or industrial ecosystem/industrial symbiosis case studies (see Chertow, 2002) and found a correlation. They did not find evidence on the relationship of resource or energy efficiency and connectance in food webs or in IEs.

One of the reviewers of this paper noted that it is important to acknowledge that, in industrial systems, cooperation and competition are not necessarily exclusive or each other's substitutes (alternatives). For example, in cluster theory (see Porter, 1998), cooperation and competition are complementary features.

Ecosystems are diverse systems in terms of the actors involved, e.g., species diversity, which also means diversity in information (Ring, 1997). The use of a one-dimensional monetary value in economic systems reduces the diversity of information feed-backs. It is difficult to quantify qualitatively different things, consider the monetary value of the environment in economics science (Costanza, et al., 1998). Incomplete quantitative information on ecosystem qualitative features may lead to suboptimal policy solutions in terms of biodiversity (Ring, 1997). In nature, when certain species depart (or die), the system is able to recover and adapt through diversity in the species, organisms and in their genetic variance and information. Coral reefs or tropical rain forests are examples.

Templet (1999) found a positive relation between economic system diversity and energy efficiency. Diversity was measured in terms of the number of economic sectors using energy and equitability of energy flows between them. The developed countries were more diverse and more efficient in their energy use when compared to the countries in the developing world with low diversity. The third world economies can be arranged around the production of certain individual key products, e.g., timber, sugar or coffee, or raw material intensive agricultural and forestry products etc. Such structures are vulnerable to external and internal changes.[11] The structures lack diversity that could enhance adaptation (Korhonen, 2002b).

Some authors have suggested that growth does not necessarily have to end to achieve sustainability if diversity of the economic system increases (see Allenby and Cooper, 1994). Rather, more diverse and equal distribution of growth among the economic sectors inside, e.g. a certain national economy, could be important. It seems that for Allenby and Cooper, the overall system quantitative growth is different than the new distribution of growth within and inside this system, i.e., development. Daly (1996) argues against the quantitative growth of the physical economy. The economic system is a subsystem of the parent non-growing ecosystem. In Daly, development is more qualitative than quantitative, e.g., development of education, community and services.

Adaptation is another system characteristic or property that has been offered in the industrial ecology literature (Korhonen, 2001b; 2002a; 2002c). For example, the success of a co-production plant of heat and electricity (heat and power, CHP) participating in a local IE, can be based on the ability of the CHP plant to adapt to its external material and energy flow environment. The decomposer/scavenger metaphor was used for inspiration and creativity in the study of CHP plants in industrial ecosystems (Korhonen, 2001b; 2002a; 2002c). These are able to a) use wastes from other ecosystem actors and b) process these wastes into a form that can be used again by green plants. A CHP plant with the fuel combustion technique of fluidised bed burning (FBB) can use fossil fuels, but also other fuels such as peat, low grade forest residues from cuttings, pulp mill wastes, paper mill wastes, other wood wastes, agricultural wastes and even sludge after the water content has been reduced. Because CHP combines the production of heat and power, it can provide a) industrial actors, b) primary or agricultural producers and c) residential households with electricity, industrial process steam, district heat or heat to be used by horticulture or, for example, to melt the ice-covered city streets during winter times. Energy is derived from waste fuels i.e. integrated waste management and energy production.

It seems that the above characteristics of diversity, interdependency and adaptation are very close to each other. However, it is important to make a distinction between diversity and interdependency (Korhonen, 2000a; 2004a). Diversity in the actors involved in cultural or economic systems leads into diversity of interests, preferences and values, which can be conflicting. The use of diversity as a normative principle in IE to achieve interdependency or cooperation or adaptation between the actors involved, e.g., in recycling networks or cooperative waste utilisation, is therefore, anything but straightforward.

Also the ecosystem characteristic or property of locality has been discussed in the literature on industrial ecology, ecological economics and sustainable development (Benyus 1997; Allenby and Cooper, 1994; Wackernagel and Rees, 1997; Korhonen, 2001a; 2004a). The global economy geographically separates production and consumption. This consumes energy and creates emissions. The inter-regional and inter-national product life cycles are difficult to trace, monitor and manage. The above papers highlighted that ecosystems tend to be arranged locally (of course, there are exceptions, see Graedel, 1996) to reduce energy use. Ecosystems remain within the local carrying capacity. Economic systems import and export substituting technology or imported non-renewables for local renewables and for local carrying capacity (Koenig et al. 1972). The ecological footprint (EFP, Wackernagel and Rees, 1997) of large metropolitan cities extends over national and continental borders.

When comparing ecosystems and economic systems in terms of the local vs. global question, Ring (1997) proposes an ecological tax reform in that it can help environmental policies to gain from ecosystem principles. Taxes on fossil fuels can reduce transportation and promote the use of renewable and waste fuels.

What is the contribution of IE structural and organisational characteristics?

Competition, mass production, growth and globalisation prevail in the dominant social paradigm (Ehrenfeld, 1997; 2000) and in the dominant neoclassical economics science paradigm (Korhonen, 2002b). The characteristics of interdependency, community and cooperation, e.g., in recycling and environmental management, could be enhanced in economic and industrial systems. Energy use could be reduced through locally integrated production and end-consumption.

However, it is not clear whether these constructs or structural and organisational principles and system properties can be assigned to the merit of the industrial ecosystem concept. The importance of local solutions has long been regarded as high, note the Local Agenda 21. Networking and inter-organisational cooperation has been presented as important for sustainability in many documented studies (Roome, 2001; Sinding, 2000).

I argue that the industrial ecosystem concept's contribution to sustainability theory can arise from systems analysis, in which the many concepts and principles can be considered together, and not only as scattered around and placed under different conceptual frameworks and fields. The ecosystem is an important source for inspiration and creative thinking. Ecology and biology have a long tradition in systems analysis, while environmental policy and corporate environmental management are very young fields mainly using approaches and tools that focus on individual system components or on an individual system principle at a time.

Recycling, diversity, cooperation and locality can be studied simultaneously and evaluated together as each other's complements. A recycling system that conducts recycling over long transportation distances is not necessarily sustainable. A recycling system that only recycles between few participants, i.e., shows low diversity, is not necessarily a contribution. Diversity, on the other hand, does not mean that there is cooperation.

In sum, the contribution of IE structural and organisational principles and properties includes the following:

1. The principles are studied under a single holistic framework in which several systems principles serve as each other's complements and are studied together, not as isolated from each other.
2. The structural and organisational principles extend IE analysis beyond the physical flows of matter and energy. In this way, it can be possible to start and study also the human dimension of IE.
3. This human dimension constitutes the driver of material and energy flows, and by studying it, natural science and engineering and inventory-type material and energy flow analysis can be better connected to practical decision-making, policy instruments and strategic management systems.

4. SIX CONTROVERSIES IN THEORY BUILDING

I present six controversies and argue that these controversies are challenges and tasks that need to be addressed in industrial ecology theory building.

4.1 System versus its boundaries

Physical flows of matter and energy extend over product, process, firm, local, regional or national boundaries and borders. Consider transboundary pollution or imports and exports of physical products and the associated environmental impacts of the life cycles of the products. In the global market economy, there simply does not exist a totally closed local IE. Above, the systems approach in IE was seen as important to reduce problem displacement and problem shifting from one part of the system to another part. But the fact that all systems have boundaries still remains.

The success of waste utilisation in the Styria province/region industrial recycling network in Austria with a population of 1.2 million was described in Schwarz and Steininger (1997), but the authors did not study the inter-regional import and export flows (see Desrochers, 2002a). They note (p. 50) 'Material flows from the natural environment to the recycling structures and vice versa were not recorded.' The Styria study had many paper industry plants in it. I have not worked with this case, but it can be assumed that the use of non-renewable and emission intensive fossil fuels, at least, in absolute terms, in such a large system of 1.2 million people, is significant. The study identified (p. 52) 16 types of waste. The amount of flows that were treated or recycled was given. However, the study did not present how much energy was used in treatment or recycling. Recycling too consumes energy (Daly, 1996; Ayres, 2004).

Another case study for the local/regional industrial symbiosis or industrial ecosystem approach is the Jyväskylä city industrial ecosystem in Finland (Korhonen 2002a). Jyväskylä has reduced its emissions through cooperative waste utilisation. But the system still uses fossil fuels, which are imported, non-renewable and emission intensive. Jyväskylä uses domestic peat up to around 70%, which at most, can be defined as a very slowly renewable fuel (see Lappalainen and Hänninen, 1993; Savolainen et al., 1994; Selin, 1999; Korhonen, 2001b).

The famous Kalundborg industrial symbiosis or industrial ecosystem in Denmark has been documented in many scientific articles and book chapters during the last 10 or 15 years (Ehrenfeld and Gertler, 1997, see Gertler and Ehrenfeld, 1996; Tibbs, 1992). A coal-fired power plant and an oil refinery, a pharmaceutical plant and a plaster board manufacturer and other actors recycle wastes in cooperation. But again, the system uses imported, non-renewable and emission intensive fossil resources/fuels and is not closed. Desrochers (2002, p. 52) states that 'In short, Kalundborg is a typical industrial city in that it is a nexus of trade whose firms import and export numerous components and products on a much larger geographical scale.'

Korhonen (2001c) and Korhonen et al. (2001) studied the Finnish forest industry IE. Approximately 70% of the fuels used in this large national industrial branch are industry's own waste fuels. Further, 94% of the fuels used are used in CHP (see also Kauppi et al., 1992; Verkasalo, 1993). Korhonen (et al., 2001, p. 158) pointed out that 'The presented forest industry system has some important features, which are similar to the way in which matter and energy flow in the forest.' and further '…energy production is organized effectively by using the co-production method of heat and electricity, i.e., utilising waste energy at different quality levels.' (Korhonen et al., 2001, p. 158). CHP has been applied on a large national scale in only three countries in the world, Denmark, The Netherlands and Finland (Korhonen, 2001b).

But the authors did not study the quantitative environmental implications of the fact that 90% of the paper produced in Finland is exported, e.g., to Germany. The article did not study the fact that paper recovery projects in Germany face difficult problems with the cadmium intensive de-inking sludge created in de-inking and recycling processes of recovered waste papers (Pento, 1998a; 1998b). Moreover, the study did not address the effects on forest biodiversity occurring because part of the birch inputs used in the Finnish forest industry come from Russian forests, where forest certification is not as well developed as it is in Finland.

The IE potential of using paper industry, paper recycling process and forest industry energy production wastes, e.g., fibre sludge, de-inking sludge and incineration ash, for building cover layers for old landfills was presented in Niutanen and Korhonen (2002):

> Arguably, this method is preferable to existing practices of natural clay use for landfill building, because it (1) substitutes non-renewable natural clay, (2) consumes less energy and generates less CO_2 emissions than the use of natural clay, and (3) eliminates considerable amounts of wastes from paper production, paper consumption and from forest industry energy production. (p. 39)

The study did not take into account, nor calculate, the fact that paper industry is very energy intensive. The wastes of paper production that are utilised for landfill cover layers would not appear without paper manufacturing and the energy use of this manufacturing.

The question or the challenge for IE is, Where to draw the system boundary of a material and energy flow study or what are the boundaries of an industrial ecosystem in a global market economy? Physical flows always extend over organisational or administrative boundaries and we live in the era of globalisation.

4.2 System vs. its components

The focus in IE is on many different system components, their relations and interactions (figure 2). This departs from the traditional medium (air, water or land)-focused policy, flow (SFA), product (LCA) or process/firm/organisation (EMS)-focused approaches and tools of environmental management (Korhonen, 2002a). But it seems that sometimes the IE vision is conflicting when compared to the basic objectives of dematerialisation or pollution prevention. Why?

Consider a local/regional industrial ecosystem project that strives toward reducing or controlling the environmental burden of the system as a whole, instead of that of an individual system component. Wallner et al., (1996, p. 1765; see Wallner, 1999) argue that 'the elements of the system generate the outcome or the 'character' of the system. This character is something totally new, and cannot be found in any single component.' Consider an EMS of a single firm. It can be assumed that when a certain individual firm adopts an EMS, it tries to control, minimise or reduce its waste generation, e.g. because of societal pressure. It would seem very strange if the firm would deliberately and publicly seek to increase its waste generation through an EMS. Now, in the IE vision, the objective is to reduce the environmental burden of the industrial system as a whole. Situations may occur, in which it is beneficial for this aim that an individual firm maintains, or even increases, its waste generation to be able to supply the other actors with important waste raw materials and waste derived fuels. The other actors can perhaps substitute for imported, non-renewable and emission intensive fossil fuels.

This system vs. system component conflict must be taken into account carefully, when bridging IE to the more commonly used environmental management and policy tools. The two approaches must be seen as complementary in order to provide the decision-maker with consistent information.

4. 3 Growth vs. efficiency

The 'rebound effect' in energy policy literature (Berkhout et al., 2000) is important to study. Increases in fuel efficiency may lead to reduced production costs. The reduced costs affect the prices of end-products that go down. The purchasing power of consumers increases. The overall energy use increases, because consumers buy more or direct their buying to more energy intensive products. Now, the negative environmental effect of growth exceeds the gains achieved through efficiency.

Eco-efficiency means producing the same amount of products as before but with less resource use or less wastes and emissions (Figge and Hahn, 2001; see Karvonen, 2001). The so called 'Jevon's paradox', after William Stanley Jevons and his examination of the 'Coal Question' of 1865 (Mayumi et al., 1998),[12] describes a similar problem. Human behaviour is 'addicted' to technology and 'increase in efficiency in using a resource leads to increased use of that resource rather than to a reduction in its use' (Mayumi et al., 1998, p116). Mayumi et al. (1998) note that the doubling the efficiency of food production per hectare over the last 50 years did not solve the problem of hunger, because population and production increased (see, Giampietro, 1994).

As noted above, the often-cited Kalundborg industrial symbiosis or industrial ecosystem case relies on two key actors that use fossil fuels. If the eco-efficiency of such systems, e.g., raw material efficiency, cuts down production costs (less resources needed to produce the same amount of products as before), there is a risk that reduced prices lead into increasing demand of the produced products. The increased consumption, i.e., the negative growth effect, may exceed the environmental gains of eco-efficiency. The absolute amount of emissions generated and resources used still increases despite this would happen 'efficiently'.[13]

A regional IE study on the energy production technique of CHP provides another example (Korhonen and Snäkin, 2001; Snäkin, 2003). In CHP, high fuel efficiency of around 80–85% is reached, when producing both electricity and heat (derived from 'waste' electricity), while in isolated electricity production, 40–45% efficiencies are achieved. The study indicated that even a large-scale CHP application will not solve the greenhouse gas question of the North Karelia heating energy system in Eastern Finland if the amount of electricity produced in the region increases over a certain limit and part of the fuel basis is still in emission intensive fuels.

4.4 The base/source system vs. the target system

Another controversy is whether to focus on the 'base system' vs. the 'target system' of the industrial ecosystem metaphor (Bey, 2002; 2001; 2000; 1999 see van der Voet et al., 2001; Levine, 2001; 1999; Isenmann, 2003; 2002). Some authors (Bey, 2002. pp. 87, 91–92, Levine, 2001; 1999; van der Voet et al., 2001; see Isenmann, 2002) argue that, indeed, there are many inconsistencies when using the industrial ecosystem metaphor in industrial systems. They refer to the superficial way in which nature is described when the metaphor is used. For example, in the natural ecosystem, organisms eat each other, while in the human economic system, the economic actors do not eat each other (Bey, 2002). But the question is, What do these kinds of critical observations contribute to sustainable development or should we actually be focusing on more important things?

Below, Bey's (2002; 2001; 2000; 1999) very intensive critique toward IE and toward some of its most often-cited papers is given as an example of the base or the source vs. the target system or the application system controversy. Bey (2002, p.84) notes that '[i]n the following, three articles from the domain of industrial ecological research are examined for evaluation of their use of natural imagery in Industrial Ecology, particularly the founding idea of comparing natural systems with industrial or economic ones'. Bey's focus of critique is on texts by Allenby and Cooper (1994), Cote (2000), Schwarz and Steininger (1997) as well as the Socolow's often-cited text (1994).

The core of Bey's very harsh critique, which, at times, is presented in a destructive manner, is that there is a risk or real danger in the application of the ecosystem metaphor in industrial systems if based on vague and unclear understanding of ecosystems. I have great difficulty in understanding this critique. Socolow's often-cited text 'Six perspectives from industrial ecology' is targeted. In Socolow (1994, p. 4, 12–14), the importance of the firm and the farm are acknowledged alongside ('equal footing' in Socolow, p. 4) the household/consumer/voter. But Bey seems to read this differently and he argues that the firm and the farm are human exosomatic instruments (to use the terms of Georgescu-Roegen, 1971; 1990; see Costanza et al., 1997). Therefore, they should not be the main focus in IE. The primary and the main focus should be on the physical flows of matter and energy mobilised by the firm and the farm and the consumer/voter. This is reasoned, because, in nature, 'The organic participants are thus the *embodiments* (italics in the original) of the biomass/energy flows…' (Bey, 2002, p. 91).

In the target system, the situation is different than in the base system of the IE metaphor. Bey maintains that '…resources and energy are passed on by participants of the resource-centred economic system, as the participants do not embody them.' (pp.91–2) Bey writes that 'The individual firm and farm as economic agents, Socolow maintains, should take a central position in industrial ecosystem restructuring' (2000, p. 26). This is seen as problematic and the author presents a critique: 'It is the resources flows which must be manipulated into cyclical form and possibly constrained in order to attain ecological sustainability, the existence of the firm and farm is secondary to that' (2002, p. 92).

Bey is also troubled, because of his interpretation of Socolow in that '[e]levating "firms and farms" to central actors negates the integration of producers, consumers and recyclers, as found in all natural systems. According to Socolow's postulate, it is material and resource flows in production systems that make up the main body of work in Industrial Ecology' (2000, p. 26). In an article with a provocative title 'Quo Vadis Industrial Ecology? – Realigning the Discipline with its Roots', Bey suggests what he sees as an alternative position and a position that he has created through his critical work in 'reading' industrial ecology literature in that '[a]n extended systems analysis, reconceptualised as an integrated ecosystem approach, would include flows between production and consumption systems in the fashion of ecological succession' (2001, p. 38); and Bey also states that 'Socolow's position of the centrality of the firm and farm shows the contradiction between IE's aims and its methods' (2000, p. 26).

The type of critique by Bey (2002; 2001; 2000; 1999) toward the use of the natural ecosystem metaphor in IE can be found in other texts as well, although, I have to say, not presented in such a radical way nor based on such reading of the focus of the critique[14] (e.g. the original work of Socolow which is under attack in Bey's critique). Let us now look more closely at what is/is not the contribution of this critique. The *Journal of Industrial Ecology* reads on the back cover (1997, Vol. 1, Number 4) 'Industrial ecology is a rapidly growing field that systematically examines local, regional, and global uses and flows of materials, and energy in products, processes, industrial sectors, and economies.' Socolow's text (1994, pp. 4, 12–14), under the subtitle of 'Centrality of the Firm and the Farm', clearly states that the firm and the farm should receive 'an equal footing' (p. 4) with the household/consumer/voter. Socolow (p. 4) looks at the legacy of policy and legislation and writes:

> The focus of attention has long been on production facilities-conveniently far from the point of consumer involvement. By contrast, industrial ecology emphasizes the management of products throughout their useful life and beyond, and calls attention to dispersed sources of pollution, such as agricultural chemicals, household wastes, and the chaff resulting from the expected degradation of products like outdoor paints, roofing materials, and brake linings. The importance of the consumer is unmistakable. Rage at the industrial producer recedes in significance as a driver of policy.

Socolow (1994, p. 11) highlights that '*Industrial ecology seeks a unifying analysis, based on total flows of materials (italics in the original), that treats on a common footing all sources, all transport media, and all receptors*.' Further, he suggests (pp. 12–14) integration of production and consumption with specific service industries that would enhance waste utilisation by serving as mediating actors between production and consumption (like ecosystem decomposers). He argues for renewable energy flows to substitute for fossil fuel stocks.

Now, one finds that IE already has its main focus on the flows of matter and energy as well as on a systems approach that would study both production and consumption. Erkman wrote in the *Journal of Cleaner Production* double special issue in a historical review on IE (1997, p.1–2) that '… all authors more or less agree on at least three key elements of the industrial ecology/metabolism perspective'. The second point was 'It emphasizes the biophysical substratum of human activities, i.e., the complex patterns of material flows within and outside the industrial system, in contrast with current approaches which mostly consider the economy in terms of abstract monetary units, or alternatively energy flows'.

The texts such as Socolow's do highlight the importance of material and energy flows, e.g., recycling of matter and use of renewable fuels and take into account producers, consumers and recyclers. Based on this, one could argue that the focus of IE, indeed, is on material and energy flows between producers, consumers and recyclers and between the industrial system and the natural ecosystem. But still, in his critique and in his way of reading industrial ecology literature, Bey even goes as far as writing a subtitle 'The Kalundborg food web includes only the supply side' (1999, p.1) and when he presents three areas where industrial ecology has according to him been falling short of the natural ecosystem metaphor applied (p.1) one of these areas is 'an obsession with manufacturing'. The Kalundborg case has been studied perhaps in over 100 articles and book chapters during the last ten years or so and everybody is familiar with the case. Therefore, I am only citing Erkman and Ramaswamy, (2003, p. 11) when they describe the Kalundborg participants to include '[t]he town of Kalundborg, which receives excess heat from Asnaes (a power station) for its residential district heating system.' Now, how can one state that Kalundborg does not include consumers or households?

In this respect, the critique toward the use of the metaphor in the target system, that is, the industrial system, based on a superficial or false interpretation of the base system, that is, the ecosystem, is not alarming. In fact, it is the kind of critique like the above, which is false and wrong. The argument that the focus on exosomatic instruments neglects material and energy flows in IE does not hold. In fact, the focus on the firm, the farm and the consumer is critically important for IE and should be further strengthened (Korhonen, von Malmborg, Strachan and Ehrenfeld, 2004; Cohen-Rosenthal, 2000). This is the very feature that has received too little attention. The most emphasis has been and is directed toward material and energy flow inventories and analysis such as substance flow analysis, life cycle assessment, material and energy flow analysis etc. (the main body of articles published in JIE). Natural ecosystems and human economic systems are fundamentally different. Natural ecosystems rely on genetic information and cultural systems on cultural information, e.g., money, written texts, video, internet, oral or cell phone communication and not only on information transfer in reproduction (Norton et al., 1997). It is just these cultural characteristics of the firm, the farm and the consumer, e.g., greed and over-consumption of physical products instead of increasing reliance on services and nonmaterial goods, that need to be influenced. Only through affecting the agents driving the flows, and taking their values, interests, preferences and behaviour under careful consideration, can the flows be directed toward recycling and cascading or can we reduce our use of the flows.

Is the claimed false interpretation of the base system bad in terms of sustainability? I doubt this. After all, we are talking about a metaphor. The power of metaphors is that they are flexible, even unclear and vaque at times. The power of the metaphor is also in those aspects that it fails to show (Boons and Roome, 2000). When one states that somebody is 'stupid as a donkey', one does not have to know the IQ of the donkey to get one's message through. With the above example, the metaphor helped us to learn that it is good to focus on the human actors and their organisations, not simply on the physical flows of matter and energy, when using the industrial ecosystem metaphor in the target system, the industrial system. In fact, it seems that too much energy has been devoted to study only the engineering or natural science-type material and energy flow analysis in the field of IE. The human-dimension of IE or the importance of the firm, the farm, the consumer and the recycler (Cohen-Rosenthal, 2000; Ehrenfeld, 2000) is currently the theme, which is neglected (Korhonen, von Malmborg, Strachan and Ehrenfeld, 2004).

What is important is not to ask are we able to describe in a perfect way how nature works when considering the contribution of IE to sustainable development. Rather, one must ask how can we use the insights of IE to better preserve nature and change industrial systems in a way that their environmental burden is reduced? It will be very important to remember what is the goal of IE. It is the ecologically sustainable development of the target system, not whether industrial ecologists are able to describe in a perfect way how nature, the source/base system of the metaphor, works and then apply its operating model in a perfect way in industrial systems. Industrial ecology is different than ecology or biology. Ehrenfeld (2003) argues that metaphors cannot be wrong or right. They can only be useful or not useful.

4.5. Normative vs. objective

The question has been raised, whether IE is normative or objective (Boons and Roome, 2000; see discussion in Allenby, 1999c) and whether IE is prescriptive or descriptive (Korhonen, 2004a). For the purposes of this paper's message and simplification, normative means a 'should'. Objective means neutral. It is true that sustainable development has become a 'should' in the environmental discussions although its meaning is widely debated. It is 'good' or fashionable to commit to the cause. Boons and Roome note (2000, p. 51) that:

> … as far as the specific metaphor of industrial ecology is concerned, at least one of its dominant definitions is based on the normative notion that industrial ecosystems should be made to function in the same way that natural ecosystems operate (Frosch and Gallopoulos, 1989) …

The famous article to which they refer reads:

> … the traditional model of industrial activity – in which individual manufacturing processes take in raw materials and generate products to be sold plus waste to be disposed of – should be transformed into a more integrated model: an industrial ecosystem (Frosch and Gallopoulos, 1989, p. 95).

But the different IE principles are not clear in terms of their contribution to sustainable development, e.g. the above noted case of diversity. The rebound effect, Jevon's paradox or problem displacement can actualise in recycling and cascading. Recycling means recovery, perhaps increasing transportation, fuel use and emissions. Korhonen (2001b) noted that long-term cooperation relations (or interdependency) may turn into unhealthy dependencies or in 'lock ins', e.g., investments that tie up the funds of the organisation, require long pay back times and in this way hamper (eco)innovation.

On the other hand, IE can be used as a more 'neutral' study hypothesis, not as an absolute should. IE principles do illustrate important characteristics of any living system. It is important to consider material and energy flows and the structure of the system in terms of the actors or components of the system, their relations and the location of the system. But whether the actors should cooperate, whether there should be many different actors involved (diversity) and whether the actors should recycle or always remain as locally placed is, at most, a hypothesis and a question for research.

4.6. Tools vs. culture

Because of the focus on the physical flows of matter and energy, IE is often criticised of being too technical, instrumental or descriptive (Ehrenfeld, 1997; 2000). Some authors argue that sustainability management and tools used in it or in corporate environmental management are merely maintaining and even making stronger the dominant unsustainable neoclassical economics paradigm (Welford, 1998a; Springett, 2003; Heiskanen, 2002). Welford (1998a) argues that eco-efficiency tries to justify economic growth by using standard economic logic and this is dangerous for sustainability. Springett (2003) finds lack of critical theory perspectives in the management discourse on sustainability. Heiskanen (2002) observes that LCA is normally used to implement the preset goals although it would also have the potential to actually shape and construct the goals.

LCA could be used to study and reveal sustainable development questions of equity and futurity (Welford, 1998b). Because LCA looks at the entire life of a product, it can identify unsustainable practices also in the third world countries. The developing world can be used as the sink or the source of products refined in and driven by the developed countries. Because also the use phase of the product life is studied, the important sustainable development principle of futurity may be considered in LCA. The life of a consumer product, say, a car, and its environmental impacts can extend over national and continental borders, but also over many decades. One of the reviewers of this paper agreed that it is important to note the issue of point vs. non-point sources of pollution; the firm may be an easier target for policy than the general car-owning public. The natural ecosystem metaphor in IE has a potential to inform us of radically new world views for sustainable development culture, e.g. from global to local, and move the debate beyond technical, instrumental or descriptive tools and techniques.

5. CONCLUSION

This theoretical article considered the sustainable development potential in the *concept* of industrial ecosystem. I believe this concept is important for the theory building of the emerging scientific *field* of industrial ecology. I found six controversies that need to be addressed in the theory building. The industrial ecosystem is a provocative concept. Hopefully, IE does not become 'just another tool' in the rapidly growing toolbox of sustainable development. I invite all those who are interested in industrial ecology to respond to this article.

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NOTES

[1] See Jelinski et al., 1992; Tibbs, 1992; Graedel and Allenby, 1995; Graedel, 1996; Ayres and Ayres, 1996; Allenby, 1999a; b; c; Ehrenfeld, 2000; Harte, 2001; Korhonen, 2001a. For reviews, see O'Rourke et al., 1996; Erkman, 1997; den Hond, 2000; Chertow, 2000.

[2] *Journal of Industrial Ecology* and *Progress in Industrial Ecology: An International Journal*.

[3] For discussion on the business–environment win–win rhetorics, see Porter and van der Linde, 1996; Walley and Whitehead, 1996.

[4] Also other relevant texts were scanned, e.g., those entitled 'industrial metabolism'.

[5] Note also that the Frosch and Gallopoulos 1989 article in *Scientific American* is number 24 in the list of most commonly cited papers in *BSE* (Dobers et al., 2000). For IE articles in *BSE* see, Bey 2001; Boons and Berends 2001; Andersen 1997; van Leeuwen et al., 2003; Ammenberg and Hjelm, 2003.

[6] These are the most important materials used in this article. The author is aware of *Industrial Ecology* by Manahan and the second edition of Graedel and Allenby (2002) *Industrial Ecology*, but these are not available for the author at the time of writing this article.

[7] See the discussion later on in the paper on this difficult question: Is industrial ecology descriptive or prescriptive?

[8] See Korhonen and Pento, 1999a; Korhonen and Pento, 1999b.

[9] One of the reviewers of this paper suggested yet another example. If fishing is controlled, the fishing activities are moved to another location and this complicates the assessment of an individual project's contribution to sustainability.

[10] The classic text of Odum (1969) compares economic systems and ecosystems and is commonly accepted as being influential in IE-type theory in the background, but is not regarded as an IE article as such. The Odum paper, for example, compares different approaches and their contradictions to study ecosystem diversity.

[11] One of the reviewers of this paper remarked that this point has to be seen in the context of the long-term decline in commodity prices. However, I am unable to expand on this point in the theory building of this paper, but hope to do so in future papers.

[12] Jevons, 1990 (not the original W. Jevons). See also Georgescu-Roegen, 1971; 1990.

[13] This expression is derived from Daly's (1996) expression that optimally loaded boats can sink optimally.

[14] I am not a native speaker, but if I remember correctly, there is a saying in English language which goes something like 'building a straw man and setting the straw man on fire'. The message of this saying is that it is not scientific and it is really a form of poor research to first construct and create the focus of your critique while only after this presenting your critique.

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