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Evolution of an Interdisciplinary Course in Sustainability and Design for Environment*

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A course in 'Sustainability and Design for Environment' has engaged engineering, science, architecture, forestry, business administration, law and public policy students at the University of Washington since 1998. The course is divided into two distinct phases. Phase 1 constructs a Design for Environment (DFE) knowledge base in each individual student through lecture and homework assignments. Topics have evolved to include interactions between technology and the environment, design and other types of decision making, energy efficiency, environmental management for industrial processes, materials selection in product design, product delivery and use, product design for recovery and disassembly, environmental and cost metrics and implementation issues. Phase 2 further develops DFE knowledge through an interdisciplinary team project. Evolution of the team project has taken students from the development of a business plan, a streamlined 'Life Cycle Assessment', or disassembly process design for a company that will collect, refurbish, disassemble and recover postconsumer electronic materials to the development of a rating system for a product, process or activity of their choice based on, for example, the LEED Green Building Rating System, the US Environmental Protection Agency's Energy Star programme, or the US Department of Energy's Energy Guide programme. The five-fold growth in enrolment in the class that has occurred since its inception mirrors the growth in the number of environmentally focused courses and degree programmes on the campus. Co-listing the course in different units allows more students to use the course towards their degree and should ensure a continuing interdisciplinary mix of students.

Keywords: design for environment; interdisciplinary pedagogy; sustainability; team projects

INTRODUCTION

SUSTAINABILITY DESCRIBES THE INDUSTRIAL DEVELOPMENT and supporting technologies that meet the needs of the present while sustaining the qualities of society and the environment, so that future generations may meet their own needs. Within the context of engineering education, sustainability can be considered an aspect of professional ethics because existing and emerging technologies dictate economic, environmental and societal impact on local and global scales. Those individuals who engineer these technologies should be taught to understand and take responsibility for their consequences. Furthermore, because engineering is only one among the many disciplines that drive technological implementation, interdisciplinary learning experiences that engage disciplines beyond engineering will encourage professional practice.

Related engineering efforts that incorporate the consideration of sustainability into technology development and design include Design for Environment (DFE) [1–4]. DFE promotes resource conservation, pollution prevention and extended product responsibility within concurrent engineering design. Trends include industrial environmental management standards, life cycle design and business partnerships, product takeback and environmental declarations (certification systems, annual environmental reports, ecolabels, etc.).

Sustainability and DFE (ME415/CEE495/ENVIR415) have been taught as an elective course to engineering, science, architecture, forestry, business administration, law and public policy students at the University of Washington (UW) since 1998. The course pedagogy condenses within a 10-week quarter what Biggs [5] calls the constructive alignment of activities and subjects. Specifically, the course is divided into two distinct phases: phase 1 constructs a DFE knowledge base in each individual student and phase 2 further develops DFE knowledge through the application in an interdisciplinary team project. The first phase of the course begins with discussion-rich lectures led by the author/instructor, guest speakers from industry and local government and individual homework assignments, which are designed to provide each student with a foundation of the concepts of sustainability and DFE. During the second phase, lectures and discussion continue and students bring their DFE knowledge and the skills

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of their individual disciplines to a team project. Although this basic pedagogical structure has remained the same since 1998, the course has evolved in enrolment, content and learning activities, as follows.

UW COURSE IN DESIGN FOR ENVIRONMENT

Since its inception, the objective of the UW DFE course has been to explore the principles of sustainability, pollution prevention, life cycle assessment, total cost assessment and design for product disassembly and recovery. Given these topics, students spend the quarter examining the practice of, opportunities for, and the role of, engineering and other disciplines in DFE. A very detailed class website (see http://faculty.washington.edu/cooperjs/ME415) is used for course administration, including the provision of down-loadable course lectures and links to additional reading material and for posting homework assignments and the project description. Additional course resources include the textbook supplemented by archival and grey literature, DFE guidebooks and software tools and guest interdisciplinary speakers. The textbook, Graedel and Allenby's *Design for Environment* [4], has been used since 1998 and was originally chosen because of its breadth of content and organization. Table 1 presents the course topics as they relate to the textbook. Notable additional topics and resources beyond Graedel and Allenby's textbook in Table 1 have been added to emphasize:

- How environmental research can be used to inform decision making.
- The inherent subjectivity of environmental decision making.
- How different stakeholders (ultimately the students themselves) throughout the technology life cycle can be the impetus for change.

These additions have also helped keep the course up to date.

The course topics listed in Table 1 are presented throughout the 10-week quarter through discussion-rich lectures by the author who has professional experience in several of the disciplines represented by the students. Specifically, the author, with degrees in both mechanical and environmental engineering, has worked as a mechanical engineer (a facilities coordinator, manufacturing supervisor, quality engineer and design engineer), as an environmental engineer (as a DFE consultant) and in support of pollution prevention policy analysis (for the US Congressional Office of Technology Assessment). During lectures, the author uses these real-world professional experiences to illustrate important course concepts related to the interactions of technology and the environment from the perspective of a variety of disciplines and, perhaps more importantly, to influence students to relay their own experiences from their own perspective. This

Table 1. Supplementation of the DFE class textbook

Topics	Notable textbook supplementation
Interactions between technology and the environment (Textbook Chapter 1)	Economic, environmental and social metrics used in assessing sustainable development [6, 7]
Design and other types of decision making (Textbook Chapter 2)	Interdisciplinary environmental decision making [8] Use of decision matrices [9, 10] and subjectivity in weighting factors and scope
Energy efficiency (Textbook Chapter 3)	Conflicting environmental science, as in the use of global warming potentials [11]
Industrial process residues: composition, pollution prevention and environmental management (Textbook Chapter 4)	Environmental laws and regulations [12] Industrial facility auditing [13, 14]
Materials selection (Textbook Chapter 5)	Meaning of, availability of and use of impact equivalency factors [15, 16] MSDSs: types of information, interpretation and missing information
Product delivery and use (Textbook Chapters 6, 7)	Recyclable, recycled and biodegradable packaging (class demonstration) Emissions and impacts of transportation systems [17–19]
Design for recovery and disassembly (Textbook Chapter 8)	Electronics recycling policy and infrastructure development [20, 21], product disassembly and recycling laboratory
DFE and environmental cost assessments of products and processes (Textbook Chapter 9)	Detailed versus streamlined assessments [22, 23]
Implementing DFE in the corporation (Textbook Chapter 10)	Natural Step, the CERES Network and corporate case studies [24–27, for example]

method is employed on the very first day of class and throughout the quarter.

Next, the course topic Design and Other Types of Decision Making is used to foster discussions of subjectivity. Specifically, decision matrices, as described by Dieter and Saaty [8, 9], are used to illustrate trade-offs given multiple, conflicting metrics (e.g. cost versus global warming potential versus workplace safety) that might be used for technology evaluation. This course also provides a point at which research and professional practice can be contrasted in the classroom, whereas technology or environmental research etc. might simply present multiple, conflicting metrics as results. Professional practice (engineering design, business management, policy development) must often draw a single conclusion or provide a single eco-indicator that includes a subjective prioritization of environmental impacts. Thus, the class explores the concept that 'whereas research can be used (in class homework and projects and in practice) to inform decision making, a decision is made by choosing between or weighting metrics'. The discussion allows students to explore their own opinions and biases and those of their peers and the instructor. The lesson continues throughout the quarter and is applied to the remaining topics in Table 1, with the requirement that homework and project documentation emphasize transparency of the decision process such that when trade-offs are made, they are explained and the sensitivity of decisions to matrix weighting factors are tested.

Guest speakers are also an important part of the DFE class. All speakers have used a presentation structure that facilitates discussion between the students and the presenter similar to that of the author. Select years have included an industrial environmental management systems consultant, a non-profit environmental research scientist leading local assessment projects, Boeing engineers leading the company DFE programmes, King County recycling coordinators and the City of Seattle Mayor's Office. In particular, Lisa Sepanski, Director of the King County Computer Recycling Project and Richard Gelb of the City of Seattle Mayor's Office of Sustainability and the Environment have provided students not only with stories of the development of the local and very successful public–private sector electronics recycling and Leadership in Energy and Environmental Design (LEED) buildings programmes, but they also have reiterated the interdisciplinary aspects and importance of environmental considerations at the technology–policy interface.

Class assignments have included individual homework assignments, a team product disassembly laboratory and a team project. Homework spans all course topics, includes both qualitative and quantitative analyses and focuses on the recognition of how trade-offs, uncertainty, and how data gaps or an excess of information, can dominate decision making. Both closed-ended and open-ended questions are used. Closed-ended problems ask students to use the qualitative and quantitative methods presented and discussed in class in the comparison of the environmental aspects of companies within a region or industry or of technology design. Open-ended problems pose a question, suggesting some archival literature and websites that can be used to inform possible solutions and ask the students to create a prioritized set of recommendations. Example formats for recommendations have included the development of facility environmental management plans and the specifications for a product- or industry-specific Pollution Prevention Star label similar to the Energy Star.

Individual homework assignments act as a prelude to the second phase of the class and interdisciplinary team activities. They are intended to provide common language and assessment methods, which when combined with disciplinary-specific skills and methods facilitate a team project. Students are expected to supplement the resources and tools used in homework assignments in their preparation of a project proposal, interim and final report and an oral presentation of results. Both the proposal and interim project report become part of the final report and allow the author/instructor and teaching assistant to help identify relevant resources and ultimately work with each team on their project.

Projects have focused on recycling process automation, recycling business plan development and design for life cycle improvement. As described in greater detail below, the project topics have evolved considerably as the DFE class has evolved and are based on student assessments at the conclusion of each offering.

COURSE ASSESSMENT

The UW has a formal, anonymous instructional assessment system administered at the end of each course. The student evaluation includes two components: (i) a scanable evaluation form in which students rate general and specific aspects of the class from excellent to very poor, or much higher to much lower, and provide data related to their effort in the class; and (ii) a form allowing students to provide written evaluations. Based on the former, students in the DFE class spend, on average, between 2.2 and 3.3 hours for each of the three course credits per week including classes, reading, reviewing notes and other course work, which is similar to the UW average. They note that, relative to other college classes, the course effort and involvement effort (assignments, attendance, etc.) to achieve the expected grade and the intellectual challenge are both above average.

Students have given scores of excellent to very good for the course as a whole. This included course content, encouragement given students to express themselves, instructor-related scores (e.g.

enthusiasm, interest in student learning, contribution, explanations, effectiveness, students confidence in instructor knowledge), quality of questions posed and the use of examples, illustrations and alternative explanations. Students have given scores of very good to good for administrative aspects (e.g. grading techniques, availability of extra help, use of class time), clarity of student requirements, course organization, relevance and usefulness for the course content and reasonableness of assignments.

Student written evaluations have revealed the use of lectures, homework, the team project and examinations provide students with both an understanding of the state of the art in DFE in the public and private sectors and with experience in using analysis tools. Students appreciate the availability of lecture notes on the class website and the use of discussion as part of all lectures (for some engineering students, discussion during lecture is noted as a unique experience). Finally, students frequently note the use of final, open-ended assignments and lectures (e.g. the team project and final examination) as a condensed demonstration of concepts as a strength of the course.

Similarly, student written evaluations have revealed several areas for improvement. Specifically, the 1998 class suggested the addition of a laboratory experience to help students better understand product disassembly and recycling, which was subsequently implemented in 2000. Also, although the mid-term examination reiterated concepts and methods taught during the first part of the quarter, the time might be better used, given only 10 weeks in a quarter. In contrast, students suggested the final examination, which provided an open-ended product redesign experience intended to draw on all knowledge gained in the course, might be better suited as a final homework problem so that individual students can receive feedback on their approach.

COURSE EVOLUTION

Given the student suggestions for course improvement and enrolment changes, the UW DFE course has evolved since its inception. Specifically, enrolment has grown from 10 students in 1998 to more than 50 students in 2005. This growth can, in part, be attributed to co-listing the course in three units (mechanical and civil/environmental engineering and in the programme on the environment), each with substantial environmentally focused curricula. In fact, although the majority of students have been engineering students, because the Program on the Environment is a University-wide programme, students taking the DFE class have represented the sciences, architecture, forestry, business administration, law and public policy.

However, a review of student performance in the first 4 years that the DFE class was offered revealed a discipline-independent difference in the performance of students prior to their senior year. This difference was characterised by a lower than average course grade, primarily based on examination performance and incomplete engagement in team projects as indicated by team role documentation. As a result, and given the fact that many students interested in taking the 2002–2004 classes were deemed above the enrolment limit, in the same year that the class was co-listed in engineering and the Program on the Environment, enrolment was limited to seniors and graduate students.

The next areas of course evolution were changes in the syllabus and learning activities, as depicted in Fig. 1 in which areas of substantial change are shown as shaded boxes. First, in-class examinations have been eliminated, in part as a response to student input and in part because homework assignments were deemed adequate to ensure individual learning. Next, because students noted 'condensed demonstrations of concepts' as a course strength, a case-study-based format has been integrated into the syllabus during the second phase of the course. To institute this change, phase 1 lectures and discussions were streamlined and conclude with a presentation of categories of sustainability metrics, data sources and methods for metric estimation, and the presumption of a comprehensive life cycle scope (considering materials acquisition, processing and technology manufacture, use, maintenance and retirement).

Additional DFE knowledge that was not included in phase 1 is introduced as part of the case presentations. For example, the electronics design case study includes discussions of global public policy differences and methods for assessing the roles of product configuration and infrastructure in recycling. The automotive case study emphasises analytical model integration in the use stage of the life cycle, and compares detailed and streamlined life cycle assessments for systems in which one single stage dominates the impact. Finally, the buildings case study presents the LEED Green Building Rating System as a mechanism that encouraged environmental considerations by a variety of stakeholders and illustrates how such as system might not in reality lead to environmental improvements when impacts of life cycles are considered (see [28–30]). Students in the 2005 DFE class liked the case study format; they noted the value of demonstrating the selection of metrics, tools and scope of analysis scope when identifying industry-specific issues.

The class team project has also undergone substantial changes. Prior to 2005, the DFE class project started with an in-class product disassembly laboratory in which students disassembled a product, rated how difficult the product was to disassemble based on the method described by Kroll et al. [31] and quantified the type and quantity of materials that could be recovered. The laboratory experience was suggested by the

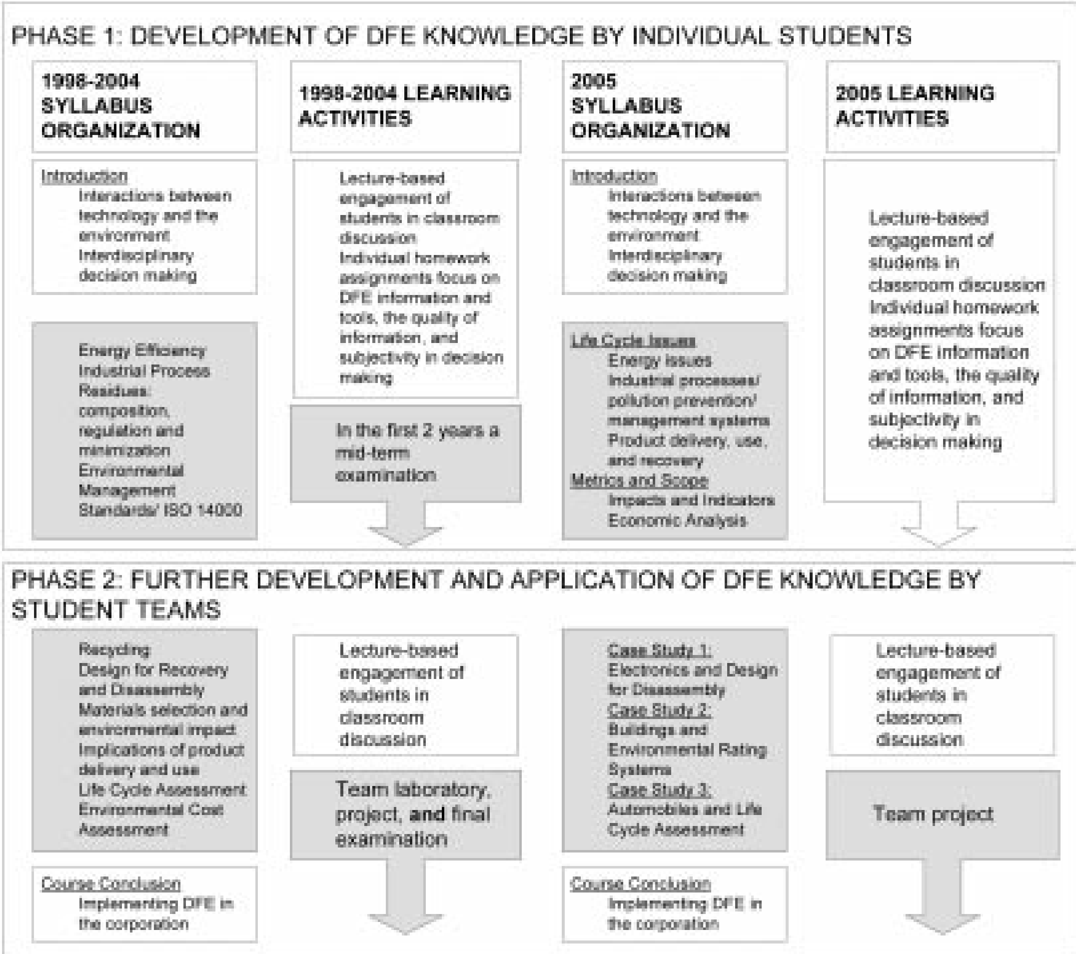

Fig. 1. Evolution of the DFE course syllabus and learning activities.

1998 class and cited as a class highlight in subsequent years.

The disassembly laboratory then became the basis for an interdisciplinary project in which students could either:

- Develop a business plan for a company that will collect, refurbish, disassemble and recover materials from their product in the Seattle area.
- Develop and analyse a life cycle inventory for their product (essentially to perform a streamlined life cycle assessment as described in the course textbook).
- Design a disassembly process for their product for use in the Seattle area. The original theme for the laboratory and project was computers: i.e. how e-waste is a global problem and how computers can be designed to reduce the life cycle impact.

In 2001, the computer disassembly laboratory experience became less enlightening for the students. The computers were very easy to disassemble, most or all plastic parts were marked for recycling, etc. As a result, in subsequent years the laboratory and project themes included printers and student-selected products such as cell phones, bicycles, toys in an effort to identify opportunities for improvement not unlike those seen in computer manufacturing. For some products, an extension in the region considered by the students was needed to reach reasonable economies of scale for business plans and recycling systems, adding new dimensions to project research.

The year 2005 also saw substantial changes in both enrolment and the class project. First, the enrolment cap was raised, because so many students had been turned away in the past. Second, the class project was substantially changed to accommodate the larger number of students. The new project had student teams who developed an environmental rating system for a product, process or activity of their choice (although eliminating new construction and building renovation and desktop computers) based on, for example, the LEED Green Building Rating System, the US Environmental Protection Agency's Energy Star programme or the US Department of Energy's Energy Guide programme. The project was initiated through a tour of LEED Seattle City government buildings in place of the product disassembly laboratory. In retrospect, although this change accommodated the larger class size, class discussions of the implications of product design on materials recovery was found to be less effective than the product disassembly laboratory.

The 2005 student projects included rating systems for bicycles, outdoor clothing, roads, surfboards, wind turbines, photovoltaic systems and residential landscapes. The quality of the student projects exceeded expectations. Students noted, in particular, the value of being able to compare typical design alternatives with those marketed as environmental options.

CONCLUSIONS

The five-fold growth in enrolment in the DFE class since its inception mirrors the growth in the number of environmentally focused courses and degree programmes on the UW campus. Co-listing the course in different units allows more students to use the course towards their degree and should ensure a continuing interdisciplinary mix of students. In 2005, both the chemical and electrical engineering departments have shown an interest in co-listing the class.

As such, it is expected that enrolment will continue to grow and, given this and continuing change in the field of DFE, the course will continue to evolve. Plans for 2006 include bringing back the design for a disassembly laboratory as a way to regain the hands-on experience lost in 2005. Further, an extensive course benchmarking activity is planned as part of the course re-design effort in order to benefit from experiences of other universities.

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