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Sustainable Engineering: A Sequence of Courses at Carnegie Mellon*

CLIFF I. DAVIDSON
Department of Civil and Environmental Engineering and Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA, USA 15213. E-mail: cliff@cmu.edu

CHRIS T. HENDRICKSON
Department of Civil and Environmental Engineering, Carnegie Mellon University, Pittsburgh, PA, USA 15213

and H. SCOTT MATTHEWS
Department of Civil and Environmental Engineering and Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA, USA 15213

A new sequence of courses at Carnegie Mellon University exposes students to concepts in the emerging discipline of Sustainable Engineering and prepares them to play leadership roles in the years ahead. This sequence includes four half-semester courses: (1) Introduction to Sustainable Engineering; (2) Industrial Ecology and Sustainable Engineering Design; (3) Life Cycle Assessment, and (4) Case Studies in Sustainable Engineering. Students successfully completing this sequence have an appreciation for the myriad ways in which engineering decisions can affect the environment and for the responsibilities of engineers in helping society cope with future challenges.

Keywords: sustainability; sustainable engineering; education; college courses

INTRODUCTION

THE ORIGINAL PARADIGM on which human civilization is based suggests that the supply of the Earth's resources, including air, water, food, materials, energy, and reservoirs for our wastes, greatly exceeds global demand and for practical purposes can be assumed to be limitless. Over the last few decades, an increasing number of scientists and engineers have adopted the view that the Earth's growing population and higher per capita resource use now imply that a new paradigm is needed, one that accounts for the limitations of the Earth in our future decision-making. This is sometimes called the paradigm of sustainability, leading to the term 'sustainable development', defined by the Brundtland Commission as "that which meets the needs of the present without compromising the ability of future generations to meet their own needs" [1].

A broad spectrum of opinions has developed regarding a possible transition to the new paradigm. Some authors [2–6] believe that technology is responsible for the current environmental problems, claiming that technological advances work against the instincts of people and must be reduced. They believe that conveniences provided by technology prevent people from having sufficient contact with the natural world and, in the long run, are destroying the quality of life. Other authors such as Samuel Florman [7] and Frances Cairncross [8] argue that technology has had tremendous benefits for human welfare and is needed to solve our current environmental problems. And while we debate these issues, the global population and resource needs continue to grow: in *Earth in the Balance*, Al Gore [9] emphasizes that the longer we wait, the greater the hardships will be once we begin the transitions toward sustainability.

Another perspective is argued by authors such as Julian Simon [10] and Bjorn Lomborg [11], who believe that environmental problems are being greatly exaggerated. Simon believes that human ingenuity has solved and will continue to solve problems of resource use. Our economic system provides the right incentives: as resources become scarce, prices rise, and this sparks innovation that leads to new solutions. Thus environmental problems will be solved in the normal course of events. Lomborg reanalyzes data from a number of sources and argues that the Earth should be able to sustain our lifestyles for a long time yet. He states that many people use data uncritically; by attempting to trace several datasets back to their sources, he found that unreliable data, or no data at all, have been used as foundations to reach some false conclusions about sustainability.

How should we react to this variety of opinions? First, the Earth's resources are not limitless, and at some future time the new paradigm will need to be adopted, either voluntarily or involuntarily. It is

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unlikely that civilization will willingly retreat from technology, despite several opinions that such actions are needed. Furthermore, even if Simon and Lomborg are right and we can continue our current lifestyles for a long time, the social and engineering infrastructure changes needed for transition to the new paradigm will themselves take a long time. Consider global climate change: the time scale over which change occurs is decades or even centuries. If we later discover that we made a mistake by not curtailing greenhouse gas emissions, it may be too late to undo serious damage, no matter how much ingenuity is applied.

In this paper, we posit that new attitudes are likely to be demanded of future engineers, and describe some of the skills they may require to face the uncertain times ahead. We then describe a sequence of courses at Carnegie Mellon designed to address these attitudes and skills. Finally, we reach some general conclusions about the need for change in engineering education.

ATTITUDES AND SKILLS OF FUTURE ENGINEERS

The literature contains many suggestions of what an environmentally literate citizenry needs to know, and some of these references are also relevant to engineers. For example, Hyde and Karney [12] summarize several lists of environmental topics from the literature that should be included in the educating of engineers. These topics, as well as those in several other published studies, have been used here to develop five broad categories of skills and attitudes that future engineers are likely to need in addition to traditional engineering topics. These broad categories are then used to form the basis of the new course sequence.

1. Environmental sensitivity

Environmental sensitivity may be defined as "a predisposition to take an interest in learning about the environment, feeling concern for it, and acting to conserve it, on the basis of formative experiences" [13]. Hence this category includes attitudes about the environment as well as attitudes toward the relationships between people and the environment. The category also includes perceptions of risk and an awareness of the need for precautions for environmental protection. Students who are beginning engineering programs are not necessarily predisposed to this sensitivity. Furthermore, some authors [12, 14] question whether education can transform the attitudes of students who are not environmentally sensitive. If not, it may be necessary to recruit students into engineering who are predisposed toward the environment. Mitchell [15] suggests that the subdiscipline of environmental engineering, where individuals are both technically inclined and environmentally sensitive, may be positioned to take a leadership role in this recruitment effort.

2. Sensitivity to human needs

A summary of some forty books, reports, and other studies on the personalities of engineers has led to the following statement: "Constricted interests are apparent in their relative indifference to human relations, to psychology and the social sciences, to public affairs and social amelioration, to the fine arts and cultural subjects and even to those aspects of physical science which do not immediately relate to engineering" [16]. This negative commentary is clearly inconsistent with desired attitudes, although in the past engineers themselves have been proud of their focus on "logic and impartiality" to provide a barrier from prejudice and other human limitations [17]. Unfortunately, this commentary is still accurate today. Nair [18] suggests that engineers have moved farther from being humanists, concerned more with functionality than with feeling. Other authors have pointed out that sustainability decisions may actually help the engineering discipline expand its horizons and become somewhat more humanistic over the long term [19].

3. An ethical foundation

Wareham and Elefsiniotis [20] claim that engineering practice is lacking an environmental ethic as a foundation for decisions. This may pose a problem as the engineering profession is asked to consider future generations that have a right to a comfortable and satisfying lifestyle such as many of us enjoy today. Left to its own devices, human nature drives individuals to seek more of everything—more money, more material goods, more meaning to life. This is true of the poor and also the rich. As Florman puts it, "We have too many people wanting too many things" [7]. What should be the role of engineers in promoting policies that help safeguard resources for future generations? How should an engineer react to clients who are not supportive of environmental preservation? These questions can be best answered by engineers who have a strong ethical basis for their decisions. It may, for example, be necessary for an engineer to justify difficult decisions that run contrary to client expectations [21]. Such clashes in ideology need to be incorporated into classroom discussions. Incorporating ethics into courses must also respect the learner's freedom of moral choice: Newhouse [22] suggests that environmental education should focus on the tools needed to make critical environmental decisions, rather than prescribing solutions.

4. Understanding of natural systems

Ansari [23] notes that many engineering students fail to understand the complexity and fragility of the web of life, in part because engineering is based largely on physics, rather than on life sciences. He argues that engineering curricula promote the notion of the world as separate, disconnected objects that can be manipulated at will. Mitchell [15] writes that ecosystems are important in representing "the basis on which our planet operates and, as such, are at the very core of the sustainability and functionality of all systems we design.'' The ecosystems, in turn, rely on the Earth's life support systems such as the atmosphere, hydrosphere, and lithosphere. These comments emphasize the need for engineering education to incorporate a systems approach, where a system is made up of components that function together rather than as disconnected parts. Nair *et al.* [24] have made extensive use of this concept in developing nine core areas for environmental literacy, all based on a systems approach. There is also a link between environmental sensitivity and understanding natural systems: Aldo Leopold [25], in his classic book *A Sand County Almanac*, notes the need for people to have contact with the Earth and to understand the Earth to develop an appreciation for its life-supporting properties.

5. *Understanding of societal systems*

Along with a more humanist attitude, engineers of the future are likely to need a solid understanding of the systems that have been set up by society as a context for making engineering decisions. These include our regulatory, political, business, economic, and other institutional systems, most of which will serve crucial roles as society changes. For example, new regulations, many international in scope, will be necessary under the new paradigm to change society's use of resources and discharge of wastes. Developing strong political leadership will be essential: passing legislation with a goal of establishing equity among disparate groups today is difficult enough—we can only imagine the challenge of passing legislation designed to help future generations at the expense of people today. Some engineers are starting to use concepts in industrial ecology to model the flows of materials and energy in industry [26–28]; in the future, engineers may need to use the results of such efforts to work with political and business leaders to effect change in the way industries operate.

Information in all of these categories will contribute in substantive ways to the knowledge base and skills demanded of future engineers [29]. Some groups have gone one step further and have defined new guiding principles [30, 31]. Ultimately, the information embodied in these principles must somehow be used to influence engineering decisions; Skerlos *et al.* [32] note that discipline-specific operational definitions in addition to conceptual definitions must be adopted if the principles now being developed are to be applied to real-world engineering problems.

INCORPORATING THESE SKILLS AND ATTITUDES: A NEW SEQUENCE OF COURSES

We are just beginning to explore how engineering programs can best prepare students for future environmental challenges [33]. At Carnegie Mellon, 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 15 and 25 students per semester. At present, the four-course sequence serves as the core for the MS in Civil and Environmental Engineering with a concentration in Green Design.

Mini 1: Introduction to sustainable engineering

This course begins with some of the first discoveries that human activities were adversely affecting the global environment, and goes on to trace the history of attempts to define the problem of an unsustainable society. Reports by the Club of Rome (1972), the World Council on Environment and Development (1987) and the Business Council for Sustainable Development (1992) are discussed [34–36]. The goals and resolutions of the three major United Nations global environmental conferences [37–39] are also summarized. With this historical background, the course then discusses a few of the major issues related to sustainability from the perspective of engineering: population dynamics and demographics, availability and distribution of food, and models for fresh water resources. The dependence of civilization on the Earth's life support systems is emphasized, focusing on human interaction with the world's ecosystems.

Readings for this Mini include material from the reports cited above, as well as sections from key journal papers and books. 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.

Mini 2: Industrial ecology and sustainable engineering design

Over the last few years, this course dealt mainly with traditional environmental management. Beginning with the Fall 2004 course and expanded in the Fall 2005 version, the second Mini now begins where the first Mini ends—examining the ways in which civilization relies on the Earth's resources. The influence of an ever-expanding population on the functioning of the Earth's systems is addressed, including changes in the world's ecosystems and climate. Use of the Earth's mineral resources is also explored, and models of global reserves of certain resources are discussed. After presentation of these global problems, strategies for their mitigation are explored. The principles of ecology from Mini 1 are used to develop the principles of industrial ecology [28] and the concept of biomimicry [40]. Engineering design for the environment (DfE) is discussed, including details such as design for disassembly, design for waste minimization, and design for energy and material conservation [41]. Innovations in Environmental Management Systems that incorporate these concepts are discussed. Programs to facilitate environmental change in industries, such as Cleaner Production, which is now used in over 40 countries, are summarized. This course includes both qualitative and quantitative components and relies on formulations taken from the basic sciences, with readings from appropriate books and journal articles.

Mini 3: Life Cycle Assessment

Life Cycle Assessment (LCA) is a framework for assessing the implications of products and processes, from raw materials extraction through component and product manufacture, use, and disposition. It is codified in the ISO 14000 environmental management standard. This course in the sequence introduces the topic of LCA, its formal definition and framework, the process and input–output based methods, hybrid models, and case studies. The Economic Input–Output Life Cycle Assessment (EIO–LCA) tool developed at Carnegie Mellon is used extensively in class. Other than LCA, the only additional topics in the course have been full cost pricing, and methods to comprehensively assess impacts from an inventory of effects. In addition to technical papers and case studies, the new text *Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach* by Hendrickson *et al.* [42] is used.

The course work includes frequent in-class exercises, problem sets, and a group life cycle assessment project. Past projects have included alternative burial practices, green furniture and waterless urinals.

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 those 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 the 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.

IMPLICATIONS OF THE NEW PARADIGM: 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 practices? 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.* [43] 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 paradigm, as the costs will be high and the changes will affect huge numbers of people. But the risks of not supporting the new paradigm 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 in training students for future challenges. The three primary institutions will host workshops for faculty members nationwide and will start a peer-reviewed Website for educational materials on sustainable engineering. 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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Cliff Davidson is Professor in the Departments of Civil and Environmental Engineering and Engineering and Public Policy at Carnegie Mellon University. He served as Director of the Environmental Institute during 1993–2003, and is currently the Director of the Center for Sustainable Engineering at Carnegie Mellon. His research, teaching, and consulting interests are in the areas of air quality and sustainable engineering. He has published on topics of emission inventories of airborne contaminants, atmospheric transport of airborne particles, atmosphere–surface exchange of pollutants, using the glacial record to interpret changes in airborne contaminants over time, indoor pollutants, history of air pollution measurement, and movement of airborne metals throughout the environment. He has also published in the area of education in the sustainable engineering field. He has three books (*Toxic Metals in the Atmosphere*, *The New Professor's Handbook*, and *Clean Hands: Clair Patterson's Crusade Against Environmental Lead Contamination*) and several monographs, in addition to peer reviewed journal papers. He previously served as President of the American Association for Aerosol Research and is active in many professional societies.

Chris Hendrickson is the Duquesne Light Company Professor of Engineering, Director of the Steinbrenner Institute for Environmental Engineering and Research, and Co-Director of the Green Design Institute at Carnegie Mellon University. His research, teaching and consulting are in the general area of engineering planning and management, including design for the environment, project management, transportation systems, finance and computer applications. He has co-authored three textbooks, *Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach* (*Resources for the Future*, 2005), *Project Management for Construction* (Prentice-Hall, 1989, now available on the Web) and *Transportation Investment and Pricing Principles* (John Wiley & Sons, 1984) and two monographs, *Knowledge Based Process Planning for Construction and Manufacturing* (Academic Press, 1989) and *Concurrent Computer Integrated Building Design* (Prentice-Hall, 1994). In addition, he has published numerous articles in the professional literature.

H. Scott Matthews is the Research Director of the Green Design Institute and an Associate Professor in the Departments of Civil and Environmental Engineering and Engineering and Public Policy at Carnegie Mellon University. The Green Design Institute is an interdisciplinary research consortium at Carnegie Mellon focused on identifying and assessing the environmental impacts of systems and helping businesses manage their use of resources and toxic materials. His research and consulting interests are in the area of valuing the socio-economic implications of environmental systems and infrastructure. Of particular interest are using the Internet to facilitate environmental life cycle assessment of products and processes, environmental supply chain management, the energy and environmental impacts of computing and the Internet, and the sustainability of infrastructure. At Carnegie Mellon, he has taught graduate and undergraduate courses in the Departments of Economics, Civil and Environmental Engineering, Engineering and Public Policy, and Computer Science. He is an Associate Editor of *The Journal of Industrial Ecology*, and an executive committee member of the IEEE Technical Committee on Electronics and the Environment.