Green Engineering:
Incorporating Sustainability Concepts into Engineering Education

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Introduction

Environmental issues have gained increasing prominence in the latter half of the 20th century and the beginning of the 21st century. Growing populations and affluence around the globe have put increasing pressure on natural resources, including air and water, arable land, and raw materials. Concern over the ability of natural resources and environmental systems to support the needs and wants of global populations, now and in the future, is part of an emerging awareness of the concept of sustainability.

Sustainability is a powerful, yet abstract, concept. The most commonly employed definition of sustainability is that of the Brundtland Commission report — meeting the needs of the present generation without compromising the ability of future generations to meet their needs (World Commission on Environment and Development, 1987). However, an internet search on the definition of sustainability will return numerous variations on this basic concept. In engineering, incorporating sustainability into products, processes, technology systems, and services generally means integrating environmental, economic, and social factors in the evaluation of designs. While this may seem simple in the abstract, converting this concept to the types of quantitative design tools and performance metrics that can be applied in engineering design is a challenge.

Quantitative tools available to engineers seeking to design for sustainability are emerging and evolving. Before describing these tools, however, it is useful to briefly review the magnitudes of the challenges that engineers will face in designing for sustainability.

The Magnitude of the Sustainability Challenge

To grasp the magnitude of the pressures on resources and ecosystems, it is useful to invoke a conceptual equation that is generally attributed to Ehrlich and Holdren (1971). The equation relates impact (I), to population (P), affluence (A), and technology (T).

$$I = P * A * T$$

This conceptual relationship, referred to as the IPAT equation, suggests that impacts, which could be energy use, materials use, or emissions, are the product of the population (number of people), the affluence of the population (generally expressed as gross domestic product of a nation or region, divided by the number of people in the nation or region), and the impacts associated with the technologies used in the delivery of the affluence (impact per unit of gross domestic product). For example, if the IPAT equation were used to describe energy use in the United States, then I would represent energy use per year, P would represent the population of the United States, A would represent the annual GDP per capita, and T would represent the energy use per dollar of GDP.

While the IPAT equation should not be viewed as a mathematical identity, it can be used to assess the magnitude of the challenges that our societies face in material use, energy use and environmental impacts. By estimating growth in population and affluence, we can get an indication of the amount by which use of energy, use of materials, and emissions might increase over the next several decades, if our technologies were to remain static. Estimates from the United Nations (United Nations, 2007) suggest that world population will increase at the rate of 1-2% per year until peaking at somewhere near 10 billion, over the next century. Affluence, as measured in economic output (e.g., gross domestic product) is growing in some regions of the world by 8-10% per year. On average, worldwide, affluence is growing by roughly 2-4% per year, depending on economic conditions. If these trends continue for several decades, then compounded growth would lead world economic output (P*A) to increase by 50% in 10 years, by 300% in 25 years, and by more than a factor of 10 in 50 years.

Invoking the IPAT equation, the implications of population and economic growth are that, if technology were to remain static, energy use, material use, and environmental impacts will grow 10-fold over the next 50 years. Reducing the impacts of technology (T in the IPAT equation) by an order of magnitude will be necessary if the world is to support 10 billion people, all aspiring to better living standards. Reducing energy use, material use and emissions will be a central challenge for engineers of the 21^{st} century, and engineers will need to develop and master technical tools that will integrate the objectives of energy efficiency, materials efficiency and reduced environmental emissions into design decisions.

The Tools of Sustainable Engineering

What are the tools of sustainable engineering? Design tools that allow engineers to improve energy efficiency, improve mass efficiency, and reduce emissions are certainly part of the tool set engineers will need. However, these are not entirely new tools for engineers. Energy and mass efficiency are objectives that have always been included in engineering design. What is new is the need to systematically and simultaneously incorporate economic, environmental and social objectives into engineering designs, at multiple scales.

Tools are beginning to emerge for performing these integrated assessments, particularly for environmental objectives. Early attempts to identify green products focused on the development of eco-labels. Generally administered by governments, these labels attempted to condense complex, multi-attribute environmental footprints of products into a single logo. Either a product was green, and could display an eco-label, or it was not. Unfortunately, true environmental performance is rarely so simple. Products and the processes used to manufacture them consume energy, utilize non-renewable and renewable materials, and generate emissions. In creating designs, product and process engineers are continually forced to make decisions that involve trade-offs between multiple environmental impacts. Consider, for example, the chemical process designer trying to determine whether to use indirect or direct contact heating in a process application. The direct contact heating (e.g., steam injection) may be more energy efficient than the use of a heat exchanger, but generates a waste water stream. Alternatively, consider the dilemma of a product designer trying to select a material for an automotive bumper. Should the designer select a steel bumper that is easily recycled or a lightweight polymer composite that leads to better fuel economy?

Such trade-offs are unavoidable. Every product and process will generate an environmental footprint, and only rarely will one design alternative be unambiguously environmentally preferable. Designers will continually face trade-offs between different environmental impacts, yet must ultimately make decisions. Further, designers must reconcile environmental performance with cost and other criteria. Informing these decisions??? requires tools that chemical engineers will need to master. Further, the tools must be robust enough to be used at a variety of scales, from molecular and process scales to the scale of national and international flows. One representative set of tools has been described by Allen and Shonnard (2001): however, approaches vary. The types of environmental, social and economic impacts that are considered vary significantly from one approach to another. Given this heterogeneity, if our goal is to identify concepts that are appropriate to broadly include in engineering education, it would be useful to perform an inventory of the approaches that engineering educators are taking to introducing these concepts.

Many engineering educators are incorporating sustainability concepts into the courses that they teach, and an inventory of what is covered in those courses represents a first step in defining the tools of sustainable engineering. An inventory of these tools has recently been completed as part of a benchmarking of the incorporation of sustainability concepts into engineering education in the United States (Murphy, et al., 2009). The results of this inventory are presented in two sections. First, the types of courses in which sustainability concepts are being addressed are described, along with the diverse subject areas covered in these courses. Then, common elements in the courses are identified. Based on these common elements, possible structures for incorporating sustainability into engineering education are presented.

Sustainability Courses and Content

Based on data provided by hundreds of engineering educators, defined here as Sustainable Engineering champions, there are four primary means by which sustainable engineering concepts are being incorporated into engineering courses: dedicated sustainable engineering courses (48% of courses identified in a 2009 benchmarking); integrating sustainable engineering concepts into traditional engineering courses (23%); courses focused on the technologies predicted to be important in developing sustainable engineering designs, such as photo-voltaic solar cells and fuel cells (14%); and interdisciplinary courses done in conjunction with a non-engineering department (15%). These data are summarized in Figure 1. The data presented in Figure 1 also show that most of the courses are stand-alone electives. Roughly a quarter of the courses (23%) are part of a formal major or minor requirement.

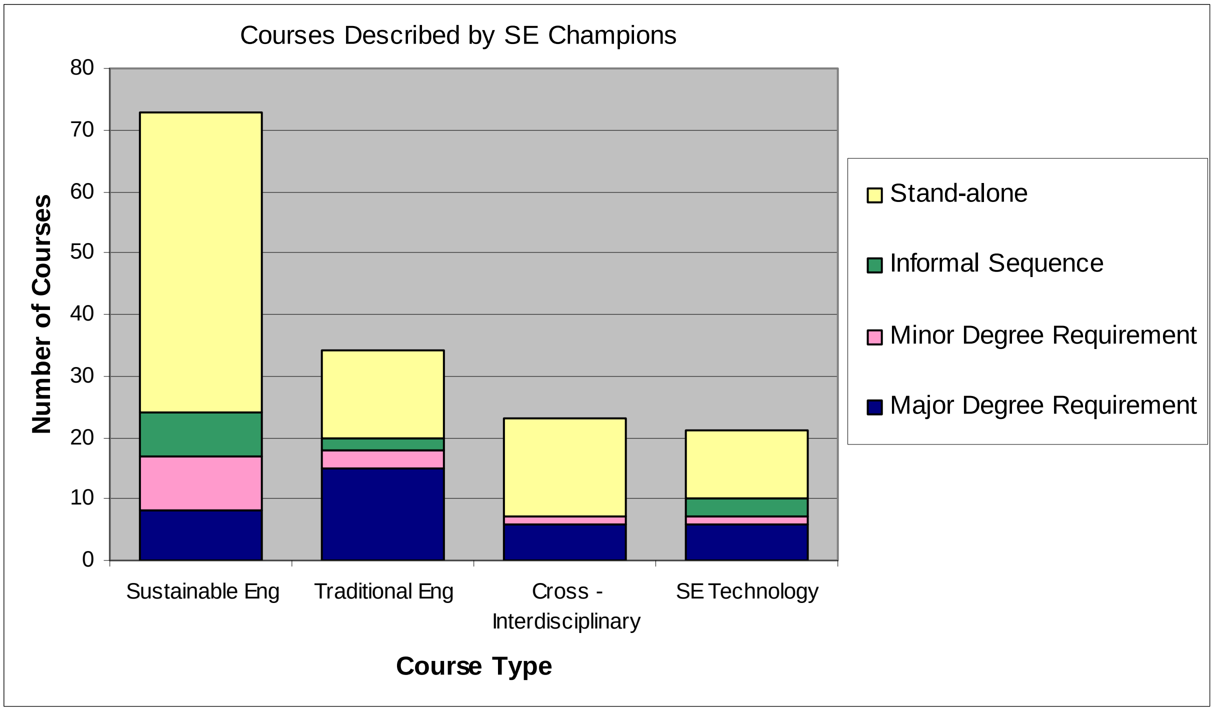

Figure 1. Courses in sustainable engineering are grouped into four categories, Sustainable Engineering (dedicated sustainable engineering courses), Traditional Engineering courses with sustainable engineering content, Cross-disciplinary courses offered jointly with a non-engineering department, and Sustainable Engineering Technology courses which address technologies viewed as enabling for sustainability. (Murphy, et al., 2009; Allen, et al., 2009)

The content of the courses can be categorized based on the scale of the systems being analyzed. Figure 2 illustrates the types of scales that are frequently considered in sustainability courses, using mobility systems as a case study. As shown in Figure 2, the personal device that is used to provide mobility in North America is the automobile. One method of incorporating sustainability into engineering design is to assess environmental and social impacts of decisions affecting the design of a new automobile (e.g., choice of paint type, or chassis and engine materials). At a larger scale, sustainability concepts can be incorporated into automotive design decisions involving the recyclability of the vehicle. At even larger scales, the impact of automobile design (e.g., gasoline or electric power) on fuel industries and road construction can be considered. Finally, the overall sustainability of mobility transportation systems is also influenced by and influences the design of homes, communities and workplaces. These scales of design will be referred to as gate-to-gate, cradle to grave, inter-industry interactions and extra-industry interactions. More complete definitions of each of these scales and the topical areas covered at each of these scales are provided in Table 1.

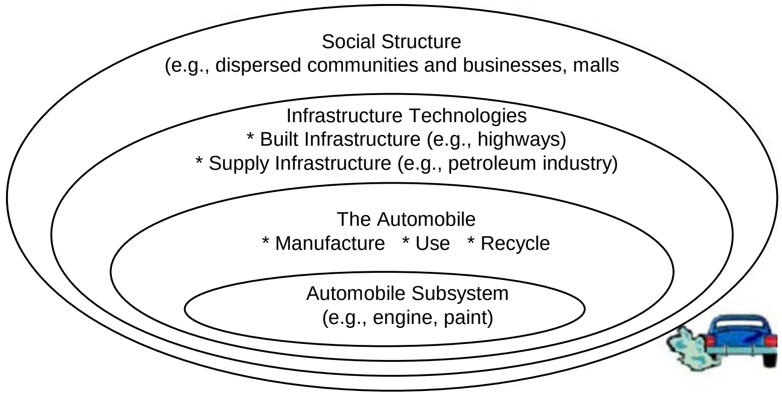

Figure 2. The technological-social system of the automobile exists in multiple layers; design decisions made in any of the layers shown influence decisions in all other layers. (from Graedel and Allenby, 1998)

Table 1. System Scales and Topics (Murphy, et al., 2009)

System Size	Description	Topics
Gate to Gate	Decisions made within a single facility or corporation by engineering and/or business units (i.e., site or industry sector specific activities).	Process design, including material and/or energy reduction
		Material or chemical selection
		Product design for a single phase of a product's life (e.g., design for recycling)
		Pollution prevention
		Media-based (i.e., air, water, solid waste) regulations
Cradle to Grave	Decisions made by different entities over the life of a product or sector activity. Activities are typically analyzed as sequential events (i.e., life cycle analysis).	Resource availability and economics
		Consumer behavior
		Product utility
		Reuse and recycling options
		Product based legislation (e.g., WEEE) and standards (e.g., ISO 14000)
		Life cycle inventory development
Inter-Industry (Industrial Symbiosis)	Decisions made by two or more entities (corporations or other stakeholders), often involving multiple sectors. The analysis typically captures spatial as well as temporal effects and scales, although temporal scales may be compressed such that activities are presumed to occur in parallel (i.e., industrial ecology)	Material flow analysis
		By-product synergy
		Eco-industrial development
		Multiple/nested LCA analysis
		Input-output analysis (either physical or economic)
Extra-Industry	Decisions made by multiple stakeholders, including industry, non-governmental organizations (NGOs), policy makers, consumers, etc.	Policy development (current and historical)
		Consumption patterns and preferences
		Eco-industrial development
		Multiple/nested LCA analysis
		Input-output analysis (either physical or economic)

As reported in the benchmarking analysis of Murphy, et al. (2009), most engineering courses address gate-to-gate and cradle-to-grave issues. Far fewer courses cover topics at inter-industry and extra-industry scales. Most engineering courses cover

i.) Analyses of energy and material use
ii.) Recycling and reuse, and
iii.) Life cycle assessment (examining the flows of energy, materials and emissions over the entire supply chain (life cycle) of a product, from raw material extraction to final disposal)

The courses cover these topics primarily in the context of product design, process design, and materials selection.

To summarize, engineering courses incorporating sustainability generally have a strong focus on minimizing material and energy resources required for the designs. The courses also are likely to cover life cycle (supply chain) impacts of the designs and the materials used in the designs. Engineering courses covering sustainability are less likely to include an assessment of the interaction of engineering designs with other industries and societal structures.

Systematically Incorporating Sustainability into Engineering Courses

Roughly 80% of the engineering programs rated among the top 100 programs by US News & World Report have some type of sustainability content in their curricula (Murphy, et al., 2009). As shown in Figure 1, this content is most commonly found in elective courses. A typical elective course in chemical engineering (Allen and Shonnard, 2001a,b) involves three major elements. Courses generally begin with a basic introduction to environmental issues and regulations. This background material identifies the types of wastes, emissions, raw material use and energy use that will be used to determine the environmental performance of chemical processes and products. Once the environmental performance targets have been defined, tools for assessing and improving the environmental performance of chemical processes are examined. This includes analyses at the molecular, unit operation and flowsheet level. This portion of the course can conclude with the economics of environmental improvement projects. A final topic is often related to improving product stewardship and improving the level of integration between chemical processes and other material processing operations. Note that this is not the only model for an engineering elective course addressing sustainability. More than 100 sample syllabi are available through the references cited in Murphy, et al. (2009).

If sustainable engineering content were to transition from elective courses into required courses, the topics covered would need to match educational objectives of the required courses. Based on the content currently covered in courses addressing sustainability, adding sustainability content to required courses would be done most logically in freshman engineering and senior design courses.

Freshman Engineering Required freshman engineering courses are beginning to emerge in engineering curricula. The most common educational goals in freshman engineering courses are to expose students to the nature of the design process, the creativity inherent in design, the trade-offs associated with meeting design objectives, and the iterative nature of the engineering design process. Courses necessarily have no pre-requisites and often involve engineers from multiple disciplines. Because these courses frequently seek to expose students to the contributions that engineers can make in solving the grand challenges facing human societies, the design problems used in these courses frequently incorporate environmental constraints and objectives. For these types of freshman design courses, a number of commonly taught principles of green or sustainable engineering could be included. Since most engineering designs involve the specification of materials, students can be introduced to the energy and environmental footprints of commodity materials as they select materials for their designs. The introduction of material footprints would also introduce students to supply chain (life cycle) implications of their material choices and would introduce students to engineering trade-offs, as they seek to simultaneously minimize energy use, materials use and emissions. Recognizing that product functionality, energy use, material use and emissions targets are often in conflict leads directly into topics of environmental cost accounting practices that attempt to monetize environmental performance. All of these principles can be applied at multiple scales, ranging from the molecular (e.g., design of molecules that could serve as replacements for gasoline) to the product or process level (e.g., design of a process to grow algae to make diesel fuel) to the design of infrastructures (storage and delivery systems for biofuels).

Senior Design Senior capstone design courses are ubiquitous in engineering curricula. As capstone courses, they seek to synthesize material students have been exposed to throughout their curriculum through a design challenge. The educational goals parallel freshman design courses. The goals are to expose students to the nature of the design process, the creativity inherent in design, the trade-offs associated with meeting design objectives, and the iterative nature of the engineering design process. Just as in freshman courses, the design problems frequently incorporate environmental constraints and objectives. So for senior design courses, like freshman design courses, the commonly taught principles of green or sustainable engineering that could be incorporated are life cycle assessments, environmental cost accounting, and energy and material use profiling of designs. In senior design, case studies can draw on more sophisticated engineering analyses, but the underlying elements remain the same.

Summary

There are multiple mechanisms and approaches for incorporating green or sustainable engineering concepts into engineering curricula. Although the approaches used by different institutions have been diverse, there is a group of core sustainable engineering concepts that have become widely accepted by engineering educators, and increasingly, 21st century engineers will learn to master and practice the principles and tools of sustainable engineering.

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