Curricula For A Sustainable Future: A proposal for integrating environmental concepts into our curricula

Linda Vanasupa and Frank G. Splitt*
Materials Engineering Department, California Polytechnic State University, San Luis Obispo, CA 93407, *lvanasup@calpoly.edu*
*McCormick School of Engineering and Applied Science, Northwestern University, Evanston, IL 60208, *fgsplitt@ece.northwestern.edu*

ABSTRACT

The global scientific community recognizes the critical need for industries to develop and practice manufacturing techniques that minimize harm to our environment. In the National Science Board's report *Environmental Science and Engineering for the 21st Century*, the National Science Foundation was urged to promote "Environmental research, education, and scientific assessment [as] one of NSF's higher priorities." Although there are a number of independent efforts to fold environmental issues in existing undergraduate curricula, no dominant method has emerged as a means of including these concepts. One of the difficulties in adjusting our materials science and engineering (MSE) curricula is the problem of how and what to include in an already full curriculum. In this paper, we propose a path for integrating environmental and sustainability concepts within the framework of existing curricula. We will suggest learning outcomes for each year of the MSE curriculum and offer examples.

INTRODUCTION

Stanford University's recent establishment of its *Institute for the Environment* is but one of many signs that "this is the century when human beings must learn how to live on this planet in an environmentally sustainable way."[1] The engineers of tomorrow will no doubt play a critical role in humanity's success (or failure) to do so. One obvious challenge is that these future engineers are learning from engineering specialists, educated within an "infinite supply" model: our focus has been material performance, while questions, such as supply or environmental impact, are answered after the design work is done. In order for tomorrow's engineers to derive more sustainable solutions, their curricula must contain the elements necessary for sustainable thinking.

Several have proposed clear educational objectives for incorporating sustainable development concepts into the undergraduate curriculum [2,3,4,5]. Anastas and Zimmerman have identified *12 Principles of Green* Engineering [6]. Indeed, the proposed 2005-2006 accreditation criteria for engineering programs in the United States calls on programs to directly address issues of sustainability and environment. However, in an already crowded engineering curriculum, it is difficult to envision where and how these concepts can fit. In this paper, we refine the recommendations of others into yearly goals and objectives for the undergraduate curriculum. Our hope is that these will serve as a starting point for programs to integrate these critical concepts and continue the global transformation toward sustainable development. We begin with a vision of the graduating engineer.

THE END PRODUCT: THE GRADUATING ENGINEER

Ideally, graduating engineers would be able to create a process flow and a life-cycle inventory for competing product (or process) designs with the aid of a computational software tool. From the inventory, they would be able to assess the relative merits of the competing designs based on ecological and resource indicators. These advanced skills draw on the students' knowledge of their discipline. But they also require a set of analytical approaches that encourage holistic, *systems* thinking. In *systems* thinking, one pays attention to the inputs and outputs of the system and their effects on the surroundings. These approaches can be integrated into the framework of existing engineering curricula.

CURRICULAR FOCUS OF YEAR 1: AWARENESS OF ISSUES

The first step toward a sustainable focus is becoming aware of the issues: What is sustainable development? What is the need for it? What role does the engineer play? Yet, even the answers to these questions require groundwork, as typical 18-year old engineering students have gravitated toward engineering as a career because they have an aptitude for math and science; the weighty issue of one's societal contribution is rarely the primary reason that students cite as their motivation for choosing engineering. So the first year serves as a way of orienting the engineering student for the holistic and ethical approach that sustainable design in engineering requires. The goals and objectives are meant to promote the sensitivity that is needed (and missing) in engineering curricula [7]. Below is a table of five items that could be addressed to lay the groundwork for sustainable design. We offer suggestions on how to achieve the learning objectives in the section that follows Table I.

Table I. Listing of Curricular Goals and Learning Objectives for the first year of the engineering curriculum.

Year 1:Curricular Goals	*Year 1: Learning Objectives (The student should be able to…)*
1. Imbue students with the engineering profession's social responsibility to better human welfare.	State the purpose of the engineering profession as expressed in the Engineer's Creed (that the engineer dedicates his professional knowledge and skill to the advancement and betterment of human welfare).
2. Illustrate how technology has affected the quality of life.	Generate a list of both positive and negative impacts of a particular technological application on the quality of life.
3. Communicate the reality of "trade-offs" in all engineering design decisions.	Identify multiple, specific consequences that producing an engineering product could have on society.
4. Orient students toward holistic thinking.	List the three major categories of interests that must be balanced in any engineering endeavor (economic, environmental, societal); generate aspects of the design that impact each of the three categories.
5. Educate students with the facts of the present state.	Generate ideas by which engineers can improve human welfare by applying their knowledge.

1. Imbue students with the engineering profession's social responsibility to better human welfare. A method of educating the students in this area is allowing them to study the Engineer's Creed from the National Society of Professional Engineers Code of Professional Ethics [8]. This simple but elegant statement of engineers' professional responsibility to society rarely enters the engineering curriculum. Many engineering freshman see the profession as a means for pursuing personal interests or ensuring a steady income, but some would gladly adopt a more society-oriented role if given the opportunity. Exposing them to the Creed at least raises their awareness that engineers are expected to use their knowledge for the betterment of human welfare. It may even inspire those who are motivated to contribute to society.

2. Illustrate how technology has affected the quality of life. It is easy to imagine that technology has only improved the quality of life. There are examples, like nuclear weapons, in which the societal costs of the technology may be greater than the benefits. However, there are multiple examples where a "benign" technology has caused unintended societal challenges. For example, the development of clean water supplies and technology-mediated advances in medicine have prolonged life expectancy and shifted the balance in the earth's capacity to recover from the global sum of human activity. The larger resulting population presents a challenge for earth to support the overall greater drain on resources. One group's computations indicate that human activity has overshot the earth's bioproductive capacity in 1977 and has continued its upward trend through 1999 to 120% of earth's biocapacity [9].

3. Communicate the reality of "trade-offs" in all engineering design decisions. As freshmen, students are often unaware that engineering solutions involve pros and cons. It's important to illustrate that engineering decisions have consequences beyond the performance of the engineered product and that these consequences must be factored into the design process. For example, graphite fiber reinforced composites have exception strength to weight ratios, but they are non-recyclable and usually non-reusable.

4. Orient students toward holistic thinking. To set the stage for sustainable approaches, we must introduce the concept that betterment of human welfare requires a balance of economic, environmental and societal interests (i.e., the so-called "triple bottom line" [10]). Engineers can no longer only consider economic interests alone when conducting a cost/benefit analysis. A way of communicating this idea is to study the negative consequences of considering only the economic interests. The problem of electronic waste is an excellent example: boatloads of it are shipped to southern China for stripping and recovery of the precious metals. This activity has led to a total contamination of the water supply for the life forms (animal and plant) of those communities and exposure of entire communities to high-levels of hazardous biotoxins [11].

5. Educate students with the facts of the present state. Providing a litany of sobering facts of the present state (e.g., consumption/waste figures [9,11], pollution rate figures [12], toxicity rate figures, green-house gas emission figures and predictions [13], loss of arable land figures [14], projected date of depleting the global fossil fuel supply [15]) has the effect of presenting the students with picture of the urgent need for change. It also presents them with a multitude of opportunities for engineers to contribute to the solutions.

CURRICULAR FOCUS OF YEAR 2: SYSTEMS PERSPECTIVE

Year 1 activities have the potential to introduce the students to the problems and orient them toward holistic solutions. Year 2 activities are meant to enable the students to analyze processes as systems. Recognizing the system nature is key to a comprehensive sustainable design. The goals and objectives are listed in Table II, followed by a discussion of each goal.

Table II. Listing of Curricular Goals and Learning Objectives for the second year of the engineering curriculum.

Year 2: Curricular Goals	*Year 2: Learning Objectives (The student should be able to…)*
6. Enable students to realize that earth is a closed system.	Distinguish between open and closed systems; identify the source for all system inputs and outputs (i.e., earth for open systems, unless they involve solar energy).
7. Educate students with earth's inherent capacity to recover from human and natural activity (regenerative rate).	Compute one's personal consumption rate ("environmental footprint"); identify activities that lead to larger consumption rates of bioproductive land; generate ideas by which engineers can improve human welfare by applying their knowledge.
8. Expose students to new ways of thinking about product life cycle and design.	Create a cradle-to-grave flowchart of a product; identify opportunities within a product's lifecycle (i.e., cradle-to-cradle) in which fewer resources can be consumed.

6. Enable students to realize that earth is a closed system. Viewing processes or products as systems (with inputs, outputs and surroundings) is a simple but powerful means to enable sustainable engineering solutions. One of the authors (LV) taught a two-quarter freshman sequence in which the concept of systems (and the earth as a closed system in particular) was introduced in the second quarter. Each quarter the students were asked to propose ways in which engineers could alleviate the problem of global warming. During the first quarter the responses were fairly discouraging in that many concluded either it was not truly a real phenomenon ("I don't believe in global warming."), that it was not possible to prevent it if it was, that someone else would solve the problem or that they would be dead by that time, so it did not concern them. After the idea of systems was introduced, students were able to make the connection that open systems, like cars, emptied their outputs into the surroundings. They further linked the idea that the outputs were "stuck" on the closed system of the earth. With this perspective, they had many more concrete ideas on how engineers could alleviate global warming when asked.

7. Educate students with earth's inherent capacity to recover from human and natural activity (regenerative rate). The earth has a natural capacity to recover from most animal and human activity (the exceptions are those activities that produce bio-incompatible toxins). Photosynthesis is a straightforward example of ability of plants to renew the oxygen that animals consume. The problem that we face can be simply stated: There is a limit to the earth's capacity to regenerate and human activity is exceeding this limit. Put another way, on an annual basis we are consuming more than the earth can regenerate. At the sophomore level, faculty can introduce the tool of "environmental footprinting," a means of converting human activities to an equivalent area of bioproductive land [16]. Some tools provide detail on the computations so these students can get a sense of which activities are most damaging to the environment.

8. Expose students to new ways of thinking about product life cycle and design. The traditional approach to engineering is to focus on the performance of a product or a process. One can introduce case studies in which the entire product lifecycle (i.e., cradle-to-grave) is accounted for. Braungart and McDonough outline a number of unconventional product scenarios (e.g., replaceable carpet tiles) that could greatly reduce the consumption of natural resources in their book *Cradle-to-cradle: Remaking the Way We Make Things* [17]. Nature provides many examples of completely sustainable activity, such as a simple fruit tree, in which the waste product (i.e., output) of one process is the food (i.e., input) for the next, the so-called "Cradle-to-cradle" approach proposed by Brangarh and McDonough. Merkel also identifies Kerala, India, as a society, which operates sustainably [18]. Studying their methods can offer a great deal of insight.

CURRICULAR FOCUS OF YEAR 3: ACCOUNTING METHODS FOR SYSTEM INPUTS/OUTPUTS

Once students are able to visualize a system, its surroundings, and create system inputs and outputs, they are ready to begin the accounting process that is required to assess a design's impact. Many global companies (primarily outside of the U.S.) have adopted the strategy of assessing the impact of a product over its entire life cycle. The focal point of Year 3 could be to introduce the concept and practice of life cycle assessment. In its entirety, life cycle assessment requires a comprehensive account of process inputs and outputs, including transportation and energy consumptions. The concept of life cycle assessment, however, is straightforward and can be introduced with a simple product or process. A reference like *A Technical Framework for Life-Cycle Assessment* [19] can assist faculty in developing the background needed for life cycle assessment.

Table III. Listing of Curricular Goal and Learning Objective for the third year of the engineering curriculum.

Year 3:Curricular Goal	*Year 3: Learning Objective (The student should be able to…)*
9. Provide students with a systematic means of accounting for process inputs and outputs	Create a life cycle inventory for a simple product.

CURRICULAR FOCUS OF YEAR 4: EVALUATION AND DESIGNS OF SOLUTIONS

The aim of Year 4 would be to equip students with the necessary tools to assess the relative merits of competing engineering solutions and summarize the application of environmental design concepts. Software tools like SimaPro [20], GaBi [21], or TRACI [22] facilitate complete life cycle assessment with relatively shallow learning curves. Within the software, students can create the process flows needed for an engineering design. Alternative design scenarios, such as using different alloys or utilizing a manufacturer-led "take back" system, can be compared easily and directly. With the aid of the software, students can employ the *Principles of Green Engineering*, espoused by Paul Anastas and Julie Zimmerman [6, 23], which provide a summary framework for designing new materials, products, processes and systems that are benign to human health and the environment – moving beyond baseline engineering specifications for quality and safety to consider life-cycle environmental, economic, and social factors as well.

Table IV. Listing of Curricular Goals and Learning Objectives for the fourth year of the engineering curriculum.

Year 4:Curricular Goal	*Year 4: Learning Objective (The student should be able to…)*
10. Enable students to generate their own assessments and evaluation of their product designs and summarize.	Generate the process flow models for products and assess the relative merit of the competing product life cycle models in relations to several factors (toxicity, environmental impact, and energy consumption). Utilize the 12 Principles of Green Engineering in their designs.

SUMMARY

We have presented a 10-goal sequence for integrating sustainability and environmental issues into the framework of existing engineering curricula. The focus of Year 1 is to cultivate awareness and sensitivity to the societal issues involved in sustainable design; Year 2 goals serve to orient the students toward systems thinking; Year 3 is dedicated to learning accounting methods, like life-cycle inventory, to keep track of process inputs and outputs; Year 4 activities should equip students with the software and analytical tools to evaluate the relative merits of competing engineering solutions. Our hope is that faculty will view these goals and objectives as feasible educational elements to integrate into curricula.

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