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Editorial article

Industrial ecology in the strategic sustainable development model: strategic applications of industrial ecology

Jouni Korhonen *,1

Research Institute for Social Sciences, University of Tampere, Kanslerinrinne 1 (Pinni B), 33014 Tampere, Finland

Abstract

In a recent article of this journal, Robert et al. [Journal of Cleaner Production 10 (2002) 197] define five hierarchical and interdependent levels for a systems approach for *strategic sustainable development* (SSD) to move toward the desired outcome, the state of sustainability. This paper evaluates the *concept* of industrial ecology (IE) by considering its application and use in terms of the strategic sustainable development model. The author argues that the applications of the concept of IE can contribute to all five levels in the hierarchical model. However, the paper shows that if IE is used outside the systems model, four risks and difficulties are generated that can lead to suboptimal solutions, problem displacement and problem shifting. Recommendations derived from ecological economics and environmental management are made for ways to proceed with the integration of IE into the broader SSD concepts and approaches.

Keywords: Sustainable development; Strategic sustainable development model; Sustainability; Industrial ecology; Industrial ecosystem

1. Introduction

In an article recently published in the *Journal of Cleaner Production*, Robèrt et al. [1] (see also [2]) present a holistic systems model for *strategic sustainable development* (SSD)[2] designed to help society move toward the desired state or the successful outcome[3] of such development; sustainability [3,4].

Robèrt et al. argue that, because of the existence of a growing number of different approaches, methods and tools now commonly used in the field and practice of sustainable development, there is a risk that the tools are perceived as being in competition with each other or contradictory. The different approaches and tools can present conflicting suggestions for policy and management, and hence, can make it difficult to achieve the desired state of sustainability. To solve this problem, the hierarchical systemic model for SSD with interdependent levels is developed. Robèrt et al. argue that, when used within this model, the many tools and approaches can be complementary to each other and can be used in parallel in the process of making progress toward sustainable development. The different levels in the model are interdependent.

The objective of this article is to consider the use and the application of the concept of industrial ecology (IE) in terms of the SSD model. The article is based upon the concepts presented by authors such as Frosch and Gallopoulos [5], Tibbs [6], Jelinski et al. [7], Graedel and Allenby [8], Ayres and Ayres [9], Graedel [10], Erkman [11], Ehrenfeld [3], Chertow [12], den Hond [13], Korhonen [14, 15], Korhonen et al. [16]. The IE concepts can be applied to and be used on all five levels of the SSD model. This author argues that if IE is used outside the model, it can result in difficulties for societal members to make progress in sustainable development and to significant difficulties for the development and implementation of policy and management that can lead to sustainable societies. Hence, IE should be used within the model.

* Tel.: +358-3-215-7959; fax: +358-3-215-6502.
E-mail address: jouni.korhonen@uta.fi (J. Korhonen).
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[2] Robert et al. did not use the acronym SSD, but this author uses it for brevity in this article.
[3] See the discussion on sustainability as an end-state vs. a continuous process later on in the paper.

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2. Strategic sustainable development

Robèrt et al. [1] (see also [2]) describe a hierarchical five-level systems model for the process of sustainable development, *strategic sustainable development* (SSD). The different levels of the model are interdependent. The central thesis of the authors is that when the rapidly growing numbers of approaches and tools are applied, there is a risk that these tools are viewed as conflicting, competing or as each other's substitutes or alternatives. In this kind of a situation, the simultaneous use of the different tools may create difficulties as they may support different and conflicting suggestions for policy and management. Decision-makers and managers may have difficulties to weigh and evaluate the benefits of using the different tools. Robèrt et al. [1] show how the systemic five-level model of SSD provides a framework in which the different tools can be used as each other's complements, i.e., supporting each other by providing different contributions.

2.1. Level 1 in strategic sustainable development

On the first level of the SSD model, those principles that constitute and construct the system under study are defined. The system under study and the system that is the focus of the process of sustainable development is the global ecosystem or the ecosphere. The global ecosystem is the parent system, while the human economic system and the social system are its subsystems [17]. There are three dimensions in this system; the economic (e.g. costs and profits), social (e.g. equity, responsibility, development, human rights) and ecological (e.g. material and energy flows and ecological biodiversity). The dimensions of sustainable development are interdependent but qualitatively different [18].

2.2. Level 2 in strategic sustainable development

The second level in the SSD model is the desired state of sustainability, which is the outcome of the successful process of sustainable development. It can be noted that others (e.g., Welford [19]) contest the use of the term 'sustainability' as it implies that sustainability would be an end-state, or a tangible outcome. They argue that, instead, one should use the concept of sustainable development. Accordingly, sustainable development is a continuous process, and only the general direction toward sustainability or the direction away from unsustainability can be known. As defined in the SSD model, in fact, sustainability is not an end-state or deterministic but, once the principles of sustainability have been achieved, biological, cultural, economic and industrial evolution can continue in an ongoing development process (note that this is not the same as economic growth).

Robèrt et al. [1:p. 198–199] present sustainability by using four system conditions drawing from the well-known "*natural step framework*". The Brundtland Commission's philosophical definition of SD as '*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*' [20] leads to the natural step framework and its four system conditions:

1. 'In the sustainable society, nature is not subject to systematically increasing concentrations of substances extracted from the Earth's crust,
2. concentrations of substances produced by society,
3. degradation by physical means,
4. and, in that society human needs are met worldwide.'

Other principles that have been discussed in the context of sustainable development and ecosystem carrying capacity include the three main sustainable management rules of Daly [21], cited in [22:p. 26]; see [23,24:p. 107]:

(i) 'Harvest rates of renewable resources should not exceed regeneration rates.
(ii) Waste emissions should not exceed the relevant assimilative capacities of ecosystems.
(iii) Non-renewable resources should be exploited in a quasi-sustainable manner by limiting their rate of depletion to the rate of creation of renewable substitutes.'

But these have not been designed for the SSD model. However, Robèrt and Daly have compared the Daly principles and the philosophy of strategic sustainable development in Robèrt et al. [25].

2.3. Level 3 in strategic sustainable development

The third level in the SSD model suggests the process to achieve the successful outcome (sustainability) of level 2; the process of sustainable development. Principles of 'backcasting' and 'flexible platforms' are given. In backcasting, the vision of the management system, say, of a private firm, is established by starting from the future, from a successful outcome. This future 'landing place' enables one to construct the vision of the management system in a way that does not restrict the vision with present day constraints, e.g. lack of resources, money, know-how, personnel, presence of organisational inertia, etc. Arguably, backcasting could complement the more traditional method of forecasting, which may not be as creative and innovative, because the starting point in forecasting is the current day situation and its constraints and problems and the vision building is often limited by resistance to change.

In backcasting, one moves backwards or 'downwards' from the future-landing place. An attempt is made to identify the required path for the process of sustainable development to achieve sustainability on the level 2 and within the system constituted of the ecological and social principles on level 1. Hence, the present day situation is only considered when the first step towards the vision is taken, i.e., when the direction is reversed, 'back to the future'. After the first step, there exists a new current situation and a new inventory is made. The new inventory helps the second step to move toward the vision of the future. Such a step-by-step approach divides a big leap into 'small jumps' and makes it easier for the participants to see the big leap as realistic. The key is to maintain the overall direction for long-term development despite suboptimal solutions for minor short-term problems and challenges.

'Flexible platforms' is a principle in which the investments that are made now are not only considered for their potential to solve current 'acute' problems and difficulties but are also considered as stepping stones for future investments according to the vision of the future. A situation may occur in which such investments that will temporarily result in suboptimal solutions have to be made if they enable a 'win–win' in terms of the future vision of sustainability that exceeds the costs of the current investments.

It is obvious, that people often use the more conventional way of strategic planning that is, forecasting. We are all familiar with actors who are reluctant to engage in environmental projects, e.g., because they seem to cost too much, take up too much of the scarce present day resources and time, and seem to be too ambitious and risky in terms of the current day competitive situation, etc. Backcasting and flexible platforms seem to provide some useful room for fresh insights and thinking toward longer-term planning.

The energy question is an example [26,27]. If approximately 80% of the world's energy consumption relies on non-renewable and emission intensive (often imported) fossil fuels [28], the long-term economic, social and ecological sustainability of this situation is very problematic. However, currently, alternative fuels, such as biomass, are frequently ignored, because of perceived difficulties in the current day situation and because of short-term constraints and considerations [1], e.g., the current prices of biomass fuels or the reluctance to invest into new fuel combustion techniques such as fluidised bed burning, etc. Setting the strategic vision far into the future instead and 'forgetting' the present day problems and constraints for a moment and visioning the step-by-step path backwards all the way to the present day from that vision would be backcasting. Accordingly, the strategic plan would then 'return' from the present situation step-by-step by following the steps identified through backcasting, back to the vision in the future. When successful, this would make the overall direction of sustainability possible. Backcasting could make it possible to maintain the long-term sustainability goal as the overall direction and not compromising the goal, because of small short-term problems and constraints.

2.4. Levels 4 and 5 in strategic sustainable development

The fourth level follows with practical actions that are in line with the process principles used in order to achieve the goal of sustainability within the larger parent ecosystem and its economic and social subsystems (levels 3, 2 and 1 above). The fifth level consists of tools and metrics that audit and monitor the success of the actions, i.e., the material and energy flows and their impacts on the ecosystem and its economic and social subsystems. It is important to measure both the actions as well as the state of the system itself. We need to measure what is the employment situation of a regional economy and what is the local air quality, etc., not only whether recycling has reduced some flows or not. The flows are not the same as the impacts (the ecosystem impact of the flows depends on many factors, e.g. the local ecosystem assimilative and recovery capacity, etc.).

3. Industrial ecology and strategic sustainable development

3.1. The potential of the industrial ecology concepts for different levels of strategic sustainable development

The author now applies the SSD model to the concept of industrial ecology (IE) to consider the applications and use of IE. The following arguments are presented: (a) IE has much potential as a concept that can be applied to and used on all the SSD model levels; (b) If IE is not used within the SSD model, there are many risks that IE will actually contribute to unsustainability rather than to sustainability, thereby, making sustainability policy and sustainability management more difficult. The author presents four risks or undesired outcomes that may result if IE is used outside the SSD model.

3.2. Level 1—on the ecological economics of industrial ecology

Although the concepts of IE increased in popularity since the publication in *Scientific American* of the article by Frosch and Gallopoulos [5], the concept existed before and was even used for similar purposes (see [11,29–35]). The attraction in the concept of IE lies in its application of the natural ecosystem metaphor to 'industrial ecosystems'. The ideal of the metaphor is that industrial ecosystems function according to the system development principles of natural ecosystems. Perhaps, the most commonly used of such principles is 'roundput' [14,15], i.e., closed loops and waste utilisation between industrial actors to learn from the processes of natural ecosystems where material cycles and energy cascades are the foundation of the system operation, solar energy being the only external input to this materially closed system that emits only waste energy or heat (infrared radiation to space), while cascading energy in the food chain [7,8,10,16,36,37].

I argue that industrial ecology contributes to the first level in the SSD model. First, by comparing the natural ecosystem and the industrial system, the concept shows the dependency of the industrial subsystem to the parent ecosystem (see [38]). The modern society or the dominating neoclassical economics have not been aware of this. The dominant neoclassical economics position has viewed the ecosystem as an isolated system from the economic circular flow of abstract exchange values (and factors of production) between firms and households [39].

Because of the dominant neoclassical economics and its reliance on monetary values, the new (or newly accepted) ecological economics and industrial ecology positions are important frameworks for sustainability and can help to challenge the neoclassical economics position. These perspectives highlight that the economic system is the subsystem of the larger social system. Furthermore, both systems are subsystems of the parent (mother) ecosystem and are totally dependent upon it. This is important for understanding the system under investigation and the system that is the focus of the sustainable development process in the SSD model at level 1; the focal system is our common planet, the subsystems of which the economic and social systems are.

Second, IE has alerted economists and policy-makers of sustainable development to study the physical flows of matter and energy, instead of only abstract monetary flows [11]. IE and industrial metabolism [40] maintain that physical flows of matter and energy are the basis of the operation of both the human economic subsystem as well as the natural ecosystem. The places where the flows cross the boundary between the subsystem and the mother system determine the sustainability of both the systems.[4]

Daly [17]; (see O'Hara [41]) describes the focus of sustainable development with the 'full world' metaphor. He writes that the modern world has become 'full' of human-manufactured capital and 'empty' of natural capital. In other words, the metaphor is for alerting decision-makers to the fact that the natural resource use and waste and emission generation of economic systems is unsustainable. Human-manufactured capital includes machines, technology and infrastructure, etc. With the industrial revolution and rapid economic expansion, the human economic system has grown rapidly relative to the ecosystem making the ecosystem 'full', because the economic system is the subsystem of nature and nature is not growing and materially closed.

Natural capital, e.g. renewable and non-renewable resources and the ecosystem services that the natural capital stocks provide, are now the limiting factors of economic development. Together with natural capital, social sustaining functions, e.g., intimacy, love, nurturing, caring, child rearing, housework, gardening, social bonding and other community ties, are now the limiting factors of economic development [41,42]. Workers will need these functions, which are usually not valued in the monetary economy/markets, to be able to contribute to the monetary economy (for discussion, see the work of Georgescu-Roegen [43]). No consensus exists on developing a single measure for these qualitatively different dimensions of sustainability [18].

It is true that IE applications still lack the thorough consideration of the three dimensions of sustainable development or the three qualitatively different forms of capital. IE researchers have mainly concentrated on the physical flows of matter and energy. But the development of the concept is possible. Because IE highlights the importance of the systems approach, networks and diversity of many different actors participating in these networks [15,44–46], it can, possibly, be developed to better include the social aspects of sustainable development as well. Such contributions could result in participatory planning and democratic decision-making processes, network analysis and network management, etc. The contribution may be achieved through such (re)emerging theories as corporate social responsibility [47] and stakeholder theory, the focus of which is on inter-organisational [48,49] rather than only on intra-organisational management issues.

The three first system conditions of the state of sustainability, the goal of the SSD model of Robèrt et al. [1:p. 199] in the ecosphere, i.e., the societies and the surrounding ecosystems, are about material and energy flows and biodiversity. The fourth one reads '... *in* ... *society human needs are met worldwide*'. This author's interpretation is that one must include such features within this social principle such as corporate social responsibility, stakeholder cooperation and participation, transparency, dialogue and community. In addressing the social dimension, the inter-organisational and cooperative approach in the industrial ecosystem systems approach can be fruitful.

In sum, the IE contributes to level 1 in the SSD model. It shows that economic systems are dependent on the parent ecosystem. Further, the IE focus on the physical flows of matter and energy alerts us to the thermodynamic limits of eco-efficiency and economic growth, i.e., the importance of physical (thermodyn-

[4] When natural resources are used and when emissions and wastes are dumped back into nature, resource depletion and environmental effects occur and this can endanger societal sustainability. Perhaps, it would be more accurate to say that it is the human or societal system drivers that are the cause of unsustainability.

amic) principles in the constitution and construction of the system on level 1 in the SSD model. After further development of the concept, the social dimension of the system definition of level 1 in the SSD model can also be addressed through the network and systems perspectives of IE.

3.3. Level 2 and material and energy flows

This author asks how can the concept of IE contribute to defining the goal, the vision, and the desired state of sustainability in the SSD model?

The kinds of principles included on level 2 of the SSD model can be derived from the industrial ecosystem concept's use of the natural ecosystem model in industrial systems. The ecosystem material and energy flows have been divided into four categories of matter, base cation (BC) nutrients, energy and carbon, for IE [16]. This study observed that nature does not use nonrenewables, or renewables in the way we do. Nature does not exceed the assimilation or recovery capacity of the ecosystem in case of substances or flows that organisms 'release' to the ecosystem. Nature is also able to maintain the nutrient cycles by not disturbing them with harmful flows beyond the point of recovery while relying on the infinite solar energy input and maintaining the ecosystem capacity to assimilate the CO_2.

A sustainable industrial ecosystem that would follow nature's model is a system in which the sustainable yield in its use of renewables is maintained (compare to system condition 3 in the 'natural step' framework) and nonrenewables are not used (compare to system condition 1). The industrial ecosystem does not extract vital nutrients from the ecosystem in a way that would endanger the reproductive capacity or biodiversity (compare to system condition 3), releases vital nutrients back to the ecosystem cycle in a non-harmful state (compare to system condition 2), secures the ecosystem capacity to bind the CO_2 released by industrial activity (compare to system conditions 1–3) and the capacity of the natural capital stock to yield fuel flows for energy production (compare to system condition 3 in natural step).

But it can be concluded that these principles for the outcome of the process of sustainable development, the desired state of sustainability on level 2 of the SSD model, are not the merit of the natural ecosystem model of IE. Therefore, this author concludes this section by stating that the contribution comes from the ability to show that the IE concept is applicable to level 2 in the SSD model and there is an important similarity here between the SSD concept and the IE concept. The authors of the SSD model did not arrive at the sustainability principles by using IE, but by using knowledge about thermodynamics, primary production through photosynthesis, the biogeochemical cycles and the biological need for homeostasis in natural systems.

3.4. Level 2 and economic and social aspects

The desired state of sustainability on level 2 in the SSD model could be presented with the 'win–win–win' (ecological, economic and social) vision of a local/regional industrial ecosystem [50,51], (for the business—environment win–win rhetoric, see Porter and van der Linde [52], Walley and Whitehead [53]) (see Fig. 1).

3.5. Level 3—learning from application of the ecosystem metaphor for developing strategic guidelines

Level 3 in the SSD model gives the generic strategic guidelines for the process of sustainable development. How can the concept of IE contribute to the principles of sustainable development?

IE can add a principle to the SSD model. The principle is defined here as 'learning from nature'.[5] The learning from nature can happen through the creative, innovative and inspiring power of a metaphor, the natural ecosystem metaphor in IE. Ehrenfeld [54] (see [55]) states that metaphors cannot be wrong or right, only useful or not useful.[6]

[5] This observation is based on the thorough remarks of one of the reviewers of this article.

[6] One of the reviewers of this paper argued that, because human industrial systems are subsystems of the global ecosystem, then one can argue IE is not a metaphor. The reviewer continued by stating that this is particularly true if we acknowledge that ecological functions and limits determine sustainability. This author does not agree with this argument. The ecological limits are known to us through natural sciences or biological and systems ecology. These sciences like all sciences are human and social constructions. Biology itself is a metaphor and so is language and both of these are part of human culture, which cannot be studied only with natural sciences and biological ecology. Rather, social sciences and cultural studies are needed too. If we would deny that the industrial ecosystem is a metaphor then we would think that natural ecosystems and industrial systems can be very similar to each other. We might even think that a 'perfect industrial ecosystem' is possible to achieve and that would operate in exactly the same way as nature does. We might think that, because the two systems are one, we can study these with same research methodologies. But a 'perfect industrial ecosystem', of course, will never happen and is impossible. Why? Nature does not have culture in a way we have culture. If we think that the two systems are very similar, which they are not, then we would only need natural sciences and biology, not social sciences, cultural studies, management and organisational studies, decision-sciences, philosophy and studies on human behaviour. But all these sciences and their methodologies are critical to enable us to change the way in which humans and their organisations act and behave in practice. Therefore, actually, it is just the metaphor that makes industrial ecology practical. If we believe that IE is an analogy and the two systems are the same, then we would be very theoretical and abstract, because we would deny the existence of human culture. This is the important distinction that Ehrenfeld [54] makes when writing that the analogy means a much more similar and closer relationship between two systems than does metaphor. Metaphors cannot be right or wrong. They can only be useful or not, while analogies can be objectively false.

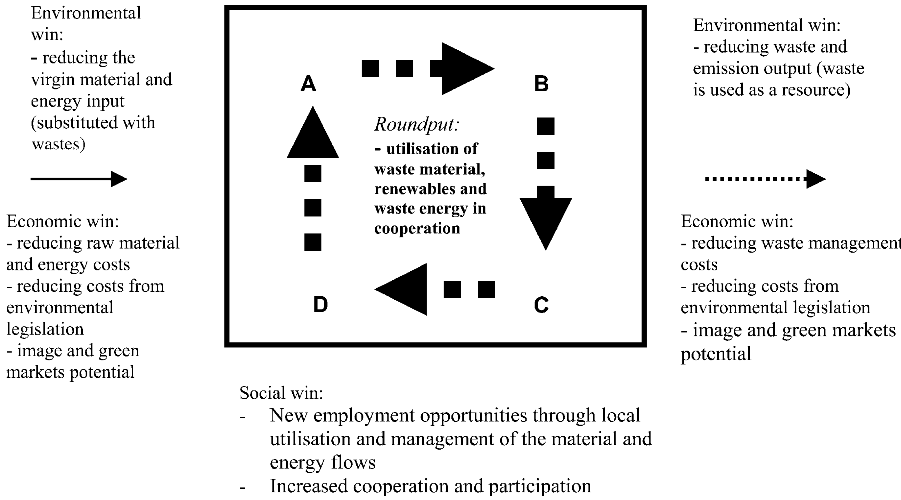

Fig. 1. Industrial ecosystem. Environmental, economic and social 'wins' in the *vision* of a successful local/regional industrial ecosystem. A local or regional industrial system is encouraged to move towards an interactive system based on the metaphoric system model of an ecosystem, i.e. 'a roundput system' of material and energy flows. Through cooperative waste material and waste energy utilisation (recycling of matter, cascading of energy) and sustainable use of local renewable natural resources of matter and energy between the industrial actors (industrial firms, other private and public organisations, agriculture and consumers) A, B, C and D, the virgin material and energy input as well as the waste and emission output of the system *as a whole* are reduced (virgin resources substituted with wastes and non-renewables with renewables). The arrows within the system boundaries are bigger than the arrows to the system and from the system. By reducing the waste management costs, emission control costs, raw material and energy costs, transportation costs, costs resulting from the implementation of measures required in environmental legislation and by improving the environmental image as well as the 'green market situation' of the system, the economic gains are possible. Banks, financial organisations or other funding organisations may be attracted to invest to this 'risk free' regional system. In this highly idealised picture of the local/regional industrial ecosystem vision, the social win arises through increasing the utilisation of local/regional resources and increasing the self-reliance of the local economy, which can offer employment opportunities for the regional inhabitants. Local material and energy flow management can also yield new areas of business and economic activity, e.g. recycling or waste management firms. Corporate social responsibility (CSR) and Local Agenda 21 can benefit through networking, cooperation, participation, stakeholder dialogue and democratic decision-making. Waste material and waste energy flows (dotted line shows the waste material and waste energy flows).

IE metaphors include roundput, diversity, interdependency, community, connectedness, cooperation and locality [3,14,15,51,56]. From thinking about ecosystems, even though in a superficial metaphoric manner (note that this does not undermine the great importance of metaphors, see below), one can alert oneself to recycling of matter and cascading of energy and term these as 'roundput', 'closing the loop' or the 'closed system' or 'industrial symbiosis'. The recycling and cascading thesis is the most commonly used natural ecosystem metaphor in IE. Roundput argues that throughput systems of industry that rely on non-renewables and are materially open should learn from the cyclical and cascading ecosystem that relies on renewables.

Some authors have applied IE metaphors [3,15,44,50,57,58] while others have been very critical toward these efforts [59–62]. The critical authors argue that metaphors must be grounded properly to their source and metaphors must be accurate when describing their source or their origin. This author believes that metaphors derived from ecology or biology, from nature or for that matter, from any other system, domain or world view [42], can be important even though they would only describe their source in an incomplete and unclear way. Surely, it would be impossible for an industrial ecologist to try to be a natural scientist, biological ecologist, an engineer, economist, business and management scholar and policy scholar all at the same time? The important question is not the source of the metaphor, in this case, how nature works, rather how can the metaphor be useful where it is applied, that is, in the industrial/economic/social system.

Furthermore, note that the power of a metaphor is also in those characteristics it fails to describe or inaccurately describes [63]. It is clear that recycling (part of roundput) also consumes energy and creates wastes and emissions of its own, i.e. the laws of thermodynamics. Diversity in the actors involved in human economic systems may actually make sustainability more difficult to achieve, because of diversity of possibly conflicting interests and preferences of the system participants. Interdependency may lead to unhealthy dependencies, e.g., heavy investments made jointly by a group of firms that result in long payback times preventing the possibilities to adopt new technological innovations or to 'break free' from the contracts

[64,65]. Correspondingly, it may be more sustainable to abandon the locality principle in certain biomass-rich regions. Perhaps, transportation and exporting enable reducing the dependency on fossil fuels in other regions that lack renewables or suitable waste fuels.

The contribution of IE means that the metaphors or principles derived from nature and used in industrial ecosystems can also be contrasted with the principles that are needed for sustainable development of industrial or economic systems. In fact, this is very likely, because the natural ecosystem does not have culture in a way we have culture nor cultural information flows such as oral or written records [66]. Whether 'shoulds' or 'coulds', the IE systems principles can be useful either for stimulating creative thinking and for providing inspiration when one is seeking to establish goals for planning or for sources for useful hypotheses for systems analysis, from which these or new and contrasting planning principles and strategic guidelines can be derived.

Locality, diversity and cooperation or community would seem to be important to take into account when challenging the dominant social or neoclassical economic paradigms of globalisation, mass production or competition. This is especially true as one strives toward equity, futurity and human rights i.e. the corporate social responsibility [39]. Fruitful metaphors may also be found in other word-views outside the neoclassical economic paradigms or outside the paradigm of modernity, e.g., from arts, poetry, sports or indigenous and village cultures [42].

3.6. Level 4

The practical actions can include, for example, substitution of non-renewables with renewables or with waste derived fuels or reducing the material intensity of products and services i.e. substitution and dematerialisation.

The contribution of the IE concepts to this level arise out of the use of the systems approach. Industrial symbiosis [12,67], eco-industrial parks [68], industrial recycling networks [69,70], or industrial ecosystems [65,71] offer inter-organisational management perspectives [48,49] that complement, but not substitute for the more traditional intra-organisational corporate environmental management approaches and tools.

The network and the systems approach may prevent problem displacement [72,73] between production and consumption [74], between different forms of wastes [75–77] or between different environmental media [40]. Environmental policy and corporate environmental management can, at times, result in the creation of new problems while one seeks to solve old ones. Suboptimal solutions, problem displacement or undesired outcomes have been observed. The 'environmental bad' can be shifted or recycled from one part of the system to another part. Production emissions have been decreased but the problem has been shifted toward the later steps of the life cycle, to consumption emissions, which are more widespread and occur scattered, and therefore, are more difficult to trace, monitor and control. Recycling of paper may create de-inking sludge that contains heavy metals. Using forest residues from cuttings as fuels can substitute for non-renewables in energy intensive forest industry or paper production, but on the other hand, can shift the problem back to the forest ecosystem when nutrient rich forest residues are removed from the ecosystem nutrient cycle or when cadmium containing incineration ash is returned to the ecosystem [16,78]. Through single media-based policy or legislation, airborne emissions can be transformed to sludges that are disposed of to the land; however because of decay processes, the landfills emit emissions to air and to the water [40].

Moreover, the problem displacement/shifting can happen between the dimensions of sustainability, the ecological, the social and the economic. Actors, societal sectors or geographical regions that have dependent their livelihood on certain resources may loose while others win when resources are substituted with other resources [79]. Recycling, e.g., of paper, can be very labour intensive, but on the other hand, imports may have to be reduced if the amount of regional/domestic (waste) raw material increases through recovery [50,75]. The exporting economy may loose, while the recycling economy may gain.

In sum, the contribution of the concepts of IE to the SSD model level 4 arises out of two points. First, IE approaches offer many innovations for waste material and waste energy utilisation. Consider that when 80% of the global energy production is in non-renewables, the energy production of the vast industrial branch of the forest industry of Finland relies to 70% on industry's own wastes, e.g., black liquor from pulp mills, twists, bark and needles and forest residues from cuttings, saw-mill, furniture mill and paper mill wastes. Further, 94% of these fuels are used in co-production of heat and electricity i.e. waste energy use for heat [16,80].

Second, waste materials and waste energy utilisation are considered in networks and collaborative partnerships in a systems approach, not simply looking at an individual product, process, firm or organisation. While there is always much room for improvement in terms of the first point in our industrial society, the innovation potential is particularly with the second point.

3.7. Level 5

With tools, metrics and instruments, the success of practical actions is measured. Correspondingly, the actual impacts within the focus system (level 1) can be measured.

As opposed to the more conventional environmental management system (EMS) of an individual firm such as ISO 14001 or the EU's EMAS, the network and systems approach in IE may support regional environmental management systems (REMS, [81,82]) or regional industrial ecosystem management systems (RIEMS, [83]). In the concept of REMS, not one but many organisations and firms jointly develop and implement the EMS steps. REMS includes audits and monitoring of the success of the suggested actions as measured against the set targets and objectives in the REMS that have been designed based on a vision and an initial review.

It is critically important to note that when developing tools and metrics, one has to remember that a metaphor cannot be used directly as a practical measure, indicator or a quantified model. But this does not prevent us from learning from the creative power of the metaphor and from getting ideas and inspiration when thinking about potential visions, goals, policies, tools and metrics. The roundput or closed loop principle of IE could, for example, be quantified by measuring the amount of renewables and wastes in the raw material and fuel basis of an industrial system. The diversity concept can denote the number and type of different actors and processes involved, e.g., large or small companies, public and private, diversity in industrial activities, agriculture and consumers, etc. Perhaps, researchers could consider whether a connection exists between the two principles: e.g., does diversity imply recycling or vice versa [56].

After further development of the theory, the conceptual basis and after learning from more case studies, the interdependency and cooperation philosophy of IE, could be measured in quantitative terms to determine the number of cooperative contracts or other relations between the actors in the industrial ecosystem. It must be noted that, in many cases, cooperation is something that cannot be measured. Cooperation is related to the culture of the firms and their partners or to the exchange of tacit knowledge among individuals or to trust. We may be able to use the industrial ecosystem locality feature as an indicator with studies that investigate what is the share of the local fuels in the industrial system or how much of the product life cycle is retained within the local/regional boundaries, e.g. consider product exports in the global market economy and the environmental and energy implications of the product life cycle.

Indicators such as the possibilities cited above are crucial when considering the decision-making process of policy or of corporate environmental management. The indicators could be used in measuring the success of previous actions, but also in 'what if?' scenarios to illustrate different alternative future situations of the industrial ecosystem and show environmental, economic and social effects of suggested policy and management. Scenarios show the effects of changing market, demand, technology, policy and legislation assumptions and predictions [51,84,83].

Consider a simplified example of 'what if?' scenarios to illustrate the point. A system scenario with 100% dependence on local biomass can be compared to a system scenario, in which the fuel supply is 50% derived from renewables and 50% derived from imported non-renewables. The first scenario would comply with the locality and the roundput principle, while the second would not. CO_2 emissions are calculated as well as fuel costs and employment effects, e.g., of using locally derived fuels, e.g. forest residues from cuttings. One can ask the question, whether the locality or the roundput principles affect the emissions, costs or employment opportunities? Scenarios simplify and, of course, always leave something out of the system boundaries. But they can alert the decision-makers to consider the industrial ecosystem philosophy with clear and provocative presentations of ecological, economic and social questions of regional development.

Fig. 2 sums up the concepts of IE when considered with the strategic sustainable development model of Robèrt et al. [1].

4. The risks and the difficulties when using the concepts of IE outside the strategic sustainable development model

By identifying four risks or barriers of IE, the author argues that if IE is used and applied outside the SSD model, it can be difficult and risky for sustainable development and for sustainability. The SSD model has been developed for the purpose of using a tool or an approach in a manner that takes into account the context in which the tool or the approach is used. The five hierarchically interdependent levels of the SSD model are the context.

4.1. Risk 1: substitutability vs. complementarity or eco-efficiency vs. ecological economics of sustainability

It seems that the argument that technology and engineering are the solutions to the environmental problems is embedded within the concepts and approaches of IE [8,11]. However, the previous discussion on problem displacement or problem shifting illustrates, that we have to apply policies, approaches, technologies and the tools, instruments and techniques with caution to avoid suboptimal solutions.

Level 1. Principles for the constitution of the system
- IE argues for systems interdependency between economic and social subsystems and the parent ecosystem
- IE contributes to material and energy flow principles
- IE systems and networks philosophy has the potential to contribute to social principles, e.g. with inter-organisational corporate social responsibility management

Level 2. Principles for a favourable outcome of planning within the system; principles for sustainability as the desired outcome
- IE provides material and energy flow limits and thresholds of ecological sustainability

Level 3. Principles for the process to reach the above outcome of sustainability, e.g. principles of sustainable development to reach sustainability
- IE offers planning principles

AND/OR
- IE offers constructs that can be used as hypotheses in sustainability systems analysis, from which systems planning principles can be derived

Level 4. Actions and concrete measures
- IE offers suggestions for material and energy flow reduction
- IE offers suggestions for material and energy flow substitution, e.g. recycling of matter and cascading of energy
- IE provides a network and systems approach for these reductions and substitutions

Level 5. Tools and metrics to monitor and audit
- IE offers inter-organisational management systems and concepts, e.g. regional environmental management and auditing systems (REMS)
- IE can be used to develop systems-level indicators
- IE suggests for 'what if?' scenarios, the economic, ecological and social effects of which one can measure and calculate for decision-making, policy and management

Fig. 2. The concepts of industrial ecology (IE) applied to the strategic sustainable development (SSD) model of Robèrt et al. [1].

Those who are critical argue that eco-efficiency suits large companies, because it enables them to continue with current practices with only incremental, if any, real environmental improvements [85]. Indeed, eco-efficiency seems to fit nicely within the dominant social paradigm (for DSP, see [4]) or the dominant neoclassical economics paradigm [39]. To simplify for the sake of illustrating the point, eco-efficiency is interpreted here as producing the same amount of products as before, but with less resource and energy use and/or with less waste and emission outputs.

Hukkinen [86] writes that eco-efficiency is disruptive for environmental policy if it is used to suggest that our concern for the environment can be decoupled from our material flow dependency on the environment. If this risk of misuse is ignored, the use of IE on the level 4 of the SSD model is not in line with the overall objectives and goals of sustainability of the SSD model on level 2. Correspondingly, the decoupling assumption implies that the important thermodynamic principles of material and energy flows may be neglected when the focus and the target of the SSD process is defined on the SSD model level 1.

The question is eco-efficiency vs. adaptation, or in ecological economics terms, substitutability vs. complementarity [17,24].[7] Neoclassical economics' basic position is for substitutability [87,88]. Accordingly, it is possible to substitute human-manufactured capital for natural capital [see 89,90]. Some see eco-efficiency as evidence for the success of the substitution [91].

Let us look more closely at the substitutability assumption and with a critical eye (for the ongoing debate on the substitutability vs. complementarity positions in economics, see [87,88,92]). The role of natural capital is qualitatively different from that of human-manufactured capital in an economic production process. Capital is the quantity of input while efficiency is

[7] One of the reviewers of this paper argued that, at times, we can substitute human-manufactured capital for natural capital. An example of an engineered or constructed wetland was given. I would challenge this point. Like in the case of agricultural farms, the Daly [17] concept of 'cultivated natural capital' is what accurately defines an engineered wetland and the natural component is very important also in cultivated natural capital. If we could construct trees that produce fuel oil for cars, then we would be able to substitute for natural capital, or could we, because the construction and the building process would itself require energy and increase entropy?

the ratio of output to input. The machines are the efficient cause of production, while natural capital is the material cause. Both, the agent transforming input resource flows into product outflows, and the resource input flows undergoing this transformation, are needed.

An eco-efficient machine transforms fuels into energy. However, it will always need fuels, even if it is very efficient in its use of the fuel. A sawmill will always need timber although; it could be a more efficient sawmill than some others. A fishing boat is not able to decouple itself from the fish in the sea despite the fact that it can move fast, use less fuels per mile than before and despite the fact that it has all the modern fishing techniques. Moreover, all of these machines are constructed from natural capital, from materials and energy.

One can substitute recycled paper for virgin paper with an eco-efficient technique or recycling plant/process, but this is one resource input (recycled paper) substituting for another resource input (virgin paper), not human-manufactured capital substituting for natural capital; the role of a recycling plant (manufactured capital) in an economic production process is qualitatively different from that of the resource inflow (natural capital). Recycled paper has its origin in forests. Consider replacing paper with purely electronic formats for communication. Again, this is not substituting a quantity of one resource input for a quantity of another resource input when producing a certain/given product in a certain economic production process. Rather, this is substituting a product (newspaper) with another product (say, a computer screen) to achieve a similar service/function. The two products have totally different economic production processes, e.g. you cannot produce paper only with computers, because you will need timber too (and paper is not the same as a computer screen, e.g. one can burn paper for heat, etc.). If you would be able to produce paper only with a computer and without wood, then this could be regarded as evidence of substituting man-made capital for natural capital. Then again, computer manufacturing requires energy and materials and technology that transform these energy and materials into computers. In addition, one could note that it has been documented that E-mails and Internet have actually increased paper consumption.

Because of qualitatively different roles of natural and human-manufactured capital (flow vs. agent) and of capital and efficiency (quantity vs. ratio), quantitative substitution of human-manufactured capital for natural capital is not possible. Efficiency improvements, such as recycling efficiency, can achieve reductions in resource use or waste generation, but this is not a quantity of one form of capital being substituted for a quantity of another form of capital. Rather, this is the success of using human-manufactured capital efficiently (or technical improvement) that will always need natural capital to function. Efficiency will never achieve complete decoupling from material and energy flows, because efficiency is not capital. If one believes that efficiency is capital and its ability to reduce resource use is evidence of man-made capital substituting for natural capital, then there are no limits to substitution, no limiting factor of economic development and no limits to growth.

The substitutability assumption is not in line with the SSD model level 1, which includes the material and energy flow principles, nor with the level 2, which presents goals for material and energy flows. Level 1 maintains that the economic system is growing as a subsystem and inside the materially closed and non-growing parent ecosystem.

The types of 'industrial ecosystems' such as the most famous recycling symbiosis at Kalundborg [67] will not be able to adapt to the ecosystem if they exceed a certain limit in the growth of the system. The Kalundborg system is based on fossil fuels or fossil raw materials resources. The global fossil fuel economy is not adapting to the reproductive capacity of nature or to the emission assimilation capacity of nature. The question is: Can efficiency gains in recycling the outputs exceed the negative growth effects resulting from increased use of input resources and fuels?

IE seems to have the potential to represent the complementarity position of human-manufactured capital and natural capital. In this position, it is acknowledged that both forms of capital are needed for economic development. IE proponents see the industrial system as a subsystem of the larger parent ecosystem. Furthermore, IE argues that the physical material and energy flow basis of economic and societal systems cannot be ignored in economics. At most, eco-efficiency improvements can be a useful practical instrument for action when applied with caution. Eco-efficiency is not suitable as a basic sustainability principle. One of the central points made by Robèrt et al. [1] was that one should not mix actions (level 4) and fundamental system conditions, goals (level 2) or principles (level 1).

Two provocative concepts are helpful here; the 'Jevon's paradox' [93,94] and the 'rebound effect' [95]. The Jevon's paradox holds that efficiency will increase consumption, because of the desires inherent in human nature. When manufacturers produced more fuel efficient cars in USA, people drove more. Many now have two or three cars; the net fuel use increased. The rebound effect underscores the point that efficiency can increase economic growth. When fuel efficiency is enhanced, the production costs and eventually prices can go down. Demand increases up to a point that fuel consumption will increase. Similarly, the increased purchasing power of consumers may be redirected to more energy intensive products than before and the energy use and the environmental burden will continue to increase.

The examples of IE application, e.g. the 100+ articles and book chapters on the 'master' industrial ecosystem example of the fossil fuel/raw-material fossil resource-based Kalundborg (which, of course, has been very important and valuable for our field), illustrate that IE can also be used under the substitutability and the eco-efficiency assumptions. Such applications risk long-term sustainability and are outside the SSD model levels 1 and 2.

4.2. Risk 2: physical flows vs. the culture of the flows

Among the central features of the SSD model, is that sustainability has the material and energy flow dimensions, as well as the cultural, social (and economic) and human dimensions.

In the Kuhnian theory of a paradigmatic shift in science [96], two stages are identified. Accordingly, both are needed for the paradigm shift to occur. The first stage is the paradigmatic, metaphoric and normative stage. The second stage is the practice stage, which is positive and analytical or technical. Analogously, the stages can be used to study the stages of the process of sustainable development or the concept of industrial ecology [3,39]. When compared to the SSD model, the first two levels would perhaps fit the paradigmatic stage, while the last two the practice stage, leaving the third stage, the principles for sustainable development, somewhere in between. Such a division is a question of presentation and is this author's (tentative) interpretation, but again, hopefully serves to illustrate the point for my purpose of discussion here.

The practice stage implements the goals under given questions and set targets, while the paradigmatic stage sets the questions and constructs the goals and includes social construction. The practical stage is not challenging toward the fundamental world views, values or norms, nor is there social construction involved with this stage. It is positive, practical and analytic, while the paradigmatic stage is critical and can be utilised to challenge the dominant paradigm. One could suggest that IE concepts, when used successfully, can contribute to both stages.

In the practice stage, IE offers tools and techniques for studying systems or networks of physical flows of matter and energy. The contribution is the systems approach, which complements the more traditional intra-organisational approaches. In the paradigmatic stage, the contribution is the use of the natural ecosystem metaphor. Clearly, the dominant social paradigm [4] is not a sustainability paradigm while the ecosystem offers contrasting metaphors of locality, cooperation, interdependency, community, connectedness and diversity. Those who would make progress on local and regional sustainable development should consider both stages in the paradigmatic shift. Recycling of material and energy flows in the second stage does not happen without a cooperation or community culture in the first stage.

4.3. Risk 3: tools vs. tools or tools vs. the basic objectives

The authors of the SSD model argue for using the different tools and approaches in parallel and as complementary tools. If the eco-industrial park, local industrial symbiosis or the industrial ecosystem approaches are used to contrast individual product-based environmental life cycle assessment (LCA) or an environmental management system (EMS) of an individual firm, conflicting suggestions for policy and management may occur. LCA and EMS may support waste reduction of a single product life cycle or waste reduction of a single firm, i.e., eco-efficiency, while IE may require wastes to be used as raw materials or as fuels in a network of firms to reduce the environmental burden of the system as a whole.[8]

Note how LCA is usually used as a technical and analytical tool to quantify the physical flows of matter and energy along a given product's life cycle, from cradle to grave (for discussion, see [97]). Now, consider the principles of sustainability of futurity and equity [98] or the principles in the SSD model on level 2. LCA can contribute to equity. It can be used to study what effects the products have in developing countries, when LCAs are used to trace the sources of raw materials and include the ultimate end-destination of the product wastes, not only the production or refining of products in the developed world.

This paper suggests that the LCA approach has potential beyond a practical tool, instrument or metric and can, in fact, be used for the level 1 and 2 in the SSD model. In addition to production, the cradle-to-grave LCA studies can also be used in the use phase of a product life. The generation of wastes and emissions may continue to occur years or decades after the initial production of the product. Some aspects of the future generations' possibility to achieve sustainability can be studied. Similarly, as LCA focuses on the entire

[8] To elaborate on the above example of paper recycling [50,76,77], one can note that IE is insightful in that it provides insight into the fact that wastes will always occur and seeks ways to utilise them and, at times, even encourages the production of wastes, because recycling in a network system can reduce the overall burden from the network system as a whole. It can be assumed that the system, as a whole, is more important for sustainability than the efforts done in an individual firm. But, when recycling too can create wastes such as heavy metals in paper recycling, one needs to ask, where did those heavy metals come from? Most probably they came from the inks and other additives used in paper-making or in magazine making. Thus, the real prevention of them at the sources should also be taken into account, when weighing and evaluating alternative actions.

life, the design principles for future sustainability may be considered in the planning and design stages of a product life. In other words, the fundamental and normative as well as the practical and instrumental stages of the sustainability paradigm must be taken into account when applying the practical instruments and techniques such as LCA.

4.4. Risk 4: green investments vs. flexible platforms

The idea in 'flexible platforms' is that investments and other applications in the process of sustainable development should always be planned in a way that also enable further development and/or continuous improvement in the future. This author argues that there is a risk that industrial ecology's emphasis on networks and inter-organisational environmental management can result in difficulties if long-term continuous improvement is *not* considered. Unhealthy dependencies [64,65,99,100], technological 'lock-ins' or path dependencies [101] may occur.

Co-production of heat and electricity has been noted in many cases as a possible 'anchor tenant' or a 'key player' and a driver of a local/regional industrial ecosystem (see [65,102,103]). By applying the combustion technique of fluidised bed burning, CHP plants can use waste flows from residential households, agriculture, forestry, forest industry, food industry and produce electricity as well as heat to be used either as process steam or district heat, even to heat horticulture, etc., i.e. produce for all of these actors and sectors. One could argue that CHP has the potential to serve as an anchor tenant and the driver of a local or regional network of actors that work together for an industrial ecosystem. But when considering the social or the human side and economics of the material and energy flows, we can encounter difficulties and barriers. CHP is a relatively capital intensive investment and has long payback times. Further, CHP is a long-lived investment. Once the investment has been made, the actors involved will want to wait for the gradually appearing paybacks. In this kind of situation, a new and perhaps greener alternative might be neglected or ignored or it is simply impossible for the actors involved to adopt such a new alternative, because of the commitment to the CHP investment. Networking can hamper innovation. Such a scenario would not be in accordance with the type of investments suggested with the strategic principles of flexible platforms or backcasting.

5. Conclusions and discussion

IE is a set of emerging concepts from the research and practical fields of sustainable development. IE has stimulated extensive scientific debate as well as initiatives in industry, corporate environmental management and in the design and implementation of public policy. This article applied IE to the five levels of Robèrt et al. [1] model of strategic sustainable development. The author argues that the applications of the concepts of IE offer a contribution to all of the five interdependent levels of the model of strategic sustainable development.

On the other hand, IE is a risky and difficult approach. These risks become evident, when IE is used in an unsystematic way outside the model of strategic sustainable development. The paper addressed four risks or undesired outcomes that result when strategic thinking is not used in IE applications. IE should not become only a technical tool or instrument that is applied without considering the more fundamental critical questions such as economic growth, the ability of technological progress to deal with environmental problems, or the human addiction to consumption. The SSD model is important in that it situates IE among the many other approaches and tools that are used in ecological economics, cleaner production, pollution prevention, life cycle assessment and corporate environmental management. Further, strategic thinking is the key to achieve real success in practice, because IE must be bridged to business strategy and decision-making in firms, e.g. under the philosophy of corporate social responsibility.

The review process of this paper noted that the analysis in the paper shows that IE has been developed without a strategic perspective. The lack of strategic thinking and understanding can lead to reductionism and costly piecemeal approaches or to failing to see 'the forest in spite of all the trees'. The holistic, big picture, in turn, encourages IE to look beyond the many system boundaries such as local or regional or those that result from applying the boundaries of a certain specific field of expertise. To this author, it seems that IE has mainly been developed in engineering and natural sciences, while the human-dimensions, the social sciences, cultural studies, management and organisational aspects are now observed as those that would enable us to identify and analyse the deciding factors of sustainable development, and in particular, in practice when dealing with the practical challenges in organisations and business strategy as well as when learning about and trying to change the behaviour of individuals or their groups and networks. This does not mean that IE should include everything. Rather, this only suggests that the strategic sustainable development model is a fruitful example of a kind of '*breakthrough*' thinking and of perspectives that are needed in any emerging and young concept or scientific field. Such thinking helps to identify what is important and what can be left to lesser attention.

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