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Four ecosystem principles for an industrial ecosystem

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Abstract

The industrial system operates through different principles of system development than the ecosystem. Industrial ecology can be a fruitful metaphor for facilitating the development of industrial systems toward the principles of system development of ecosystems. In this paper the industrial ecosystem analogy includes the four ecosystem principles of *roundput*, *diversity*, *locality* and *gradual change*.

Keywords: Industrial ecosystem; Ecosystem principles; Roundput; Diversity; Locality; Gradual change

1. Introduction

During the last two decades the industrial 'risk society' [1] has tried to establish antidotes for environmental risks that result from its activities. Many approaches to corporate and industrial environmental management as well as methods, techniques and tools have been created and environmental or sustainability programs have been implemented. Needless to say, the problems still remain. In fact, in some cases a new problem is created when the old one is dealt with. This holds true with the policymaker's efforts as well as with the implementation of the corporate environmental management agenda, note the familiar notion of 'end-of pipe policy' or the tendency for 'problem displacement' [2]. For example, due to decisions in the legislative sector, 'an environmental bad' can be exported from one medium to another or from one stage in a product's life cycle to another, e.g. from landfills to de-inking sludges in the case of paper life cycles and paper recycling [3,4].

The notion of 'environmental problems' could be defined as a societal construction in the sense that society will define a certain condition in the ecosystem to be of concern only after societal actors have observed it, reported on it and eventually engaged in an effort to deal with it. For instance a certain condition in an ecosystem that results from outputs from industrial activity is not an environmental problem as such, despite the fact that it may create harm in nature. In other words, effects caused by pollution, say, in a lake, become what we know as 'environmental problems' only after scientists observe the problem, media report on it, the local public authorities, firms, land owners and environmental groups, i.e. the societal actors, engage in a societal response to deal with the problem. To follow this line of arguing, environmental or sustainability programs are also societal constructions [5–7]. Perhaps, then, in a societal decision making process one may face the risk of abstracting too much from the actual ecosystem operation, which obviously should be the focus point of sustainable development discussion in general, or its subset the industrial environmental management agenda in particular.

The 'voice of nature' will always be indirect in a societal process such as that of corporate or industrial environmental policy and management. Also, our knowledge about the ecosystem functions will be based on uncertainty. However, the fundamental 'cause' of modern societal environmental problems is the fact that the two systems, societal, economic or industrial and the ecosystem operate through different principles of system development. Therefore, industrial environmental management questions should be approached with an effort to compare these two systems and to try and find the problem areas in their coexistence.

In this paper we attempt to learn from ecosystem prin-

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ciples in an industrial system, to try and illustrate some of the important challenges of industrial environmental policy and industrial environmental management and to try and initiate discussion on the direction along which the industrial ecosystem (IE) approach could be developed. We also reflect on some examples of IE case studies.

2. Ecosystem principles for an industrial ecosystem

The IE analogy is based on the provocative ecosystem model calling attention on the basic condition of natural recycling systems or *roundput* systems[1] [9–15]. In ecosystems, waste equals food, and the energy is cascaded along the food chain while the only input to the system is the solar energy from the sun. The basic philosophy in the IE approach is then to enhance the emergence of an industrial system that relies on co-operation between the actors involved, in that they use each other's waste material and energy as resources and in this way minimise the system virgin material and energy input, as well as the waste and emission output. It is obvious that a perfect IE will never happen. But it also seems to be clear that the direction we should follow when striving toward sustainable development is to learn from the ecosystem, although this effort may still be only at a metaphoric level. The ecosystem has demonstrated its capability for sustainability [16–19].

To the author's knowledge, the most commonly used IE analogy is for facilitating the emergence of industrial roundput systems, where the actors involved cooperate through waste material and energy utilisation. In this paper the ecosystem principles that are considered in the IE analogy include *roundput*, *diversity*, *locality* and *gradual change*. Table 1 sums up the following application of these four ecosystem principles in industrial systems.

Table 1
Ecosystem principles in industrial ecosystems

Ecosystem	Industrial system
Roundput	*Roundput*
Recycling of matter	Recycling of matter
Cascading of energy	Cascading of energy
Diversity	*Diversity*
Biodiversity	Diversity in actors, in interdependency and co-operation
Diversity in species, organisms	Diversity in industrial input, output
Diversity in interdependency and co-operation	
Diversity in information	
Locality	*Locality*
Utilising local resources	Utilising local resources, wastes
Respecting the local natural limiting factors	Respecting the local natural limiting factors
Local interdependency, co-operation	Co-operation between local actors
Gradual change	*Gradual change*
Evolution using solar energy	Using waste material and energy, renewable resources
Evolution through reproduction	Gradual development of the system diversity
Cyclical time, seasonal time	
Slow time rates in the development of system diversity	

2.1. Roundput

The carbon–oxygen cycle exemplifies the way in which an ecosystem operates. "Plants consume carbon dioxide and produce oxygen as a waste. Animals, in turn, require oxygen for respiration, but produce carbon dioxide as a metabolic waste" [11]. Ecosystems tend to keep most vital nutrients within the system and benefit from waste as food. The 'recycling of energy' (or utilisation of residual energy) happens through cascading in food chains with the only driver of the system being the input from the (infinite) solar energy.

The industrial system operates with the 'free energy' stock of fossil fuels that has (up to now) made it possible to proceed with an unlimited growth paradigm. Following Daly [20], one might note that in modernity the limiting factor of economic development is changing now as economic development is limited by natural capital instead of human manufactured capital, e.g. it is the oil in the ground instead of the pumping capacity that is the limiting factor, the fishing population instead of the fishing boats, forests rather than saw-mills. The fossil fuel stocks have enabled the industrial system to proceed with a throughput paradigm, i.e. from raw materials to products to wastes. To learn from the ecosystem principle of roundput, when facilitating the emergence of an IE, is understood to mean recycling of matter and cascading of energy between the actors of the system[2]. Roundput should promote increasing reliance on renewable resources, on the use of waste materials (recycling of matter), waste energy (cascading of energy) and waste fuels.

[1] For the concept of industrial ecology see [8].

[2] We understand that the basis of the IE analogy is to mimic the utilisation of waste of an ecosystem in an industrial system. We feel that the term 'roundput' may serve to describe this condition of an IE as it suits the purpose of being opposite to the term 'throughput', which is commonly used to illustrate the linear nature of the material flows in an industrial system; from raw materials, to products, to wastes. William Ashworth [21] used the term 'aroundput' for similar purposes and described the operation of a forest ecosystem, its cyclic flow of materials, with the term.

2.2. Diversity

Ecosystem survival is based on diversity, diversity in species, in organisms, in interdependency, in ‘cooperation’ and in information. By allowing high flexibility and adaptability, the existence of diversity can be seen as a long-term survival strategy of ecosystems as a consequence of permanently changing environmental conditions. Also, when the environmental conditions are almost unchanged, but severe resource constraints exist, the coral reefs or tropical rain forests for example, optimise their functions through diversity [22].

Human economic and industrial systems are also diverse. We can consider the diversity of product structures and supply for instance. However, when understanding the system under one single denominator, i.e. monetary value, the diversity is reduced. In addition, the diversity is reduced through the ideal of mass production, focusing on maximising the rapid increase of homogenised industrial output products. However, the dominant Taylorist or Fordist ideal is beginning to be challenged by the increasing emphasis on quality, variety and diversity in the industrial output structure of products [11]. Societal information regarding the ecosystem functions is in many cases based on parameters that are transformed to policy decision making by monetary values. To find monetary substitutes for natural goods is always difficult. Therefore, human interventions into the natural ecosystem can be based on incomplete information and tend to be selected (e.g. because of increasing specialisation) without taking into consideration the existing diversity in nature.

The ecosystem principle of diversity, when considered in industrial environmental policy and management, could then mean diversity in cooperation. The existence of diverse and interdependent cooperation systems could for example facilitate the existence of systems, where the actors involved use each other’s waste materials and energy through cooperation, i.e. IEs. Actors that do not usually cooperate with each other would need to do so, e.g. large manufacturers, SMEs, the public municipal organisations, waste management companies, consumers etc.

Further, the diversity analogy would promote diversity in industrial inputs and outputs. The fuel basis of a power plant for example, could include the traditional coal and oil inputs but also peat, wood wastes, forestry wastes, REF (recycled fuels) from households or from industries. A case study on the IE of a regional energy supply system of the Jyväskylä region in Finland [15] showed how the system is based on cascading of energy with the co-production principle of heat and electricity (co-production of heat and power, CHP) [23,24]. In CHP, the waste energy from electricity production can be used in the production of district heat for households and industrial steam for local industry requirements. The input basis of the Jyväskylä energy supply system includes, to a large extent, forestry, saw-mill and plywood mill wastes. The technique of fluidised bed burning is very flexible in respect to fuels as low-grade solid fuels like forestry and saw mill wastes can be easily used as fuel. The technique also makes the use of various REF possible. With the CHP method the output structure of the key power plant in the region is also relatively diverse as electricity, heat and industrial steam can be produced from the same source. The CHP is operational on a large scale only in three countries in the world, Finland, Netherlands and Denmark. The 1999 share of go-generation of total national electricity generation in Denmark was 50%, in Netherlands 40% and in Finland 35% [23,25]. In the EU the share of go-generation is under 10%, in Germany 10% and in the UK 6%.

2.3. Locality

The ‘actors’ in the ecosystem adapt to the local environmental conditions and cooperate with their surroundings in diverse interdependent relationships. Ecosystems need to respect the local natural limiting factors [26]. Regional economic or industrial systems have been able to substitute the local natural limiting factors, of energy for instance, with imported fossil fuels. Furthermore, the assumption prevails that natural capital can be substituted with technological innovation or with human manufactured capital and therefore the sustainable use of regional or local resources has in many cases been neglected.

To ‘achieve’ the ecosystem metaphor of locality, industrial systems would need to try and replace imported resources with local renewables and with local waste material and energy sources. The regional industrial system would adapt to the local natural limiting factors. Further, transportation would be reduced and cooperation with regional actors (public and private) would be enhanced.

2.4. Gradual change

Ecosystem survival relies on the flow resource from the sun and the evolution respects the renewal rate of the ecosystem. Further, as evolution happens through the gene as the information storage medium, the information moves through reproduction. This is of course in stark contrast when compared with the cultural evolution, or its subset the industrial (r)evolution. In cultural and industrial evolution, culture serves as the information storage medium, e.g. oral, written, video, internet etc. records, and hence development happens much more rapidly than in the natural system [27]. Here lies one of the fundamental problems of the environmental question, as a rapid increase in demand for a certain market good for instance, can lead to the extinction of the natural resource required for its production. As already noted, the industrial evolution has up to now been based on the stock resource in fossil fuels and therefore the renewal rate of the ecosystem has not been respected.

In industrial environmental management, the gradual change metaphor could be interpreted as increasing the reliance on renewable flow resources not exceeding their renewal rate instead of using non-renewable stock resources. The industrial system should rely more on sustainable use of renewable natural resources as well as on the use of waste material and waste energy flows, e.g. as fuels, and in this way adapt itself to the renewal time cycles of local natural resources instead of exceeding these with unlimited use of non-renewables that are often imported. The forest industry of Finland could provide an example of a national industry, which is based on the renewable resource of the forest ecosystems. Annual cuttings are lower than the annual growth of the forests in Finland [28]. In addition, the use of wood wastes, saw-mill wastes, forest residues, waste paper, black liquor from pulp mills, waste pulping chemicals and the implementation of the CHP method in the industry power plants are factors that, when further developed, could make it possible for the whole forest industry to rely almost entirely on renewables or waste material and energy inputs [29][3]. At the moment fossil fuels are still used to some extent, for example in energy production. In other words, the application of the ecosystem principle of gradual change to an industrial system would promote the use of renewable resources and waste material and energy and hence nature's time cycle could be respected in industrial systems.

The use of the gradual change metaphor in an IE project could also be seen to facilitate a gradual development of system diversity in a potential IE. It is obvious that regional industrial systems for example, are diverse systems, where ecological, economic, social and cultural issues need to be taken into account when planning or trying to enhance the system interdependency and cooperation, for instance in waste utilisation between the actors involved. To rapidly 'create an industrial ecosystem from scratch' borders on the impossible [30]. Therefore, the direction to follow, at least with the current limited experience from IE case studies, could be to build on existing strengths, for example on a certain big industrial actor that can utilise a diverse fuel basis and hence also promote the other actors in the region to provide the actor with wastes to be used as fuels [15,31]. Also an environmentally active municipal organisation could provide the needed support for enhancing cooperation between private industrial actors that might otherwise be reluctant to engage in cooperation with each other because of competitive attitudes etc., and as such could be seen as a support system around which the IE development could be build.

3. A vision of a perfect industrial ecosystem

Fig. 1 presents an ideal of the Perfect Industrial Ecosystem. Such a system would be constructed from the two systems; the industrial subsystem and the mother ecosystem in which the industrial system is embedded. The only input to the system as a whole would be the (infinite) energy from the sun and waste heat would be the only output from the system. The inputs to the industrial system would include only renewable resources and recycling of matter as cascading of energy would then happen between the industrial actors of the system. Here the outputs that are dumped into the natural system from the industrial system include only such things that nature can tolerate or perhaps re-use and recycle in its own

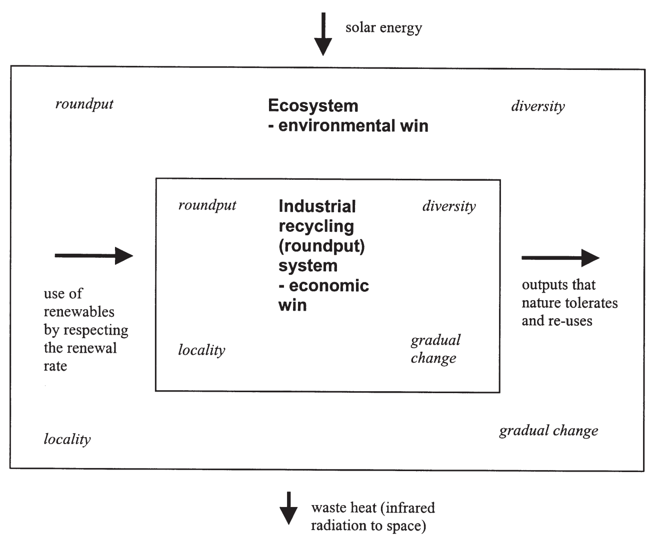

Fig. 1. A vision of the perfect industrial ecosystem. The vision of a perfect IE would be constructed from the two systems; the industrial subsystem and the mother ecosystem. The two systems would operate through the same principles of system development, i.e. roundput, diversity, locality and gradual change. Together the systems would form a single system. When succesful, IE can achieve an environmental win as the virgin material and energy input to the industrial subsystem as well as the waste and emission outputs to the natural (mother) system are reduced by using wastes between the industrial actors. Economic gains are possible through the reduction of raw material and energy costs, costs resulting from environmental legislation, waste management costs and 'image costs'. Also the green market potential presents an opportunity for the industrial system.

[3] Discussion exists in Finland on whether the management of economic forests neglects the biodiversity values of forests. However, efforts are beginning to be implemented to better preserve the ecosystem. The tree species in economic forests in Finland are mainly domestic natural species, i.e. not plantation forests. The re-production is to a large extent natural. The protection of biodiversity is currently incorporated into forestry practices. The certification of good forestry respecting natural values is increasingly common, and 7.6% of the total forested area is protected on the basis of different conservation programmes. In particular, cuttings are being reduced at areas which can be defined as sensitive with regard to biodiversity.

operation. This 'inter-system ecology' could be possible for example in some cases in forest industries. Recently some studies have been conducted with regard to the use of nutrients embedded in the forest industry power plant waste ash, with the aim of returning the nutrients back to the natural cycle as fertilisers [29,32][4]. In addition, this idea could be illustrated with the Finnish forest industry carbon cycle [28]. The annual binding of CO_2 in the forests of Finland exceeds the amount of carbon released through forest industry cuttings. In other words, here nature is recycling the waste of industrial activity, which is practically impossible to 'recycle' by man. CO_2 emissions are very difficult to sequester directly on a large national scale, because this would create high costs.

In a perfect IE both of the systems (the industrial (sub)system and the (mother) ecosystem) operate according to the same principles of system development; roundput, diversity, locality and gradual change. In other words, the industrial system is also based on recycling and diverse interdependency and cooperation. The industrial system would be arranged as a local cooperation system that respects the local natural limiting factors and develops gradually following the renewal rate or the reproduction cycle of the local renewable resources.

The vision presented is of course highly idealised and the industrial system will always differ from the ecosystem operation. The goal of the vision should be what the industrial ecology community is calling type III ecology, i.e. an ecosystem that has evolved from linear and quasi-cyclic material flows into a situation where the resources of life are limited and therefore the system operates through almost complete cyclic nature of the material flows [18,33]. In type III ecology the only external resource is the solar energy from the sun and 'resources' and 'wastes' are undefined as waste is a resource.

The perfect IE would, when successful, be a business–environment or industry–environment win–win situation [34]. As in theory, when properly implemented, recycling can reduce the virgin material and energy input to the industrial system as well as the waste and emission output from the system, the environmental win would happen. Here the economic gains appear as raw material and energy costs are reduced if waste serves to substitute the need of these inputs. Similarly, costs resulting from environmental legislation can be reduced, e.g. legislation that is focused to limit the use of certain non-renewable resources. Further, waste management costs as well as 'image costs' can be reduced and possibly the green market potential is better utilised.

The four ecosystem principles cannot be seen as 'answers' to the industrial ecology dilemma. Rather, these could be potential initial directions along which the IE analogy can be developed. It is important to note that recycling (or roundput) will not always generate solutions that are desirable from the environmental perspective, e.g. recovery of used papers and the following de-inking process create de-inking sludges or alternatively incineration ash when some amounts of the recovered materials are incinerated. The end-result may, at times, be that, because of the high recovery rates that create side-effects, the total amount of waste that is generated in the paper industry life cycles remains unchanged regardless of the recycling efforts. The capacity requirements, for example for de-inking plants, can also present an (economic) barrier for implementing the recycling plans. Similarly, application of the ecosystem diversity principle to an industrial system may require the companies to extend their operation into areas unfamiliar to them, redesign processes and products and change their routines.

However, an industrial system which achieves advanced roundput, diversity, locality and is in tune with the gradual change metaphor, can be argued to be more likely to fulfil the IE philosophy than an industrial system which does not follow these ecosystem principles. In other words, recycling of matter and cascading of energy, diversity in co-operation and in inputs and outputs, local arrangement of activities as well as the resource basis, and the substitution of non-renewable stock use with the use of renewable flows by respecting the renewal rate, can be important goals that an industrial system, which is striving toward the vision of an IE, should consider.

With regard to the industrial ecology vision the biggest weakness in the often cited Kalundborg regional system [12] is the fact that regardless of the waste material and energy utilisation between the actors involved, the system still relies on imported non-renewable fossil raw materials i.e. the two key actors of the system are a coal fired power plant and an oil refinery. The weak point in the Jyväskylä IE, the study on IE with a regional energy supply system in Finland [15], is the use of peat as fuel input to the energy supply system.

[4] The idea of a complete cycle, i.e. starting from the natural source functions and continuing through the industrial system and eventually to a stage where the industrial wastes are returned back to nature in a form that nature can tolerate and re-use in its own operation, could be illustrated with an example of using industrial sludges as fertiliser in agriculture in fields, as is the case at Kalundborg. A similar activity is the effort in Kalundborg to utilise industrial waste heat in a fish farm for heating. (For case studies of e.g. regional IEs, see [12].) Here, then, one might get confused with regard to the question what is 'natural capital' and what is not, because usually natural capital is understood as something that we cannot make. In the case of plantations, fish farms and the like Daly has used the term 'cultivated natural capital' [20]. Further, examples of a complete cycle starting from nature and coming back to nature after the flow through an industrial system and in a form that nature can tolerate and re-use could arise in the case of the paper life cycle. It is possible to use paper wastes as inputs in packaging board manufacturing, and waste packaging board as inputs in seedling protector (that protect the newly planted trees in the forest) manufacturing [3].

However, peat used in the Jyväskylä energy supply system is a local resource and peat is abundant in Finland, in fact some would argue that it is a renewable resource[5]. Every IE case will be different, and hence it is very difficult to come up with some universal design principles for or define 'conditions of a successful industrial ecosystem' for 'industrial ecosystem management'. The important point is to be aware of some of the main conditions of industrial ecology-type development. Here, the four ecosystem metaphors of roundput, diversity, locality and gradual change could be helpful. Then, the challenge is to try and adapt to the local conditions considering the material and energy flows, and also the societal context of the flows.

4. Conclusion and discussion

The aim of the approach presented, with the four ecosystem principles reflected in a potential IE, is to generate discussion on the possibility of gradually facilitating the development of industrial systems toward the system development principles of ecosystems. We have understood here the IE as a regional collection of industrial actors, that cooperate in each other's waste material and waste energy utilisation. The approach may benefit industrial environmental management and environmental policy in the following ways:

1. The fundamental cause of environmental problems is the fact that the ecosystem and the industrial system operate according to different principles of system development although the industrial system is always only a subsystem of the larger ecosystem, and dependent on it. By applying the four ecosystem principles of roundput, diversity, locality and gradual change to the context of industrial systems, there is an opportunity to learn to understand some of the basic problems of the industry–environment interaction.
2. By using the four ecosystem principles, e.g. roundput, we may be able to identify the weak points of a certain industrial system or the possible points of improvement with regard to this principle, and then facilitate the emergence of industrial ecology (roundput or recycling systems).
3. With the four ecosystem principles we can perhaps better 'evaluate' or assess the 'ecology' of an industrial system. One could argue that an industrial system based on recycling of matter and cascading of energy, and which is a diverse cooperation system arranged locally and mainly relying on renewable flow resources or wastes, may better 'fulfil the conditions of sustainability' than a system where these principles do not happen.

The question in industrial ecology will always be about implementation, to change and redirect the routine behaviour of economic activity. We are beginning to see efforts to study and design regional industrial ecology with eco-industrial parks for example. The four ecosystem principles presented could be seen as potential conditions that one could try and achieve in a regional IE project. In other words, in the planning phase the principles could serve as the basis of the goal definition, e.g. with locality to reduce the dependency on imported fuels of the local energy supply system. Then, when determining the action proposals and when auditing and evaluating the success of the project (with for example material flow models) the principles could serve as a model toward which one must strive. One framework that could be used with the four ecosystem principles may arise from the concept of a Regional Environmental Management System (REMS) [38]. Here the Environmental Management System (EMS) structure is extended beyond the boundaries of a single firm to include various regional actors, private and public, into a common regional environmental management agenda. The idea is to get companies, public authorities, local research institutions, environmental and citizen groups and consumers involved in a common regional environmental agenda. An initial environmental review, environmental policy definition, formulation of the goals and action proposals as well as conducting an environmental audit to improve the process in the next phase following the continuing improvement philosophy, are the steps that are followed in REMS.

It will be difficult to construct any universal design principles for IE management with such limited experience of regional IE efforts or eco-industrial park initiatives. With the four ecosystem principles, we have tried to further stimulate discussion on the potential directions for the development of the IE analogy. The development of the concept must take place with interdisciplinary perspectives and the approach needed is theory building alongside comparative case studies.

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[5] Totally in Finland, about one third of the land area is covered by peatlands. About 20% of peat volume could be harvested economically, but at the present use rate this would last for 400 years. This would constitute only about 2% of the original peat land area, because only the thickest layers can be harvested for energy production. However, the growth of peat, if integrated over all Finnish peatlands, exceeds the present use rate. [35–37].

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