

Teaching Industrial Ecology to Graduate Students

Experiences at the Norwegian University of Science and Technology

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Summary

We reflect on our experiences in developing and teaching industrial ecology to interdisciplinary classes of M.Sc. and Ph.D. students. During a three-year period different ways of teaching a course in industrial ecology were tested. We conclude that an industrial ecology course has positive effects on the students' ability to acquire a holistic understanding of life-cycle environmental performance, a skill much in demand by industry. Such a course should be based on problem-oriented learning. We recommend the use of thematically-focused seminars with time for both lectures and workshops. We found that substantial participation by teachers from different disciplines and partners from industry and government is very effective. Such a course also facilitates a broader process of change within the university. Implementing industrial ecology in the university requires a joint effort and collaboration among various faculties and departments, where research activities, student projects, as well as regular student teaching and tutoring, must be complementary elements of a major interdisciplinary strategy. Such a strategy has been employed at the Norwegian University of Science and Technology (NTNU) since the first initiatives in this area were taken in 1993, and this has led to our present more comprehensive Industrial Ecology Programme (IndEcol).

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Introduction

The concept of industrial ecology (IE) is a promising new paradigm enabling industry and society to approach sustainability (Ehrenfeld 1995). The concept is also a challenge to the scientific community (NTVA 1999). Industrial ecology was introduced at the Norwegian University of Science and Technology (NTNU) in 1993 and has been developed over the last six years. Various activities, including teaching, research program initiatives, establishment of an LCA laboratory, and integration processes among the faculties and staff at NTNU have been initiated. This paper will by and large focus on the experiences in teaching industrial ecology to graduate and Ph.D. students from both technological and nontechnological faculties.¹ Our experience, however, is that the teaching has to be followed up with parallel activities to achieve the necessary progression in the studies. In this article, the development of the Industrial Ecology Programme at NTNU is presented so that the teaching in industrial ecology can be examined in a broader context.

NTNU—Its Mandate, Organization, and Former Environmental Teaching

NTNU, located in the city of Trondheim, was established on 1 January 1996. It replaced the University of Trondheim, which included the Norwegian Institute of Technology (NTH), the College of Arts and Science (AVH), and the distinguished Museum of Natural History and Archaeology (VM). NTNU comprises 11 faculties, 72 departments, and 18,500 students (10,100 taking various degree programs in natural sciences, social sciences, or humanities, and 8,400 in professional masters-level degree programs in engineering, architecture, and medicine).

Prior to the establishment of NTNU, the former NTH had offered course modules on environmental science and various aspects of environmental engineering since the early 1970s. During 1989–1992 four new environmental engineering study programs were

started as elective course programs in existing graduate-level programs. Since 1992 the environmental studies have changed slightly by focusing more on developing knowledge in systems and holistic thinking, and in the synthesis of fragmented in-depth knowledge. Furthermore, the life-cycle perspective and the focus on product orientation in environmental thinking have also been given more attention. The Industrial Ecology Programme at NTNU has followed and contributed to this line of development.

NTNU is a national center for technological education and research. However, the principles on which NTNU was established also stipulate that it is to be a university with social commitment and a comprehensive approach to the challenges it faces. Thus, NTNU is a university with broadly based expertise in the classical university disciplines such as the social sciences and the humanities. NTNU's mandate is consequently one that combines the responsibility universities have for reflection, critical thinking, and the quest for true knowledge, with the demands from professional education to find constructive solutions. An important instrument here is multidisciplinary and interdisciplinary cooperation.

As a response to NTNU's new mandate, focusing on interdisciplinary approaches in research and education, NTNU is now developing several so-called multi-faculty study programs. Such study programs are currently being started in "Energy and Environment" and "Industrial Ecology," as well as in nonenvironmental areas such as "Materials Technology" and "Project Management." These programs were started because of a need in society, and due to an interdisciplinary-oriented philosophy at the university which was also in line with the new mandate NTNU received in 1996.

Initiating Industrial Ecology at NTNU

The process of establishing NTNU as an interdisciplinary university proceeded parallel, but not necessarily in close connection, to the process of establishing industrial ecology at the university. Other internal and external interests were much more significant in the latter process.

The Industrial Initiative

The first initiative to implement industrial ecology at NTNU came in 1993 from the Norwegian company Hydro Aluminium, a subsidiary of Norsk Hydro. The company's experience with improvements in the field of Health, Environment, and Safety (HES) provided the main impetus for this. Norsk Hydro learned two major lessons:

1. HES can be fundamentally improved through organizational ownership, careful attention to detailed, clear links between defined goals, and through systematic follow-up of these same goals.
5. Improvements in HES are centered on the operation of plants and other equipment, but are not necessarily linked with improvements in the environmental performance of products over their life cycle.

In the late 1980s, Norwegian industry began to advance its environmental thinking, including new concepts with respect to products, markets, and environmentally friendly consumption. After extensive efforts to put together an internal education program, Hydro Aluminium reached the conclusion that it was difficult to meet the ambitions under item 2 above fully, when it came to the concept of industrial ecology—so that product life-cycle improvements could also be successfully achieved. Moreover, by looking into the studies offered at Norwegian universities in general, and at NTH in particular, the company found that students recruited from NTH had been given only fragmented education in topics related to industrial ecology. Consequently, Hydro Aluminium contacted the President at the University of Trondheim in 1993 and suggested that the university introduce a course in industrial ecology.

NTVA Seminars and International Contacts

This initiative was supported by the President, and faculty members who were active in interdisciplinary teaching and research in such fields as system engineering, environmental engineering, ecology, and product design. They quickly took an active part in the realization of

the intentions of the industrial initiative. With two seminars organized through the Norwegian Academy of Technological Sciences (NTVA 1994, 1996), we² expanded our understanding and prepared the basis for the present curriculum on industrial ecology at NTNU. Participants from companies, the public authorities, and international universities contributed significantly to this. The third NTVA seminar, which had a particular emphasis on the teaching aspects of industrial ecology, brought this process even further (NTVA 1999).

Of special importance in this preparatory phase was the ongoing close collaboration with the Massachusetts Institute of Technology, particularly with Dr. John Ehrenfeld in their Technology, Business, and Environment Program (TBE). MIT's experiences in teaching industrial ecology at the graduate level were indeed valuable when determining the underpinnings of the structure of the first pilot course in 1996/97. In our critical initial phase we also had fruitful collaboration with Georgia Tech, Delft University of Technology, and the Technical University of Denmark. As a result of these discussions, and the stimulating first seminar hosted by NTVA (1994), we decided soon after this seminar to establish a course and an adjunct professorship in industrial ecology at NTNU. We also understood that NTNU, by doing this, would be one of the very first universities to launch such a program in a systematic way. This was positively accepted both by the leaders of the university, a core group of faculty, and external partners in industry.

The NTNU Vision of Industrial Ecology

Through the industrial initiative, the NTVA seminars, the international contacts, and the establishment of NTNU in 1996, the development of industrial ecology at NTNU highlighted the complementary, and possibly new role of the university in society. Our understanding of this new role can be summarized in a new vision for NTNU with a view to industrial ecology:

- NTNU should engage in the formulation and implementation of longer-range strategies for sustainability in addition to the present strategies for improvement of the

environmental performance of products in industry.

- NTNU should create a program that will encourage teachers and students to strive for a dynamic, creative, and innovative approach to the problems of sustainability.
- NTNU should teach students a holistic and life-cycle oriented view of products, processes, and their interaction with the environment, implemented through project work that will give important contributions to the understanding and the realization of sustainable development on an individual, company, local, national, international, and global level.

This vision has been realized through some guiding principles for the development of industrial ecology at NTNU.

Guiding Principles

During the period 1993–1996, we received significant support from the President and from major Norwegian industrial companies. Early in 1996 a broadly recognized multifaculty Steering Committee was established to promote the development of industrial ecology at NTNU. Furthermore, a formal home was established in one of the faculties, coordinating resources from the faculty-neutral “Center for Environment and Development” were made available, and an adjunct professor from industry was appointed. This made it easier to gain acceptance for our ideas from faculties at NTNU. Establishing this organizational framework was one of the guiding principles for the development of industrial ecology at NTNU. Some others were :

- We had to start with one particular collective activity, a student course at the graduate level, to promote involvement across different NTNU disciplines. We intended to recruit students from both technological and nontechnological faculties.
- We wanted the studies to be case-oriented. Using life-cycle related teamwork projects, the students should work in teams and play different roles regarding a

common project target, contributing on the basis of their own academic specialization, and with due respect and understanding for the other special disciplines involved. The curriculum should be multidisciplinary. Of special importance was the need to include economics and social sciences in addition to the more obvious technical disciplines.

- We believed that long-term success could only be secured through research-based activity (post-doctoral research, doctorates, and Master of Science theses). With the concept of industrial ecology all research activities should theoretically and methodologically be developed in close collaboration with established disciplines.
- We understood that LCA methodology and access to an LCA laboratory with representative databases on different materials and manufacturing processes had to be developed. The LCA laboratory should be staffed in order to provide support to students, research staff, and industrial partners.
- As industrial ecology is a concept that strongly relates to industrial and governmental activities, we had to include these actors as partners. Without them, we would lose the bridge between theory and practice by not providing real-life input to case studies and Master of Science thesis research.
- We recommended that NTNU should actively seek to establish international alliances through seminars and through the exchange of ideas on teaching, curricula, and research. We also proposed to NTVA that the Academy could host a series of biannual seminars on key topics related to industrial ecology.

These were, and still are, some of the guiding principles at NTNU. As these principles emphasize, the initiation of parallel activities is very important. However, in the next section, we move from principles to practice, to our main activity during the first three years of regular industrial ecology studies at NTNU, the teaching of industrial ecology to graduate and Ph.D. students.

Empirical Description of Three Years of Teaching Industrial Ecology at NTNU

In this section we will thematically describe what has been taught during the courses and how this was undertaken (i.e., the administrative structure employed). We allowed ourselves a test period of three years, with different students every year. All the three years of pilot teaching in industrial ecology at NTNU are included here.

First Pilot Year (1996/97)

Eighteen students, some industrial representatives, and academic staff participated in the first pilot year course. With the exception of two social-science students, all students were from technological faculties on the graduate and Ph.D. level. The study load was one-fifth of a full-year study program.

Structure of the Course

The course was based on full-day seminars (50%) and project work (50%). One-third of the seminars was devoted to lectures, while the rest of the time was dedicated to interactive discussions through workshops, company presentations, and project work. During the intervals between the seminars the students worked on their projects.

The lectures were presented by academic staff from NTNU, by personnel from industrial companies, officials from the Norwegian Ministry of the Environment, and by other external interests from Norway, Denmark, and the USA. The industrial professor introduced each seminar to help the students more easily discover the coherence among the different seminars and lectures, and moreover, he commented throughout the seminars, helping the students to follow the governing idea of the course. Members of the Steering Committee also contributed significantly to the seminars.

The aim of the workshops was to stimulate activity and delve more thoroughly into the topics of the lectures by inviting interaction between participants and the lecturers in an

evolving and a maturing learning process. We organized the workshops basically according to three different models: i) Predetermined questions for the participants, ii) questions from the participants based on the lecture, and iii) discussion based on an article read prior to the session in question. The participants first worked in small groups, followed by a plenary discussion. We also invited selected professors from NTNU to contribute to these workshops, mainly because they were found to be potentially interested in industrial ecology, and thus, had a potential for further collaboration.

Finally, the company presentations were intended to link theoretical and “high-flying” lectures to practical examples from the real industrial world to encourage critical thinking and discussion among the participants. Seven companies, all collaborating with the Industrial Ecology Programme at NTNU, were invited to lecture on “Why is industrial ecology important for our company, and what have we done about it.” The companies were: Statoil (energy producer), Norsk Hydro and Norske Skog (materials producers), Kværner and ABB (producers of infrastructure and industrial equipment), Siemens (producer of consumer products), and Storebrand (financial services and insurance company). Moreover, the Secretary General of the Ministry of Environment presented the approach to and thinking about industrial ecology as seen from the perspective of the government and the authorities. The companies also helped to establish Master of Science thesis projects for the students.

Thematic Issues of the Course

The title of the course was “Industrial ecology and sustainable product design.” The thematic content, shown in figure 1 below, consisted of what we considered to be the main topics within industrial ecology at that moment.

As shown in figure 1, the seminars covered several disciplines working on environmental issues. Seminar 1, “Introduction to the course and industrial ecology” gave the students an overview of the history of industrial ecology at NTNU, and the intentions and ideas behind the

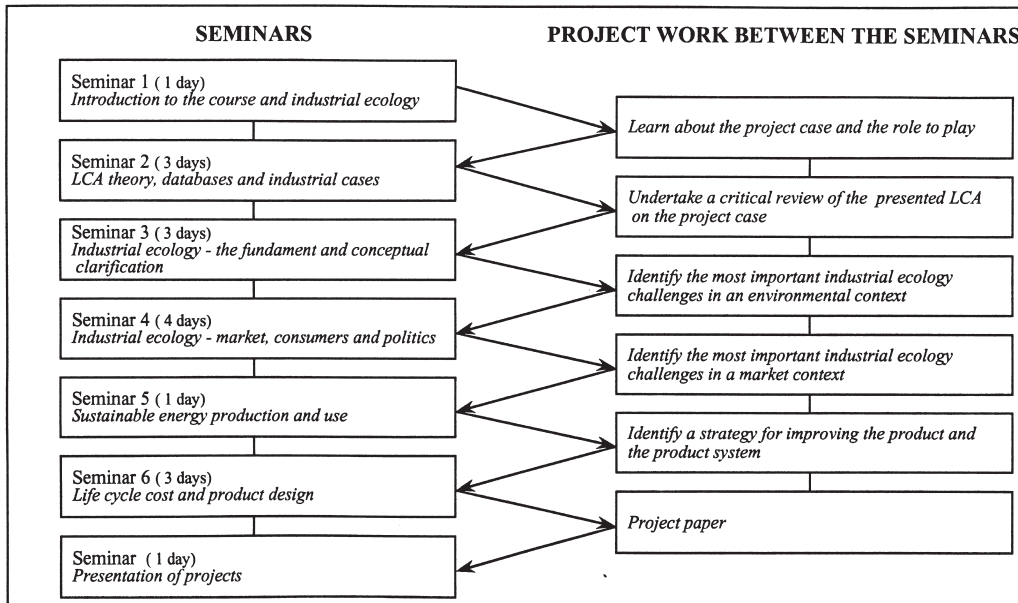


Figure 1 The structure and thematic content of the first pilot year 1996/97.

program in general and the course in particular. Industrial ecology as a concept was introduced by showing the transition from industrial focus on health, environment, and safety, which is process-oriented, to industrial ecology, which is systems-oriented. Environmental management systems, considered as one substantial element within industrial ecology, were also presented.

Seminar 2 gave the students an introduction to systems engineering and life-cycle thinking and methodology, highlighting the importance of defining the system and its boundaries, the interaction between the system and the surroundings, and the critical parts of an LCA. Furthermore, practical industrial case studies on LCA and systems engineering were discussed. Seminar 3, aiming at clarifying the conceptual underpinning of industrial ecology, introduced, on the one hand, thermodynamics and ecology as the natural-science basis for industrial ecology, and on the other hand, environmental sociology, philosophy, and anthropology as the social and human-science basis for industrial ecology.

Seminar 4, “Industrial Ecology–Market, Consumer and Politics” focused on other important nontechnological parts of industrial ecology. The roles of nonindustrial actors such as consumers and government authorities, and the

interaction between these and other actors, for example industry and NGOs, were stressed. An introduction to economy and its role in an industrialized market was also given. Seminar 5 focused on sustainable energy production and use, while the last seminar offered lectures in product design and life-cycle cost assessment.

The thematic content in the course can also be described by employing two dimensions within interdisciplinary teaching; i) qualitative versus quantitative aspects and ii) conceptual versus instrumental aspects. This is shown in figure 2.

Given that industrial ecology has emerged as a consequence of and a response to the notion of sustainable development, it is obviously easy to embrace too many topics in a course such as this. On the other hand, the systems-oriented basis of industrial ecology, and the “new” principles of industrial ecology call for a broad-minded and holistic approach. We deliberately tried to obtain a good balance between conceptual topics and practical implementation and methodology. We offered lectures which are classified along the ordinate (vertical) axis shown in figure 2. The distinction is drawn between i) the fundamental, conceptual, principal introductory and systems-oriented lectures, such as “Ecology as a model for industrial ecology” and “Irreversible

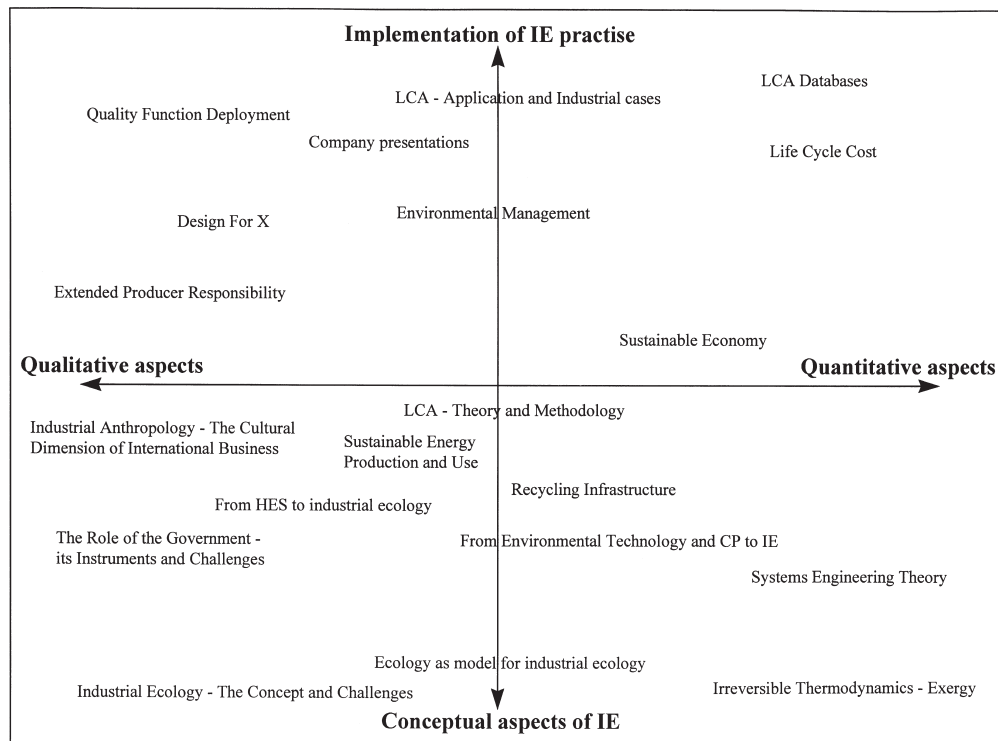


Figure 2 The interrelations of the various topics in the first pilot year course.

thermodynamics” and ii) the more practical lectures showing the implementation of the industrial ecology principles in a firm’s design process.

Another challenge in the designing of the course was to combine quantitative and qualitative aspects, as shown by the coordinate (horizontal) axis in figure 2. As we wanted to attract students from different faculties, it was important to make as many students as possible comfortable with the learning process. Even within the technical departments the background knowledge is quite different. We ended up with a program both embracing quantitative methodology and tools such as LCA and life-cycle costing (LCC), and more qualitative and descriptive methodologies such as Quality Function Deployment and Design for X. A third dimension in composing the seminar schedule was the relation between technological and nontechnological topics. As can be seen from figure 2 above, the qualitative aspects are very well represented, and many of these have a social-science profile.

The topics of the workshops were basically related to the lectures, but two of them are

worth mentioning because these encompassed the totality of industrial ecology: i) the role of different disciplines in industrial ecology and ii) industrial ecology—a critical review.

The syllabus this year was *Industrial Ecology* (Graedel and Allenby 1995) and *Environmental Assessment of Products* (Wenzel et al. 1996), as well as selected articles and lecture notes.³

Project Work

The design of the project work was given much consideration. The project work focused on an electronic programmable and intelligent control unit from Siemens to operate electric panel heaters. The unit can be programmed to switch the heater “on” or “off” in the course of a day and a week. With most Norwegian homes and offices being heated by electricity, the unit represents an economically interesting product for many of them. The task was to consider this unit in an industrial ecological context. The project covered i) energy consumption, ii) life-cycle analysis of the product involved, iii) the relation between the producer and the market (how the market will re-

act to differing environmental performance of products), and iv) the possibility of designing product or product system changes.

Figure 1 shows the proceedings of the project work and the seminars. To cover the different aspects of a complete industrial ecology system, including preferences expressed through the market, by regulatory bodies, producers, or suppliers, the students were divided into five groups, each of three to four students, with the following roles to “play”: producer, user, supplier, NGO, and authorities.

As seen in figure 1, the first part of the project work was to review critically a presented LCA on the unit. The functional unit was defined as “A living room of a particular size, two persons using it and with a specific comfort temperature when people are present.” This part was common for all the groups. In the next part, the groups were free to define the system boundaries based on their particular role. Would they, for instance, choose only electricity or also alternative energy forms? Would they choose to compare with alternative uses of electricity, for instance, compare heat pumps with the given product system? Would they include the production of electricity or limit themselves to the supply of electricity as such? The intention was that the students should choose and argue on the basis of their role and on the industrial ecological principles.

Second Pilot Year (1997/98)

The second year followed more or less the same route as the first year. The number of students was increased to 40, with 30 from technical departments and 10 from nontechnical departments.

The course was based on seminars structured as in the first year, however, with the key difference that we offered two courses running simultaneously. One course consisted of both seminars and project work and was therefore quite similar to the course offered the first year. The other course consisted of seminars only.

Academic staff from NTNU contributed more significantly to the lectures during the second year course. The companies still presented themselves and their thinking about the concept of industrial ecology, but this year they did this collectively in a one-day seminar near the end of the course.

Three major thematic changes were implemented the second year. First, more emphasis was put on economics. Second, industrial metabolism, particularly with emphasis on material and energy cycles, was presented to the students more extensively. Finally, technological change, innovation, and implementation were given more attention in the second year.

The students could choose between two different cases as their project work this year: i) the electronic-unit case employed the first year and ii) a case focusing on a Norwegian innovation, the electric vehicle “Think,” developed by Pivco and subsequently purchased by the Ford Motor Company. The objective of this case was to highlight the importance of material systems. The students had to carry out an LCA on this vehicle and suggest improvements in an industrial ecological context based on their particular roles. The relation between the car as the product and mobility as the function was significant. The same structure for the project work was more or less followed. A closer interaction, however, among the various roles the students played was encouraged, for instance by arranging consensus conferences.

The syllabus this year was more or less the same as the previous year, although more emphasis was put on selected articles.³

Third Pilot Year (1998/99)

The third year we had two separate courses; one basic course in the autumn (1998) and one advanced project course in the spring (1999). The former consisted of weekly lectures with weekly lecture-related exercises. The thematic content of this course was even more focused on systems approaches and understanding than the first two years, on eco-efficiency and on the implementation element of industrial ecology. Thirty-five students participated in this course, while eight students enrolled in the latter course. The latter course consisted of project work only. The students evaluated the eco-efficiency of beverage packaging in a specific product system. Both student groups, consisting of four students each, used LCA to examine and ascertain what a Norwegian brewery company could do to improve its environmental and eco-

conomic performance in relation to the life cycle of a selected beverage packaging product (glass and plastic bottles).

The syllabus in this year was based on selected articles only.

Discussion

Our experience so far is that the teaching activities have to be considered in concert with the general development of the program. Without teaching, the general development will suffer, and vice versa. The main reason for this is that our intentions and visions as stated in Section 3 are quite demanding. Below we will briefly discuss which organizational parameters have contributed significantly to both the teaching and the general development of the program.

Organizational Success Parameters

First, we achieved a valuable balance between top-down and bottom-up initiatives within NTNU. The top-down support from President and Senate at NTNU, whereby we were encouraged to continue the development of the program, was extremely valuable. The fact that our ideas perfectly corresponded with the ideas of NTNU made our efforts even more legitimate and paved the way for the faculty members to become involved in our initiatives. This may, however, also be viewed the other way around. *Because* of the bottom-up support from enthusiastic faculty members, mainly initiated through participation in the teaching activities, it was easier for the President and Senate to give their support. In sum, this mutual interaction has been of great importance. Furthermore, the multifaculty-based Steering Committee, the main catalyst for this development, had one foot in both organizational levels, with a substantial foothold in the faculties and with, in practice, direct access to the President. Moreover, the deep involvement from many very good students from various departments and faculties ensured that the program touched on all levels of the university.

Second, the role of the multidisciplinary and neutral Center of Environment and Development (SMU) as the program secretariat was invaluable. With available resources, personal

initiatives, enthusiasm, and their experience of bridging the gap between technology/natural sciences and social sciences/humanities in teaching, research, and student recruitment, SMU facilitated the realization of the program. We doubt that such a broad-based program could have been started without the initial role of an interdisciplinary body within the university.

Third, the high degree of involvement of industry in general and the establishment of the adjunct industrial professorship in industrial ecology in particular, were of great importance in the teaching, because students and staff were directly introduced to how the industrial ecology challenge was understood in different industrial companies and branches of industry. The strong industrial involvement also helped to neutralize some internal tension and competing interests between departments and faculties, as one understood that industry was really asking for a joint and long-term ambitious and coordinated effort at NTNU, across disciplines and faculty structure.

Fourth, the recent establishment of the Department of Product Design, with its emerging focus on life-cycle product design, and its support in being the home of a new LCA laboratory, was most helpful to the development of our program. Closely connected to this, many activities started up in parallel with the teaching activities, for instance success in funding new Ph.D. projects, and the formulation of a new long-term research program for competence development in the Norwegian manufacturing industry—"Productivity 2005" or "P2005"—where "Industrial Ecology" was proposed to become one of three key areas in addition to "Integrated Product Development" and "Enterprises in Networks."

Finally, financial support, basically from the Norwegian Research Council, but also from industry, the Nordic Industrial Fund, and NTNU made the transition from visions to practice easier.

Three Years of Teaching Industrial Ecology

All these organizational arguments affected the teaching activity in our program. Some success parameters and danger signals from these three pilot years will be discussed below.

We believe that the use of seminars as the teaching form has been successful in our courses.

Although some students complained that such seminars posed scheduling problems with parallel lectures in other courses at NTNU, provided too much information in a short period of time, and presented it in an unfamiliar and demanding seminar teaching form, the overall impression was that the seminars were well suited for these courses. Seminars provide concentrated learning and encourage interaction between students and lecturers. Feedback from the students emphasized the need for and the effectiveness of the seminar form.

Furthermore, in the first and second pilot year enough time was allocated to discussions and workshops, and the students were very satisfied with this opportunity to argue and reflect, which is not at all, at least up to now, common in regular teaching at NTNU. The fact that several members of the Steering Committee, other faculty members, and industrial and governmental representatives were participating in the discussions provided valuable input for the students in their evolving process of learning. In particular, the presence of companies and representatives from the authorities willing to be confronted with opinions from the students in an open, but also "heated" discussion, was successful. However, the time for workshops, discussions, and reflection was reduced in the third pilot course, and this apparently had a negative effect on the quality of the course. Nevertheless, the grades from this third pilot course were very good, and a reason for this is that much time was given to repetition of basic principles of industrial ecology. In this sense, the students were trained for the exam, which does not necessarily mean that the understanding of industrial ecology had increased. There will always be a trade-off between focusing on a few elements only and focusing more broadly, and these two didactic strategies must be carefully balanced in order not to suboptimize or to take too general an approach.

Although the majority of the students came from the engineering sector at the university, the students from the social sciences contributed significantly in the discussions and the project work. Our experience is that students from process-oriented engineering studies satisfactorily adopted the system-orientation in industrial ecology, but that students from the social sci-

ences did this more easily. We still, however, have to make the course more attractive for the social-science students.

The project work has contributed significantly to the learning process. Here the students need to delve more deeply into the problems in the project and to combine theoretical and general approaches with practical aspects. Feedback from students during all three years emphasizes this point. The structure of the projects, allowing the students to work in teams with different roles focusing on the same problem, increased the interdisciplinary training and learning. Playing different roles also allowed students to visualize the real world where different actors and interests make the decision-making process varied and difficult. Students have, however, complained about a lack of information and a lack of clear targets in the beginning of the project work. This is a problem that may easily arise when trying to grasp a broad interdisciplinary issue. But the students also said that these initial problems forced them to reflect, which definitely was advantageous in a course with a process of learning such as the case is here.

The combination of seminars and project work was very productive and guaranteed continuity throughout the course. This was particularly obvious in the second pilot year as the students not doing projects profited less from and contributed less to the seminars. During the third year exercises were introduced. These were very useful, according to the students. Projects and exercises made the students more active and encouraged them to think critically.

Teaching industrial ecology is indeed a pedagogical challenge. This has become particularly obvious at NTNU where i) the course is interdisciplinary, ii) there are students with different academic backgrounds, iii) a well-established theory within industrial ecology does not yet exist, iv) it is a conceptual and not a methodological course, and v) there are different lecturers. Furthermore, it is obvious that learning industrial ecology is a demanding process because the concept of industrial ecology encompasses so many different perspectives and methodologies. These arguments underline two important aspects: first, the need for discussions among students, through project work, workshops and

exercises, and second, the need to *synthesize* the different aspects presented during the course. To some extent this has to be done by the academic staff. In all three pilot years some students complained about not having the framework or vocabulary to grasp the new knowledge. The introduction of a new subject requires clarity as to the new content of this subject compared to previous subjects, and the relations between the various lectures. The danger of fragmentation into separate disciplines is obvious. It is important to always remain aware of this, and to a certain extent, particularly because of the experienced industrial adjunct professor and the members of the Steering Committee, we succeeded in meeting this challenge.

Perhaps the major challenge in designing a course in industrial ecology is to decide the thematic content. What do we want the students to learn? Should all students learn about the same industrial ecology topics, or should the studies be adjusted to their background? Are we educating generalists or specialists? What are the most important aspects of industrial ecology, and what are the new elements that industrial ecology introduces? These are important questions to ask, and we recommend that the designers of similar courses keep such questions in mind. During the three pilot years the courses became more systems-oriented, more focused on the broad perspectives and on the connections between the different topics presented. We emphasized the need for technological, economic, and social-science approaches to the concept. Insight into and understanding of the totality (what are the driving forces and the interests of actors) were prioritized rather than methodology and technological details. We found it more important to educate the students in understanding the principles of an LCA, rather than detailed knowledge in actually carrying out an LCA. In this context, the project work acted as a counterweight because the project necessarily demanded a sharper focus. To combine the broad perspective of the lectures with the narrower focus of the project seemed to be a productive combination.

In all three years there has been a lack of appropriate teaching material. It was all too easy to inundate the students with too much material without any clear distinction between core syllabus

literature and supporting reading material. Hence, the development of proper teaching materials must be prioritized. The industrial ecology curriculum is under continuous development, and the Ph.D. students and research projects will most likely contribute to this in the coming years. Also in this sense, these pilot years have been a learning process for us as well as for the students.

Finally a minor, but still important challenge is the difficulty in grading students from different faculties. At least at NTNU, the practice varies from faculty to faculty and particularly so between the engineering faculties and the social-science faculties.

Future Priorities in the Industrial Ecology Programme at NTNU

Three years of pilot experiences of teaching industrial ecology, and of experiences from parallel activities have given us an excellent basis for developing industrial ecology further so that NTNU will be able to realize its intentions and visions in this important area.

The major element in the future educational priorities is the establishment of our Industrial Ecology Study Programme. Students from four faculties, both from technological and nontechnological disciplines, are invited to attend this three-year program that started in the fall of 1999. Students may enter the program after two years at the university. Formally they will still be registered students of their earlier faculties, and successful students will, after another three years of studying, receive a master's degree in given disciplines of engineering or social sciences, according to where they are studying other courses. For example, a student in Mechanical Engineering will receive a master's-level degree in Mechanical Engineering, but with a certificate showing that he or she has selected industrial ecology as the main area of study as part of this degree. Consequently, students' degrees will be strongly influenced by courses and projects organized through the interdisciplinary Industrial Ecology Study Program, equal to 50–70 percent of the total study load during their last three years of studying.

The basic idea behind this new program is to provide a better opportunity for students to coop-

erate and learn across the traditional structure of faculties and disciplines, aiming at the development of better knowledge on strategies for sustainability. This learning will be based on a systems orientation and a common set of perspectives and methodologies, as well as on insight into the thinking of different disciplines and respect for other students' background. The Industrial Ecology Study Programme will focus on i) management and changing processes, ii) resources, life cycles, and recovery, iii) eco-efficient and eco-effective products and infrastructure, iv) energy consumption, and v) interactions between product systems and the environment. The aim is to educate students in their original background disciplines, but with the addition of specialization in industrial ecology. This is based on the assumption that specialists who employ broader perspectives on environmental challenges are needed, and that these students will complement the traditional specialized students within each discipline. Our aim is that the students develop good skills in examining complex environmental problems in a life-cycle perspective, skills in systems analysis and synthesis, as well as skills in assessing the economic efficiency and environmental effectiveness of product and loop closing systems.

A great effort will be made to recruit good and motivated students from the involved faculties to the Industrial Ecology Study Programme. There should be a balanced proportion between the industrial ecology part and the "original" part of their studies.

One of our fundamental ideas is that industrial ecology should be integrated into every field and discipline at the university. Industrial ecology loses its legitimacy and its intentions if it aims at becoming its own field. One strategy for avoiding "standing alone" and encouraging integration is to *introduce* industrial ecology to all students at the university in their first or second undergraduate year. Communicating methodological approaches and ways of thinking in industrial ecology at this stage of education appears to be a beneficial approach. This strategy, however, may be difficult to implement in practice. Nonetheless, at NTNU we succeeded in including some industrial ecology articles, lec-

tures, and project assignments, as part of an introductory course that *all* new students at NTNU had to take during their first or second year at the university.

Equally important as educating students is the recruitment of professors and academic staff at different faculties to provide the quality education needed within industrial ecology. As industrial ecology is a broad and new perspective, it is a challenge to "educate" professors, and hence to obtain a beneficial interaction between students and academic staff, among the academic staff members themselves, and between education and research within industrial ecology. All faculty members will be offered an introductory course in industrial ecology where they can discuss how their own specialty field is related to industrial ecology. Furthermore, we have initiated an Industrial Ecology Forum in which academic staff and doctoral students/postdoctoral researchers can find a place for dialogue and development of industrial ecology. The Industrial Ecology Forum will include seminars and joint projects highlighting development of expertise and the need for cooperation among academic staff members with different backgrounds. The Industrial Ecology Forum will also serve as the arena for creativity and innovation related to long-range industrial and political strategies for sustainability, and thus constitute the professional competence of the program.

These internal activities at NTNU are of the greatest importance. In both studies and research, however, it is essential to cultivate the international academic network with the purpose of creating high-quality course material, joint research programs, and exchange of students, postdoctorate researchers, and faculty members. Furthermore, it is also important to ensure a strong interaction with industry and governmental authorities by offering continuous education courses in industrial ecology, and by bringing company management, industry specialists, and governmental authorities into the teaching, workshop, and reflection activities.

An LCA laboratory has been established at NTNU in conjunction with a Nordic LCA network, and it is to serve as a reference laboratory

for Norwegian users. An adjunct professor is now being appointed to chair this laboratory. Finally, a number of Ph.D. students and other research projects are also supporting the efforts to establish the comprehensive Industrial Ecology Study Programme.

Concluding Remarks

Introducing a course in industrial ecology at NTNU has been a significant challenge to the staff and the system at our university, requiring many discussions of educational policy and of practical details. In general this has been a process met with joy and enthusiasm at all levels, and with strong external support, suggesting conclusions along two lines.

First, regarding the overall effect of an industrial ecology course at our university, we have found that implementing such a course is an important tool in order to realize two major objectives discussed in Section 3:

- The course has helped us to recruit candidates with a more holistic understanding of the life-cycle environmental performance of product systems to industry, which Norsk Hydro maintained was a critical objective.
- Such a course has facilitated a process of change within the university, involving new types of policy discussions and efforts beyond teaching, in a large number of departments, recognizing the benefits of interdisciplinary activities and stronger and broader industrial collaboration. We believe that this may help the university take a more active role in society in relation to these matters.

Second, we have tested and evaluated various ways of designing and delivering such a course, and have arrived at the following three main conclusions:

- The issues related to the broad concept of industrial ecology were best transferred to students as a problem-based learning process, combining lecture seminars and projects including industrial cases.

- One to three days of lecture seminars should be preferred to regular lectures during the week. The seminars should have a thematic focus, but with interdisciplinary contributions, and with sufficient time for deeper discussions and reflection, for example using workshops as part of the seminars.
- The seminars should have a strong presence of experts from different disciplines, as well as partners from industry and government so that problems can be viewed from different perspectives. This would help students develop more holistic thinking and gain an understanding of the tension among different disciplines and between theory and practice.

The measures proposed in these three conclusions may be difficult to implement in practice, due to costs, lack of resources, formalities, and so on. NTNU is only in the initial phase of fulfilling these conclusions. To overcome these challenges, however, we encourage the university to discuss some ambitious targets that it would like to work towards in the design of future courses. By doing this we believe that the university will make major advances into the process of change that is explained in the first two concluding points above. The overall objectives should, after all, involve a new role for the university in close collaboration with industry, focusing on holistic thinking and expertise that will meet long-term needs in society.

Notes

1. In many European universities such as NTNU, the term “faculty” refers to groups of academic departments. In the U.S., the equivalent term is often “college” or “division,” whereas “faculty” is more frequently used in that country to refer to individual professors and related academic staff.
2. Throughout this article, “we” refers to both those at NTNU involved in developing the industrial ecology program. It includes not only the four authors as active participants in this process but also a variety of colleagues throughout NTNU.
3. For more detailed information on the syllabus, see the *Journal of Industrial Ecology* web page on education and industrial ecology: <http://mitpress.mit.edu/JIE>.

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