Graduate Courses in Sustainable Engineering: The Carnegie Mellon Experience

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Introduction

More than 300 definitions of Sustainable Development have appeared in publications worldwide since the Bruntlandt Commission's report *Our Common Future* was published in 1987. That report contained one of the earliest definitions of this widely used term: Sustainable Development is "that which meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987). The responsibility for ensuring sustainable development has fallen within the domain of engineering, and political leaders are hoping that engineers can develop the technology needed to transition society to sustainability without requiring major changes in lifestyle.

As engineers, we recognize that compromises will need to be made. A combination of new technologies and new societal behaviors will undoubtedly be necessary to allow future generations a high quality lifestyle. Furthermore, the limited resources available on the planet will need to be used for both an increasing population and an improved lifestyle for millions of the world's poor. Achieving sustainable development in the face of these challenges will require engineers to acquire new knowledge and skills that go well beyond technology.

In this paper, we examine the some of the characteristics that will enable engineers to meet the demands of the next few several years. We first state the skills and attitudes engineers will need to provide the leadership required, using as an example the complexity of an ethical basis for decision making. We then examine the sequence of graduate courses at Carnegie Mellon that we anticipate will help to fill this need. Finally we summarize the changes needed in engineering education.

Attitudes and Skills of Future Engineers

In previous work, we discussed five categories of skills and attitudes that we feel will be vital to successful engineers in the 21st century (Davidson et al., 2007). These categories include (1) environmental sensitivity, (2) sensitivity to human needs, (3) an ethical foundation, (4) understanding of natural systems, and (5) understanding of societal systems. As global problems have become more complex, the world can no longer afford to have engineers who are content to simply respond to the requests of decision makers.

Rather it is important for engineers to engage in dialog with both decision makers and the public so that the risks associated with engineering decisions can be understood. This requires educating engineers more holistically so they are able to fulfill this expanded role, and educating decision makers and the public so they are able to communicate effectively with engineers and contribute to difficult decisions. One particularly difficult decision concerns the issue of sacrificing comforts today for the benefit of future generations. Let us explore this issue briefly.

A person generally acts out of self-interest. This is one reason for the effectiveness of the Golden Rule: "Do unto others as you would have them do unto you." One does not have to resort to morality, religion, or belief in a greater force to realize the importance of this command. One simply behaves acceptably out of a desire to further one's own goals.

Adopting a sustainable lifestyle – a lifestyle that safeguards resources for future generations – goes beyond the Golden Rule. Past generations did not need to change their behaviors for our sake. Furthermore, the current generation can claim that we don't know anything about future generations, or even whether there will be future generations. Believing in a world after we are gone requires faith, and resorting to faith causes us to enter a murky realm beyond logic and reason. Thus conventional ethics based on self-interest breaks down when arguing for sacrifices now to promote sustainability.

The Bruntland Commission recognized this in 1987, when they stated that it is difficult enough for political leaders to argue for short-term sacrifice in favor of later benefits within a person's lifetime. How can they argue for life-long sacrifices for yet unseen generations (World Commission on Environment and Development, 1987)? Vesilind (2007) argues that individuals have differing interpretations of what will happen in the far future, and thus it is difficult to argue ethically for decisions that impact a time beyond an individual lifespan.

It is clear that engineering education must go beyond technology and even beyond conventional rational thought. The sequence of graduate courses in sustainable engineering at Carnegie Mellon is a small move in that direction. We now describe the course sequence, noting that the five categories of skills and attitudes of future engineers provide some direction for these courses as they evolve.

Incorporating these Skills and Attitudes: A New Sequence of Courses

We have developed a sequence of four half-semester "mini" courses focusing on environmental sustainability. The courses can be taken by graduate students and qualifying seniors from all departments in the engineering college. The skills and attitudes discussed in the previous section provide threads that run through all four of these courses. The sequence was offered in modified form as two one-semester graduate courses during Fall 2002 and Spring 2003, and was presented as four mini-courses beginning in Fall 2003. Enrollment has typically been 20-30 students per semester. At present, the four-course sequence serves as the core for the M.S. in Civil and Environmental Engineering with a concentration in Green Design.

Mini 1: Introduction to Sustainable Engineering

Society has generally assumed that the earth's resources are limitless and wastes can be disposed of without serious consequences, but the validity of these assumptions is now being challenged. This course begins with an overview of the concept of sustainability and its history, including changing attitudes and values toward technology and the environment through the twentieth century. Key conferences and reports that helped define sustainability are reviewed. Models for population growth, global food production, and global water resources are then presented, and current problems of land use, urbanization, and energy and material resources are discussed. Overall, the course material provides a context for future engineering decisions, which are quite different from decisions of engineers in the past.

Readings for this mini include material from key journal papers and books, as well as from the gray literature on Sustainable Development. The first half of the class is primarily qualitative, investigating social, political, and ideological issues related to sustainability. The latter half is more quantitative and incorporates simple mathematical models. There are several homework assignments based on the lectures and readings, as well as an individual research project to study one aspect of sustainable engineering of the student's choosing.

Mini 2: Industrial Ecology and Sustainable Engineering Design

This course uses the context established in 12-712 to explore the solution space of engineers in tackling basic problems facing human civilization. The course begins with the concept of a system, using the earth's life support systems as examples. The potential damage of conventional engineering decisions on these life support systems is discussed. Models of industry based on life sciences are then explored, and tools for sustainable engineering are presented. These tools include metrics of sustainability, principles of design for the environment, methods for pollution prevention, and use of mass and energy balances in the design of sustainable systems. Finally, the principles and tools of sustainable engineering are used to explore solutions to some of the most challenging problems identified in 12-712.

Once the tools for sustainable engineering are presented, some of the problems examined in 12-712 are revisited, and the tools are applied to develop potential solutions. The students realize that many critically important problems still have not been addressed in a satisfactory manner, and that they can indeed contribute to developing long-term solutions. The material presented throughout the course includes both qualitative and quantitative components and relies on formulations taken from the basic sciences, with readings from appropriate books and journal articles. The course structure is similar to that of 12-712.

Mini 3: Life Cycle Assessment

Cradle-to-grave analysis of new products, processes and policies is important to avoid undue environmental harm and achieve extended product responsibility. This mini-course provides an overview of approaches and methods for life cycle assessment and for green design of typical products and processes. Process-based analysis models, input-output and hybrid approaches are presented for life cycle assessment. The Economic Input-Output Life Cycle Assessment (EIO-LCA) tool developed at Carnegie Mellon is used extensively in class (Hendrickson et al., 2006). In addition to LCA, additional topics in the course include full cost pricing and methods to comprehensively assess impacts from an inventory of effects. The coursework includes frequent in-class exercises, problem sets, and a group life cycle assessment project. Past projects have included alternative burial practices, green furniture and alternative energy systems.

Mini 4: Case Studies in Sustainable Engineering

The last mini of the sequence builds upon a variety of concepts in sustainable engineering to explore a few cases in detail. Each case incorporates data from industry in both closed and open-ended problems where students encounter challenges not unlike what they would experience in the real world. To-date, cases have been developed on (1) energy use by automobiles, (2) use of materials in complex products such as automobiles and computers, (3) water resources, and (4) renewable energy. More case studies are being developed. A variety of databases and reading materials have been assembled for each case study.

All four minis have been critically evaluated by students taking these classes. Results show that the students like the option of taking any or all of the four courses, but downside is that the later minis are not free to build on previous material presented since new students enter the class at each mini. This has now been somewhat rectified by having mini 1 as a prerequisite to mini 2, and mini 3 as a prerequisite to mini 4. The students also comment on the need for a better balance of "big picture" issues and engineering details, and between qualitative and quantitative issues. Nevertheless, despite the usual problems in developing a sequence of courses in a new topic area, the students are overall enthusiastic about the sequence, noting that its emphasis on engineering problems using real-world data is an asset. Pre- and post-testing of the students with surveys has shown that the students are generally adopting the desirable knowledge, skills, and attitudes needed by future engineers. Furthermore, the students are developing an improved understanding of sustainable engineering: when the students are asked about "the length of time it will take to reach a sustainable world," the estimates given after completing 12-712 are substantially longer than their estimates before the course. However, the pre-tests show that students choosing these courses are generally inclined toward the importance of environmental issues.

The Need for Change in Engineering Education

With mounting evidence that an ever-growing population is straining the earth's resources, why have engineers not made changes in their practice? The answer is clear: there are always pressures to get the job done at the lowest cost and following what the client wants, which usually means using tried and tested methods. It is simply not good business to deviate from accepted methods until changes are required by regulations – or by a changing environment. The challenge is to enact regulations for manageable transitions before environmental change forces us into less manageable transitions. Luthy et al. (1992) note that an engineering career may span 40 or more years, requiring educational goals consistent with a long time frame.

The next generation of engineers is likely to find that very different pressures are emerging, such as limitations on fossil fuels, restrictions on the availability of land, and use of products that are less harmful to the environment. Furthermore, controversy is likely: there will certainly be opposition to the new paradigms being developed, as the costs will be high and the changes will affect huge numbers of people. But the risks of not acting boldly on the problem will also be high, and some of the most-feared changes may be irreversible.

In mid 2005, the Center for Sustainable Engineering (CSE) was established as a three-way consortium at Carnegie Mellon, University of Texas at Austin, and Arizona State University. The goal of the CSE is to assist engineering programs in incorporating issues in sustainability throughout engineering curricula. The three primary institutions will host workshops for faculty members nationwide and will start a peer-reviewed website for educational materials on sustainable engineering. They will also conduct a benchmark assessment of existing courses and programs in sustainable engineering in the U.S. Through the activities of the CSE and other groups dedicated to this emerging discipline, it is hoped that engineering graduates will be better prepared for the challenges ahead.

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