INTRODUCTION

Industrial Ecology (IE) has developed rapidly during a period of few years only. It is today a concept which is well recognised by industry, but the need for including IE thinking and methodology in university engineering programmes is urgent. A part of this NTVA seminar is a workshop on Critical Industrial Ecology Aspects related to such university programmes, with an emphasis on IE and sustainable product design and internal development strategies at the Norwegian University of Science and Technology, NTNU. The workshop specifically aims to focus the interdisciplinary perspectives and challenges of such programmes. Critical aspects will be discussed along four lines: IE as a concept in teaching; how to operationalise IE in engineering design and management teaching; the use of cases across disciplines and faculties; and how to organise the IE teaching at NTNU. This paper is written as an introduction to the workshop.

THE NEED FOR A NEW PERSPECTIVE

Environmental strategies in general, and in industry in particular, have changed considerably during the last decades (Brattebø 1995). From the "environmental revolution" in the 1960s, via and in between separate approaches like deep ecology on the one side and technology optimism on the other, one has come to a kind of global consensus during the late 1980s on the need for a sustainable development where environmental concern and economic and social development is to be combined (WCED 1987). WCED claimed that environment and development were inextricable, and that existing policy responses were handicapped by the fact that existing institutions tended to be independent, fragmented, too narrowly focused, and too concerned with addressing effects rather than causes. The Commission also concluded that environmental policy too often had a secondary status. It was time that "the ecological dimensions of policy (were) considered at the same time as the economic, trade, energy, agricultural, industrial, and other dimensions - on the same agendas and in the same national and international institutions". However, the most famous statement of the report is the Commission's definition that sustainable development is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs".

Out of these statements it is easy to focus three basic premises: i) long term needs and abilities have to be met, ii) by inclusion of ecological dimensions of policy as a major premise, iii) with the use of
holistic and preventative thinking across existing institutions and structures. If these basic premises are to be applied to industrial systems, one should come to the simple conclusions that:

- industry should focus prevention rather than reactive control
- industry should develop production and market strategies on the basis of long term considerations
- industry should adopt systems thinking across sectors, market segments and product chains
- industry should develop on the basis of ecological principles

And this is what actually was started some few years ago as part of the creation of the International Chamber of Commerce's Business Charter for Sustainable Development (ICC 1991), the Agenda'21 Chapter on Business & Industry (UNCED 1992) and the establishing of the World Business Council for Sustainable Development, BCSD and new actions within the United Nation Industrial Development Organisation, UNIDO.

The long-term needs for environmental efficiency is now being studied in several countries. The Advisory Council for Research on Nature and Environment, RMNO, in Holland reported such research in a thought-provoking report "The ecocapacity as a challenge to technological development" (Weterings and Opschoor 1992). RMNO looked towards year 2040 and concluded that in a sustainable world, the per capita emissions of pollutants and consumption of vital resources in the Western, industrialised world will have to be generally reduced to something less than 10 percent of present levels.

On the basis of the RMNO results the Dutch Committee for Long-Term Environmental Policy (CLTM) published a book where Leo Jansen wrote an interesting paper on technology and sustainability (Jansen, 1994). Jansen's message is that the use of environmental technology in industry and society has to be changed so that the overall production and consumption is kept within the ecocapacity of the world. Jansen suggests that the contribution of technology may be optimised by three approaches, see Figure 1.

![Figure 1: A three-way track (I-III) for pushing technology towards sustainability](image)

**Figure 1:** A three-way track (I-III) for pushing technology towards sustainability

Track I Janson called the "environmental protection (or care)" track. It attacks short-term needs, e.g. by stopping leaks and streamlining current production systems. It emphasises the "organisation for environmental quality of processes and products" combined with full application of supporting technologies for process monitoring and control, and periodical use of environmental audits. This approach has potentials for an increase in environmental efficiency by a factor of about 1.5 within a few years. Track II was called the "environmental technology" track. It includes the improvement and
application of existing technology, both avoidance and control related, to realise a better utilisation of the environmental capacity. The potential for environmental efficiency improvements is estimated to a factor of 1.5 to 4 within a period of about 20 years. However, Jansen states that such gradual improvements will not be able to reverse the ongoing process of deterioration of the environmental capacity. Track III was called the "sustainable technology" track. It does not concern improvements in existing technologies, but finding new technological combinations and concepts by which the future required increase in environmental efficiency can be realised. Depending on the environmental parameter under consideration and a number of assumptions, the increase in environmental efficiency through sustainable technology should be a factor of 10 to 50.

The conclusion from this study emphasises the need for a shift in strategies. It is a well-known fact that technology development takes time, and often long time. One has to push the process of innovation successfully through four phases: research and exploration, development, demonstration, and finally implementation. Leo Jansen claims that "the first challenge to society is to shape a consensus for a joint effort to reach sustainable development by creating conditions for development of sustainable technologies". He demonstrates the urgency of a contribution of technology towards sustainability and a break in the current trend of technology development. He also states that the challenge to technology is to fulfil societal needs within the ecocapacity of the world.

Strong interactions between technology, culture and structure determine nature and shape of actions to be undertaken in technology development from the basic attitude that a contribution of technology to sustainability is essential but (by far) not sufficient, see Figure 2.

![Figure 2: Interactions culture-structure-technology in making environmental improvements as response to social needs.](image)

The three elements of Figure 2 characterise development in society in a strong mutual interaction. A radical change in technology, e.g. to improve environmental efficiency, in fulfilling societal needs can never be regarded without taking the interactions with culture and structure into consideration. The "acceptability" of environmentally efficient technical means is directly connected to the economic conditions in the market and the demands in society. In this context it should be well understood that these conditions and demands are not at all static and may change radically as a result of environmental and political changes. On the other hand, the cultural and structural requirements must be met if specific technological strategies and systems should be able to function well. The overall message is that in
future it will be more crucial to optimise environmental solutions by combining theoretical and practical knowledge from technology, the social sciences and the humanities concurrently.

SYSTEMS THINKING
System thinking implies that a company considers environmental problems as part of a much larger system than company frameworks at present. One has to enlarge the system borders in two dimensions, time and space.

First, let us look at the time dimension of systems thinking. The U.S. White House, under the guidance of the National Sciences and Technology Council, have worked out a new and very ambitious national environmental technology strategy (U.S. White House 1994 and 1995). This strategy reflects the needs of up-scaling investments in avoidance technologies (preventative actions) and monitoring technologies while the focus on more traditional environmental control technologies and remediation technologies (both reactive oriented) will have to be reduced, see Figure 3.

![Figure 3: U.S. White House technology development scenarios.](image)

Avoidance technologies will dominate environmental investments in the next century. They are designed to avoid the production of environmentally hazardous substances or alter human activities in ways that minimise damage to the environment. These technologies include equipment, processes, and process sensors and controls designed to prevent or minimise the generation of pollutants, hazardous substances, or other damaging materials, as well as technologies used in product substitution or in recycling and recovery of useful raw materials, products, and energy waste streams.

Avoidance can be achieved by operational changes including the use of materials, practices, or procedures that reduce or eliminate waste, or institutional changes including employee training programmes, total quality management programmes, just-in-time inventories, "green" procurement policies, full-cost accounting, and life-cycle assessment. Avoidance may include incremental changes to existing manufacturing infrastructure, or substantial changes on the basis of new design and production strategies ("Design for the Environment").

Second, let us take a look at the space dimension of systems thinking. Some years ago environmental problems were often understood and dealt with in a local context, although national and international coordination was given high priority since the 1970s. Industry was more or less used to solve their environmental problems "in-house", i.e. within the production facility borders, in order to deal with local SHE (safety, health and environment) problems. SHE activities have expanded significantly during recent years, and as a result they have given important and needed improvements on many fields.
However, such activities have not been based on systems thinking at society level. The systems perspective was incorporated only when one started focusing product life-cycle assessment (LCA), design for recycling, materials recycling and product reuse, and energy recycling, across sectors of the economy and within or across product chains, and across production and consumption stages in society. The overall objectives of such strategies are the closure of the materials cycle and a reduced pollution intensity in society. Figure 4 illustrates how the focus for environmental thinking is (and will be) enlarged during some few decades.

In the 1970s the industrial focus of environmental improvements was limited to the production or manufacturing stages. Industry was not concerned about materials recycling and even not so much with waste management in general. Today industry is more or less forced to start thinking of what happens with their products during consumption and after the product's useful life. Internal and external materials recycling is a main objective at present, along with waste reduction and pollution prevention options (cleaner production). During a few decades one will have to consider the whole system from exploitation of raw materials through preparation, production and consumption stages, in an integrated way in order to minimise environmental degradation, health impacts, and the excessive use of resources. In such a policy closing the materials cycle will be a key strategy.

![Figure 4: 50 years of environmental focus moves towards systems thinking](image-url)

It is obvious that all industrial companies sooner or later will have to be influenced by the coming national and international systems-based environmental strategies. Such strategies are of course valid
also to European companies, as parallel strategies are being developed in our countries. Some large-and medium-sized companies who focus long-term competitiveness in combination with environmental impact reductions or environmental technology market potentials have already started adopting a proactive approach to such aspects of systems thinking.

Similar changes take place in governmental institutions. The use of avoidance technologies, market instruments, and measures to motivate for changed consumer habits now constitute large parts of national and international research programmes as well as administrative programmes within the environmental authorities. As an example, the Ministry of Environment and the Research Council of Norway at present prepare to launch a new programme aiming at improved environmental performance by focusing "sustainable production and consumption" as one combined strategy. I.e. one wishes to attack the production and the consumption stages in society combined and concurrently in order to seek for long-term and systems-based environmental improvements. It is obvious that such initiatives will have to be oriented towards different aspects within the culture-structure-technology framework outlined in Figure 2, and will need stronger priorities to interdisciplinary cooperation across traditional disciplines of technology in combination with the disciplines of natural sciences, social sciences and humanities. Particular emphasis could be given to projects seeking to optimise industrial action in a business/nature/society context, as done in a product life-cycle assessment (LCA) in order to improve the environmental qualities of a given industrial product, see Figure 5.

![Diagram](image)

**Figure 5:** Systems thinking in the optimisation of a product's environmental qualities in an LCA methodology

An analysis of the functioning of a product and its effects on the environment leads to a situation as shown in Figure 5. The functioning of the product system results in extractions from, emissions to and other interventions in the environment. Processes occur in the environment (nature) as a result of which, for example, the emission of a given substance may cause some effect. Society considers these effects undesirable to a greater or lesser extent, e.g. because they affect human health, reduce agricultural production or reduce the intrinsic value of nature assigned to it by man. Whether such negative effects are acceptable or not will have to be evaluated as part of the normative system in society (culture). In case the effect is found not acceptable, institutions and instruments will have to be organised in order to avoid or minimise the problem in future.

**THE GENERAL APPROACH OF INDUSTRY AT PRESENT**

The present strong change in environmental strategy in leading industrial companies is more and more driven by new types of market pressure (customers and consumers) and new market-based and consensus- or covenant-oriented regulation policies from government. This change seems to be based on three key elements: 1) a growing recognition of systems thinking; 2) a growing availability (existence) of appropriate deregulation instruments; and 3) a growing concern for long-term environmental cost-benefit parameters and overall competitiveness in industrial companies.
Despite such changes in mentality and top management philosophy, industry in general changes slowly in terms of overall environmental performance. Why is this so? There are of course several important obstacles in such respect, but in general I think it is necessary to emphasise three main reasons:

- Many companies wish to benefit from an environmentally friendly image, but it is easier to speak of environmental performance externally than to truly implement such in a systematic way within the company's organisation at all levels.
- There are so many new approaches and methods to apply (in environmental friendly engineering design and operation, in sustainable product design and materials technology, in cleaner production technology management, etc.), and so many economic-, technical-, and marked-related risky considerations to take, that most companies are reluctant to adopt the new engineering design and management principles in a proactive way. The common attitude is wait and see, let others be the forerunners, until we know how to make those new concepts operational and successful.
- So far there are only week sanctions against companies who take the more reactive approach.

On the other hand, literature and international business and academic fora are full of case experiences demonstrating the overall success of how to combine environmental performance and business economy. This particularly relate to the more obvious cleaner production and product design improvement options, e.g. simple redesign and good house-keeping options. The preventative approach has proven its success on a more local scale (company internal) but the systems approach in a wider context (product-nature-society) has only just started its era of implementation. In order to speed up this process there is an urgent need for research and new methods in practice, as well as teaching and training programmes in universities and industry.

Such research, training and development of methodology could be carried out on the basis of several parallel strategies, from different starting points within and across different disciplines. A most fruitful strategy is to adopt the concept of "Industrial Ecology" (Frosh 1989, Ayres 1994, Ehrenfeld 1994, Marstrander 1994).

INDUSTRIAL ECOLOGY AS A DRIVING FORCE
Industrial Ecology (IE) was proposed to the U.S. National Academy of Sciences as a new term, or rather a new paradigm to environmental thinking in relation to industrial behaviour (Frosh 1989). The term was based on an analogy of industrial systems to natural ecological systems.

“The idea of an industrial ecology is based upon a straightforward analogy with natural ecological systems. In nature an ecological system operates through a web of connections in which organisms live and consume each other and each other's waste. The system has evolved so that the characteristics of communities of living organisms seem to be that nothing that contains available energy or useful material will be lost. There will evolve some organisms that will manage to make their living by dealing with any waste product that provides available energy or useful material. Ecologists talk of a food web: an interconnection of uses of both organisms and their wastes. In the industrial context we may think of this as being use of products and waste products. The system structure of a natural ecology and the structure of an industrial system, or an economic system, are extremely similar.”

This analogy has some obvious limitations, but may help illuminate useful directions in which industrial systems might be changed. The main point is that one should find ways to reuse the available energy and materials that otherwise will be lost as waste in industrial society. Present waste management policies, with a high priority to internal/external (closed-loop/open-loop) recycling activities, illustrate the relevance of the IE concept. However, IE sometimes seems to focus more on the needs and options within industry itself - it should be understood more as a concept covering both production and consumption stages in society. This will make it easier to include waste minimisation and source reduction options within production as natural components of IE.
During its first few years the IE concept was mainly interpreted as a concept for reuse and recycling of (potentially useful) waste energy and materials among different companies. We may classify this as options at the macroscale of industrial systems (Friedlander 1994) and some existing industrial ecosystem parks (Kalundborg in Denmark and Burnside in Nova Scotia, Canada) are good examples of such macroscale options. Options at the mesoscale (industrial facility level) and even at the microscale (unit processes level, e.g. a mass separator or a thermal reactor) were not considered equally relevant parts of IE at that time.

Today IE is understood more as a concept for how to apply a systems-based approach to environmental life-cycle oriented improvements at all scales of industrial systems. Rolf Marstrander correctly emphasises this point when he distinguishes the IE approach as being fundamentally different from Safety, Health and Environment (SHE) working approaches in industry (Marstrander 1995). He regards SHE as a process-oriented approach in search for improvements in the machine-man or in the machine-environment interface locally, while he regards IE as a systems-based approach in search for improvements in the product-environment and product-society interface globally in a life-cycle perspective. That way it is easy to recognise IE as a concept for dealing with improvements in the product-nature-society framework (Figure 2) with an extended focus area over the whole product-chain (Figure 4).

When it comes to the substance of IE as a systems-oriented and ecology-based concept, I would like to refer to Allan Johansson who recommends the following two conceptual possibilities (Johansson 1992):

1. We create, in a thermodynamic sense, a closed industrial system which exchanges only energy (no material) with nature, and all material flows are confined to the system. Product flows return and are reprocessed in a truly recyclable manner.
2. We develop an industrial production system totally compatible with nature, "soft" technologies using renewable raw materials and biodegradable products.

The concept proposed by Johansson should be regarded more an aiming point than an achievable state, and he claims that the conclusion in practice is to take advantage of the efficiency of our present production knowledge combined with bio-compatible products in order to, on the one hand, satisfy the enormous production volumes required and, on the other hand, avoid the insurmountable difficulties linked to the requirement of total recycling. Also the notion of good quality products with long lifetimes and worth maintenance by high-technology products deserves attention. Finally, the most direct method for changing the situation for better lies in changing consumer habits (choice of products) as well as the willingness to handle wastes in a more conscientious manner.

In such a perspective I claim that IE as an underlying concept should affect both technology management and engineering design and operation at all levels in industry, plus the handling of waste in society. I regard IE as the main driving principle to achieve an environmental life-cycle based engineering practice in society (Brattebø 1995b), see Figure 6. This "Environmental Life-Cycle Engineering" concept adds new and needed dimensions to the conventional fields of environmental engineering as it focuses both environmental concern and life-cycle thinking as integrated parts of engineering. It emphasises that we have to regard preventative environmental engineering as an area that should penetrate relevant fields of technology management and engineering design. In such a meaning environmental engineering is not a separate engineering discipline, however, it is an area that takes care of the "Gaia" values as an integrated part of other engineering disciplines. What does it help if the 5 percent of environmental engineers do their best to solve environmental problems if the rest 95 percent of engineers do not care? We have to avoid this phenomenon in future.

The environmental life-cycle engineering concept comprise four main components: Environmental life-cycle technology management; Sustainable product design; Cleaner production process design; and Technologies for recycling. The overall effort is directed both towards production stages and
consumption stages. It is important to minimise environmental impacts both by production and consumption efforts, and one should remember the interactions between culture, structure and technology in such efforts, particularly in the consumption stages. Today most efforts deal with the production stages, but in future more emphasis will have to be given to action towards a sustainable consumption. However, sustainable production and consumption should be considered elements along two directions of the one and only overall strategy, i.e. the development towards sustainable societies.

SOME URGENT CHALLENGES WITHIN THE IE CONCEPT
IE, as a way of thinking, is the driving principle to achieve improvements as mentioned above. It challenges us in enlarging the system borders in time and space, and it also challenges us to implement cyclic thinking in local technology development projects in all parts of society.

As shown in Figure 6, there is a loop from production to consumption and back to production again, which is kept together by the "Design for the Environment" (DiE) and "Design for Recycling" (DiR) principles. This loop indicates that we also have two other important elements of the overall concept, i.e. to avoid downstream environmental impacts related to the products, and to maximise materials and energy recycling. Recycling options should be used whenever possible, as a parallel strategy to waste reduction and pollution prevention options in the production stages, prior to strategies for a safe treatment and disposal of final wastes.

In such a perspective it is important to discuss what are the critical aspects of IE. It is obvious that IE will influence on both technology management (at society and business scale) and engineering design practices. Technology management should emphasis waste minimisation, the use of resources, system and equipment efficiency, ecocapacity limits, social needs and barriers, all in a long-term perspective.
Another obvious element of the IE concept is to regard the product (at various stages of the life-cycle) as the carrier of environmental qualities. This opens up for a new strategy where the development of an environmentally driven materials policy is the essential element at the macro-scale, as the product is also the carrier of materials. Such a materials policy could include the following efforts: phasing out dissipative uses of toxic materials; phasing out emissions of persistent, synthetic materials; reducing raw material extraction and consumption; ensuring sustainable use of renewable resources; optimising materials use with respect to product life; ensuring full life-cycle assessment to be applied to material choices; and optimising material flows with respect to natural material cycles (Geiser 1993, Jackson 1993). At the micro-scale the essential element of IE will be sustainable product design and development methodologies, and the main challenge here will be the operationability of the concept in daily-life design practice.

Due to the fact that product design and production process design and operation very often interact strongly, the IE concept will also have to influence the design and operation of manufacturing processes, at least in the long run. Good housekeeping measures within a production facility, which are normally carried out as the first part of a cleaner production project or a waste minimisation assessment, are not necessarily an IE activity. However, the change of design philosophies and more fundamental process redesign options may certainly be part of an IE initiative if such options are based on life-cycle thinking.

Last, waste management and recycling technologies have to be considered part of an IE strategy because such technologies must be used much more than before because of the need to close larger parts of the materials cycle in society. Recycling project very often demonstrate that it is not technology itself which is the most difficult part, but market options for recycled components or materials, various economic issues in the recycling systems, and sociological/psychological issues related to system acceptance and participation willingness by the end users (consumers in general).

Despite such clarifications, however, it is very important to think more thoroughly into other critical aspects of IE, both related to IE as an academic area and as a concept for use in industry in practise. I have come to the conclusion that we have the following two main challenges here:

- First, it is extremely important that IE as an academic area creates its own identity and (if possible) theoretical platform.
- Second, it is necessary to document ways to implement IE successfully in industry as well as to further develop suitable methodologies in order to make IE operational, particularly in design work.

How could this be done? From which standpoints and disciplines do we get the needed theoretical support to create such an identity and theoretical platform? What kind of professional or academic input do we have to look for? How do we create a sound cooperation across faculties, and towards industry? Does IE really need its own and separate identity, or will IE benefit from creating a joint identity with other fields of science and technology (the more integrative approach)? What type of operational challenges do we foresee? Which industrial branches and sectors do we need to work with? If case-orientation is chosen, what type of cases do we include?

All such questions are important in the future development of the IE concept. A major question is nevertheless to what extent LCA methodology (on the one side) and Ecology and/or Thermodynamics (on the other side) are central parts of the IE operational and theoretical basis. Figure 7 tries to illustrate this complex discussion, which will have to be dealt with carefully when developing and implementing IE in university teaching and research, and in training and development projects in industry.
The questions which are raised above, and which one may produce on the basis of Figure 7, should be taken seriously both in industry and academia. A successful further development of IE requires clarifications along both directions, as part of joint projects. Industrial projects should be linked to university knowledge in order to open time and space dimensions of the project objectives, and there would also be valuable new expertise available, particularly within other disciplines than engineering. On the other hand, universities will have to cooperate closely with industry as it is of vital importance that university teaching and research has a root in reality and reflects long-term versus short-term needs in a balanced way.

**LITERATURE**


