Int. J. Engng Ed. Vol. 23, No. 2, pp. 276–286, 2007
Printed in Great Britain.

0949-149X/91 $3.00+0.00

Green Design in First-Year Engineering*

ANDREW S. LAU
Penn State School of Engineering Design, Technology, and Professional Programs, 213-F Hammond Building, University Park, PA 16802, USA. E-mail: andylau@psu.edu

This paper begins by describing the evolution of the concept of green design over the last several decades. In its earliest form, the focus was on reducing waste, pollution, and resource use. In its current form, it includes the concepts of sustainability and industrial ecology, adding in a focus on nature and the future. This reflects a shift to renewable resources as well as considering the impact of technology on society. The author recommends two additional principles that need to be more explicitly incorporated into green design: ecological constraints and natural systems as models. A succinct definition of green design is proposed: green design means practicing engineering with the inclusion of natural systems, both as a model and as a fundamental consideration, for the improvement of the quality of all life. Following this introduction is a description of how these principles have been incorporated into first-year engineering courses. In the author's course, students are introduced to key concepts through readings, videos, lectures, and exercises, and then they apply the concepts to hands-on projects including cardboard furniture and loudspeaker redesign. A comprehensive summary of tools, resources and techniques is presented.

Keywords: green design; sustainability; first-year; biomimicry

INTRODUCTION: WHAT IS GREEN ENGINEERING/DESIGN?

CURRENTLY THERE is no standard definition of "green engineering". Over the last several decades, there have been many developments related to the incorporation of environmental and ecological principles in engineering and design. An examination of these sheds some light on how this field has evolved and to where it may be heading. The next section concludes with a proposed definition that attempts to capture a comprehensive understanding of the term "green design." The author proposes to use "green design" and "green engineering" interchangeably, a distinction being that green design is the process through which engineers apply green engineering/design principles.

One of the first publications to use the term "green design" was *Green Products by Design* by the U.S. Office of Technology Assessment (OTA) [1]:

> OTA uses the phrase "green design" to mean . . . a design process in which environmental attributes are treated as *design objectives,* rather than as *constraints.* A key point is that green design incorporates environmental objectives with minimum loss to product performance, useful life, or functionality. In OTA's formulation, green design involves two general goals: *waste prevention* and *better materials management* . . . These goals should be viewed as complementary: while designers may reduce the quantity of resources used and wastes generated, products and waste streams will still exist and have to be managed.

This explanation is supplemented by an illustration, reproduced here as Fig. 1. A significant emphasis of OTA's explanation is that environmental considerations are best addressed in the design process as objectives. This was important at the time because much of the previous consideration of the environment in engineering was in mitigating or managing wastes and pollution at the end of the pipe. It is also significant that the impact of a product is considered not just during production, but also during service at the end of service life. Although the term does not appear in the source, the concept of *life cycle assessment* is clearly acknowledged.

In the 1990s, the U.S. Environmental Protection Agency developed the concept of green engineering [2]:

> Green Engineering is the design, commercialization and use of processes & products that are feasible & economical while:
> - Reducing the generation of pollution at the source.
> - Minimizing the risk to human health & the environment.

While similar to OTA's definition of green design in reducing waste and pollution, this definition clearly states the more overarching goal of risk minimization, a goal that is perhaps implicit in OTA's work. An attempt to capture the goals in these two sources is:

> Green design minimizes the risk to human health and the environment by reducing pollution and waste over the life of a product or service.

This takes us well along in the evolution of the concept, but consider the tone of this definition. The two active words are "minimizes" and "reducing." As architect William McDonough has

* Accepted 15 December 2006.

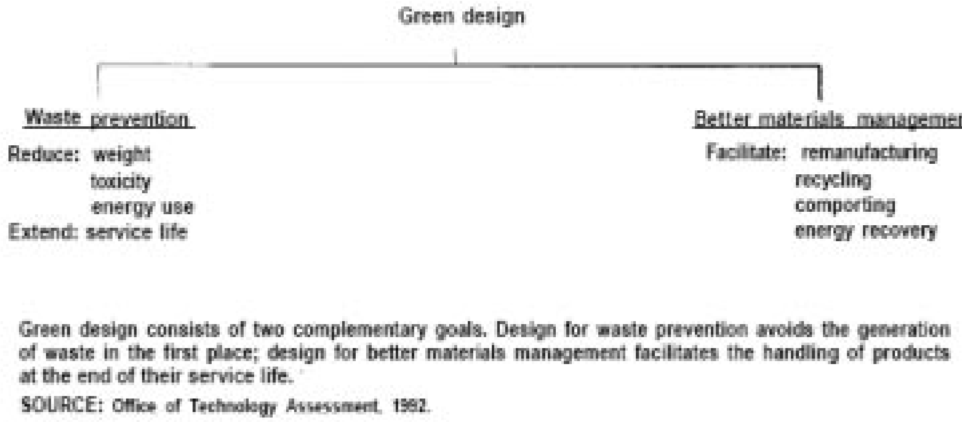

Fig. 1. The dual goals of green design. [1]

astutely observed, this definition equates to "being less bad" [3]. In a way, it implies that waste and pollution are acceptable or perhaps inevitable. Furthermore, it is challenging to get people engaged when presented in this way. What begins to emerge in the mid-90s is a more positive goal that is reflected in the next source—the concept of *sustainability*. From Carnegie-Mellon University's (CMU) *Introduction to Green Design* [4]:

> We can advance three general goals for green design in pursuit of a sustainable future:
> • reduce or minimize the use of non-renewable resources;
> • manage renewable resources to insure sustainability; and
> • reduce, with the ultimate goal of eliminating toxic and otherwise harmful emissions to the environment, including emissions contributing to global warming.
> The objective of green design is to pursue these goals in the most cost-effective fashion.

The concept of sustainability originated in *Our Common Future* [5] as the ability to meet the needs of the present without compromising the ability of future generations to meet their own needs. This concept has one distinguishing new feature: it addresses the responsibility of this generation to future generations. It recognizes that what we do today can have a profound impact on the world of tomorrow. In addition, CMU specifically mentions the distinction between renewable and non-renewable resources. Sustainability ultimately depends on no depletion of non-renewable resources and appropriate management of renewable resources. The CMU goals add another new twist, the idea of ultimately eliminating wastes. Yet we still have words like "reduce" and "minimize."

As the most recent chapter in the evolution of green design, in May of 2003 a meeting, "Green Engineering: Defining the Principles Conference", was held in Sandestin, Florida, co-sponsored by AIChE, ASME, and SAE. At this meeting, the participants prepared the following principles [6]:

> Principles of Green Engineering:
> 1. Engineer processes and products holistically, use systems analysis, and integrate environmental impact assessment tools.
> 2. Conserve and improve natural ecosystems while protecting human health and well-being.
> 3. Use life-cycle thinking in all engineering activities.
> 4. Ensure that all material and energy inputs and outputs are as inherently safe and benign as possible.
> 5. Minimize depletion of natural resources.
> 6. Strive to prevent waste.
> 7. Develop and apply engineering solutions, while being cognizant of local geography, aspirations, and cultures.
> 8. Create engineering solutions beyond current or dominant technologies; improve, innovate, and invent (technologies) to achieve sustainability.
> 9. Actively engage communities and stakeholders in development of engineering solutions.

Here we have a most comprehensive elaboration of green engineering, with several important additions. First is goal 1, the idea that systems analysis and holistic thinking are required. This author attributes this goal to the field of industrial ecology, which has been eloquently described and developed by Graedel and Allenby [7]:

> Industrial ecology is the means by which humanity can deliberately and rationally approach and maintain sustainability, given continued economic, cultural, and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems view in which one seeks to optimize the total materials cycle from virgin material, to finished material, to component, to product, to obsolete product, and to ultimate disposal. Factors to be optimized include resources, energy, and capital.

Goal 2 above is also significant in its call to go beyond being less bad to actually *improve* natural ecosystems. Goal 8 also invokes a positive message, of innovation and improvement of technologies to achieve sustainability. Finally, we have goals 7 and 9, which seek to provide the context of green engineering as embedded in people and culture.

With these nine principles of green engineering, the field has reached a reasonable level of maturity, at least in its description. Our challenge now is to incorporate and implement these principles in engineering education and practice. Green engineering is not a new discipline like mechanical engineering, but a new way of practicing all of engineering. Before moving on to a description of efforts to teach green design to first-year engineering students, the author seeks to describe an important additional development he feels needs to be added to green design.

NATURE AS MODEL—THE NEXT STEP IN GREEN DESIGN

The author proposes that two important additional principles need to be incorporated into green design. One is recognizing and elaborating natural constraints imposed on earth-based systems. These constraints are drawn from ecology. The second is looking to natural systems for models on which to develop our industrial systems. While both of these principles are at play in the nine principles of green engineering in the previous section, they need to be explicitly stated and applied to achieve sustainability.

The natural constraints have been defined by William McDonough and Michael Braungart by looking at the earth's living systems [3]. The three principles are:

1. Waste = Food
2. Use current solar income
3. Respect diversity

By practicing design using the three principles above, McDonough and Braungart believe that we can take delight in our products, and that they can replenish, restore, and nourish the rest of the world.

Figure 2 captures these principles and is based on a presentation made by McDonough at the 2002 meeting of the American Solar Energy Society. This view puts all of matter ideally into two cycles, or metabolisms. There is the technical metabolism on the left, wherein materials are recycled back into industrial goods. On the right is the biological metabolism, or the biosphere. The goal is for all of the products and materials manufactured by industry to safely feed these two metabolisms, thereby eliminating waste. Recognizing that this may not ever be perfectly achievable, particularly in the short term, because some materials are too hazardous, there is a category of *unmarketables*. These are materials that must be safely stored until we develop ways to detoxify them. Ultimately the goal is to have no unmarketables. Another principle illustrated here is that of using current solar income as the only natural and sustainable energy source.

The second new principle for green design is looking to natural systems for models on which to develop our industrial systems. In her book, *Biomimicry*, Janine Benyus describes this new vision, in contrast with the Industrial Revolution, as being "based not on what we can *extract* from nature, but on what we can *learn* from her" [8]. It is based on an ecological view of life, with emphasis on the potential for us to learn from nature how to build our systems so that they fit in. Benyus examines several different projects that exemplify biomimicry, from analyzing how spiders manufacture a waterproof fiber five times stronger than steel from digested insects, to studying how electrons in a leaf cell convert sunlight to fuel. Biomimicry extends the idea of basing our human activity on ecological principles, to actually modeling our systems on living systems. It represents a move from dominating and devaluing nature to partnering with her.

Based on all that has presented thus far, the author proposes this succinct definition of green design:

> Green design means practicing engineering with the inclusion of natural systems, both as a model and as a fundamental consideration, for the improvement of the quality of all life.

GREEN DESIGN IN FIRST-YEAR ENGINEERING

But for a few notable exceptions, green design concepts are typically incorporated into upper-

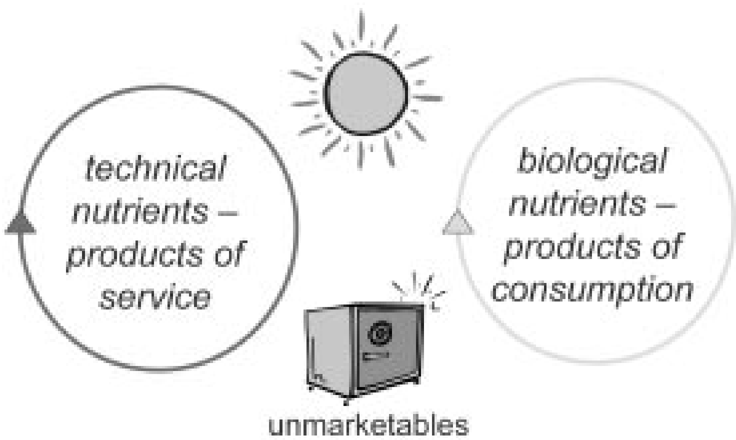

Fig. 2. The two metabolisms involved in eco-effectiveness.

level engineering courses. Yet to communicate the message that green design is important, similar to engineering ethics, students should be exposed to it throughout their curriculum [9]. Although the concepts and methods presented here are unique to the author's section of the course, some of the techniques have already been adopted by other faculty. Further initiatives in the College of Engineering regarding sustainability and green engineering are under development. Penn State is in a position to make significant advances in sustainability education.

Some of the programs with first-year initiatives are summarized first to provide further resources for the engineering education community. The two schools that stand out are Virginia Tech and Rowan University.

At Virginia Tech, the Division of Engineering Fundamentals teaches a two-course sequence, Introduction to Engineering I and II, to over 1200 first-year engineering students [10]. They have incorporated green engineering into the first of these two courses, a two-credit hour course set up to introduce students to engineering disciplines and the engineering profession, particularly ethics. The green engineering approach is to introduce a "green awareness" through expansion of traditional problems to include environmental issues. Kampe and Knott describe an "Orange Juice Problem" that raises issues of energy use, waste, recyclability, water use, and consumer preferences. Elements of life-cycle analysis arise by considering: the manufacturing process and packaging; product transportation and storage; product use; and packaging disposal. This problem is one of two substantial homework problems used in the course; the other is based on the ethics case study "Gilbane Gold" [11]. An additional method used to raise green awareness was an introductory lecture to all sections given by a prominent judge that "highlighted personal links between the students and the environment in illustrating the importance of green concerns in their careers and lives". Future plans are to expand the number and scope of the problems with green considerations.

Rowan University has incorporated green engineering and sustainability into every year of their clinic-based engineering curriculum [12]. In their first-year engineering clinic, one topic is a product dissection wherein students analyze key materials using a life-cycle assessment (LCA). Students are also provided an introduction to environmental regulations. In addition to the clinics, a First Year Experience course has been developed on "Issues of sustainable development" [13]. The course is team taught by a faculty person in engineering and one in business, and is intended to "promote intercultural dialogue and understanding as a means to reduce prejudice and bigotry." Besides increasing awareness of sustainability challenges and issues, the course explores various institutions and their roles in development.

INTRODUCTION TO ENGINEERING AT PENN STATE

At Penn State, most engineering students must take ED&G 100, Introduction to Engineering Design, and most take it in their first year. Only two majors in the College of Engineering do not require ED&G 100: Computer Science and Engineering has no first-year design or graphics course, and Architectural Engineering requires EG 130, Engineering Graphics, instead. At University Park and the other Penn State campuses, approximately 1800 students complete ED&G 100 each year.

The course is three credits and meets three times a week for fourteen (in fall semester) or fifteen (in spring semester) weeks. Each meeting is for two 50-minute periods, which is twice that for a lecture-based course, reflecting the hands-on practicum nature of ED&G 100. At University Park, our facilities for the course allow for one of the weekly meetings to be in a typical technology classroom with a computer tied to a projector mounted in the ceiling, and flexible seating with tables and chairs that can be moved around. Another class is in a room that has lab benches designed for each team to have a bench and a computer. This room, called the "design lab," also has a main computer with projector, as well as testing and measurement equipment. Adjacent to it is a workshop with woodworking tools that students can use to make prototypes. This workshop also has a rapid prototyper that students can use. The third meeting room is a computer lab with custom-designed tables allowing teams of four students to sit together and each have a computer. This room is mainly used to teach and apply solid-modeling software, but is also used to teach use of spreadsheets, web page design, and other computer-intensive applications.

The core course learning objectives are that students completing the ED&G 100 course will have:

- An ability to conceptually design a system or process to meet desired needs using design selection concepts;
- An ability to apply knowledge of basic science and mathematics to engineering;
- An ability to conduct basic experiments, as well as analyze and interpret data;
- An introductory experience in functioning in small teams;
- An introductory ability to identify, formulate, and solve engineering problems;
- An introductory ability to communicate effectively in oral, written, and graphical media; and
- An ability to use CAD, spreadsheet, and internet application tools necessary for engineering practice.

The course has continued to evolve from one that mainly taught students engineering graphics to one that focuses on the engineering design process, with graphics being one of the communication skills supporting the design process.

As it is now constructed, the course uses two significant projects as the context for teaching design. The first project ranges from product dissection to product design, with different faculty choosing and developing their own projects. The second project is industry sponsored, and typically all teams in all sections work on the same project. Students learn to apply the product design process, from customer needs assessment, through ideation, research, analysis, testing, concept selection, detailed design, prototyping, and reporting.

GREEN DESIGN OBJECTIVES IN FIRST-YEAR ENGINEERING

In the author's section of the course, additional objectives have been developed relating to green design. These include that students should be able to:

- Define sustainable development, eco-effectiveness, biomimicry, industrial ecology, life-cycle analysis (LCA), and green design;
- Apply and interpret sustainability metrics such as ecological footprint and LCA;
- Identify and investigate relevant green design issues as part of design development; and
- Incorporate green engineering attributes in defining materials and finishes.

As these objectives are developed in the course, the intention is that the pedagogy and techniques can be refined and transferred to other sections, and eventually be added to the core objectives. This paper has been written as well to inform other faculty, outside of Penn State, of these developments in the hope that they could be used to improve first-year engineering design education.

In addition to stating the course objectives, the author's syllabus begins with this paragraph, and the accompanying figure (Fig. 3):

> Engineering design describes the creative aspect of engineering, wherein engineers use their academic preparation, personal skills, experience, and judgment to make things to improve life. As shown in this picture, design can be considered as an object that is built on a solid foundation of ethics, which is built upon the cultures and people of the Earth, which in turn is built upon nature, the Earth and its living and material systems. Good design reflects and builds upon this hierarchical foundation, while also impacting, and hopefully, nurturing the world of nature and people.

In what follows, the specific techniques and resources used will be described to achieve the course goals. These have been developed over the last two years and reflect some refinement of technique based on experiences in the classroom. The reader will note that the scope of the green design topics and resources go beyond the stated course goals and reflect many of the larger set of green design principles presented in the introduction section.

GREEN DESIGN PROJECTS IN FIRST-YEAR ENGINEERING

The most significant change in the course to incorporate green design has been the first design project. To emphasize the relevance and importance of green design, projects have been developed that focus on environmental attributes and sustainability.

Cardboard furniture

In spring and fall semesters of 2004, the project was for student teams to develop working prototypes of useful cardboard furniture for their residence hall rooms. The design constraints as stated to the students are:

1. Uses mostly salvaged cardboard (95% by weight), preferably all cardboard
2. Capable of being disassembled for transport in a typical mid-size car trunk (and reassembled)

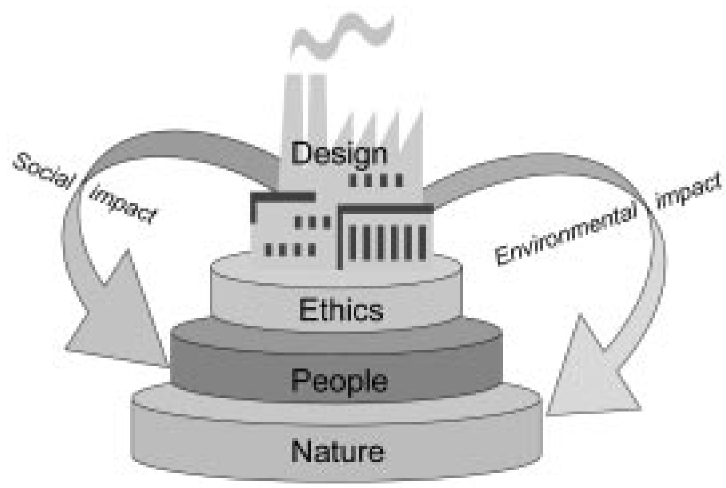

Fig. 3. Engineering design in context.

3. Supports significant weight (at least 50 lb or more as appropriate for the function)
4. Recyclable as corrugated cardboard
5. Ergonomically appropriate for college students
6. Aesthetically pleasing
7. Safe

The emphasis in this project, from a green perspective, is on materials. It is relatively straightforward to talk about product life-cycle with corrugated cardboard, as most of it is made from recycled paper and cardboard, glued with biodegradable cornstarch-based adhesive, and once its service life is up it is readily recycled into new cardboard.

One of the key considerations for the students is the other materials they may want to use in their designs and the associated environmental concerns. In particular, adhesives and finishes such as paint are often considered. Students do research to try to find data and resources to help them make informed decisions. What they find is that this kind of data is typically not readily available in a consistent and comprehensive way. This can be frustrating but is indicative of the challenges faced in green design. They are required to make judgments based on limited data and to document their reasoning.

Figures 4 and 5 show two of the more successful projects from spring semester 2004. This was the first time using the project and did not include the requirement to be able to be disassembled for transport. Figure 4 is a sturdy and attractive entertainment center designed to fit around the standard mini-fridge and microwave in the residence halls. Egg-crate like reinforcing was used inside the shelf surfaces for added strength and stability. Figure 5 is a chair that features interesting box elements with unique shapes for the arms, and salvaged tripod boxes for legs. The addition of the requirement for disassembly and transport in fall semester 2004 furthered the challenge involved while helping to reinforce the idea that the products should be so useful that one would want to keep them and use them in subsequent years.

Other valuable design experiences in this project, in addition to the green design, included testing of cardboard elements for strength using an apparatus derived from work on bridge design with manila folders [14]. Teams assembled columns using different cross-sections and lengths to study the effects on compression failure strength. Another good experience was drawing the components to scale and producing scale models using manila file folders. This allowed the teams to study how the pieces would fit together and led to modified designs in many cases. Figure 6 shows a

Fig. 4 Cardboard entertainment center.

Fig. 5. Cardboard chair.

Fig. 6. Interlocking base.

Fig. 7. Loudspeaker design using PVC and MDF.

table base that cleverly uses tabs and triangular elements to form a strong support that can be easily disassembled. This configuration emerged after experimenting with the scale models.

Loudspeaker redesign

To further emphasize green design in the first project, a new project was developed and used in spring semester 2005. In one of the first-year seminars, one-credit courses meant to introduce new students to engineering, Professor Steve Garrett in the Acoustics Program had developed a unique loudspeaker, shown in Fig. 7 [15]. The two main materials used in the enclosure are polyvinyl chloride (PVC) pipe and fittings, and a medium density fiberboard (MDF) base. Because of issues raised about PVC in the green building field, the author realized that this would be an opportunity for ED&G 100 students to redesign the speakers using green design.

Not only did this prove to have excellent green design opportunities, particularly application of streamlined LCA (SLCA), the students readily identified with the utility of an excellent sounding speaker. Many alternative materials were considered, ranging from agricultural board products to sustainably harvested hardwoods. The distinction between rapidly renewable materials, made from wheat, soy, straw, etc., and hardwoods arose during this investigation. It also became clear that, while some very interesting agri-board products are on the market, they are not readily available in small quantities, nor are they locally made. The final designs were based on three different materials:

1. Cardboard shipping tubes made from 100% recycled craft paper and glued with sodium silicate, a relatively benign adhesive. Another advantage of these tubes is that they were manufactured within 150 miles of the campus.
2. Sustainably-harvested hardwoods including poplar, cherry, and oak. Again these were produced from Pennsylvania forests within 150 miles of campus.
3. Woodstalk^{TM}, an MDF board made by Dow BioProducts from wheat straw and polyurethane resin. This product is not produced locally but does use mainly rapidly renewable materials.

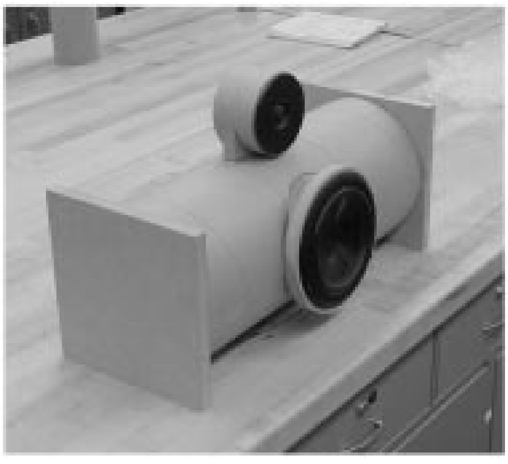

Fig. 8. Speaker design using paper-wound shipping tubes.

An example of a design using primarily the shipping tubes is shown in Fig. 8. All of the speakers sounded excellent and received good reviews from Professor Garrett. He is planning to offer an alternative design using both the shipping tubes and Woodstalk^{TM} materials in his seminar.

Student teams learn to perform SLCA and to prepare spider plots as illustrated in Fig. 9 for PVC. The labels around the outside of the diagram stand for the stage in the product/material life-cycle (number from 1 for pre-manufacture to 5 for post-use) and the factor being considered (M for Materials, E for Energy, and P for Pollution). The higher the number on the radial axis, the greater the negative impact. This process is elaborated in a chapter on Green Design, written by the author, which describes SLCA and how to construct a spider plot using Excel [16]. While this analysis does require some estimation on the part of the students, it serves to illustrate a way to make relative comparisons between materials in a design.

In addition to the green design attributes of this speaker project, students learn some basic speaker theory by testing the woofer's frequency response and moving mass, allowing them to consider the impact of speaker enclosure volume on the system performance. They also learn about two-way speakers and crossover circuits, and construct the custom-designed crossover circuit for their speaker. They furthermore gain some knowledge of cabinetry, joinery, and shop practices. Additional test equipment is being implemented to allow audio testing of the completed speakers.

Second design project

Each semester, a new project is developed in concert with an industry partner. Students are required to apply their knowledge of green design to these projects, and practice from the more structured first project prepares them for this

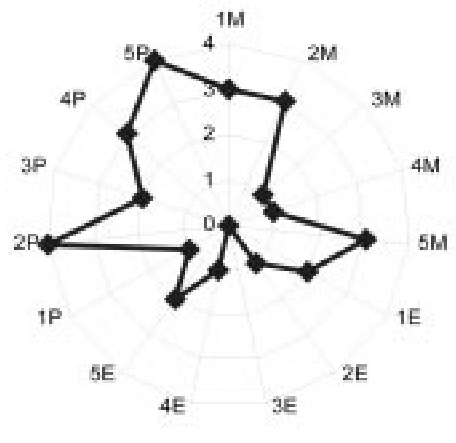

Fig. 9. Spider plot from the SLCA of PVC.

more open-ended assignment. In spring semester 2005, the project involved developing a portable stand for a portable message board used for traffic and emergency message displays. An additional design constraint in the author's section was for the stand to be constructed from materials that can be readily recycled, and that the parts can be easily disassembled for recycling or reuse. Most of the designs used aluminum structural members.

ADDITIONAL GREEN DESIGN TOPICS IN FIRST-YEAR ENGINEERING

The author has assembled many different resources and tools to teach principles of green design and sustainability to first-year students. Several of these are discussed in the previously mentioned chapter on green design by the author; key topics will be described next, and all of the additional topics and resources are summarized later. In addition to being a tenured faculty member, the author is a partner in a consulting firm specializing in green buildings. Experiences and anecdotes from this practice serve to further develop some of the concepts and to demonstrate their relevance in the "real" world.

Setting the stage—environmental impact

The concept of *environmental impact* attempts to combine the key influences on human impact on the natural world. The equation that describes this, called the IPAT equation, is [17]:

$$I = P \times A \times T$$

Environmental Impact =
Population × Affluence × Technology

This formula is used to gauge the overall effect of people for comparison with the Earth's carrying capacity. It is also used to consider estimates of future trends and technological changes necessary to manage our impact.

World population increased rapidly after WWII, and in 1999 passed the 6 billion mark. The rapid increase after WWII was largely a result of longer lives from improved access to food, medicine, clean water, and sanitation. A reduction in death rates, coupled with access by women to education and birth control, leads to a reduction in birth rates. While some countries continue to have high population growth rates, the United Nations projections for world population predict a leveling off at about 9 billion by 2050 [18]. This is good news relative to impact—population is projected to stabilize by mid-century. Of course, these are projections and the range of UN projections for 2050 is from 7.4 to 10.6 billion people.

The second component of impact is affluence; i.e. how much stuff a person has. This is why we often hear that an average American has a much higher impact than an average person in a developing country, and it is true. There is cause for concern here because, even though population is likely to level off, the desire for more stuff seems insatiable. This aspect of impact may be the most challenging to control, and it depends mostly on psychological and sociological factors, therefore not directly affected by the work of engineers.

The third aspect of impact, however, is very much the realm of engineers—technology. With regard to impact, technology refers to the level of resource use and waste generation associated with a certain level of technological development. In other words, technology attempts to account for the environmental impact of making our stuff (affluence). The historical trend of the Industrial Revolution is at first for T to increase rapidly and then to increase less rapidly as more effort and resources are put into reducing impact through technology. Consider that, over the next 50 years, P will increase by about 1.5 and A is estimated to increase by a factor of 3 to 5 [7]; therefore, just to maintain the same overall impact will require decreasing T by a factor of 4.5 to 7.5. This assumes that the present level is acceptable and sustainable, a question that can be addressed by turning to *ecological footprint*.

Setting the stage—ecological footprint

To engage students in appreciating green design and sustainability, one of the first assignments is to determine their *ecological footprints*. The concept of ecological footprint (EF) was developed to be an indicator and measure of the effective land area necessary to support human activity [19, 20]. It is a measure of the amount of the earth's productive surface required to supply our resources and assimilate our wastes. It provides a tangible indicator of our impact on the earth.

There is an on-line calculator to estimate one's EF at www.progress.org. Output from the author's analysis is shown in Fig. 10. There is a lot of information here, starting with the author's ecological footprint of 16 acres. While this seems reasonably large, it can be put into perspective in three ways. First, the average EF of a U.S. resident is listed as 24 acres per person. That's encouraging for the author, since his EF is 33% less than average. Now the bad news. As Fig. 10 shows, the earth has only 4.5 acres of biologically productive acres per capita (if everyone had an equal share and we set aside 12% for biodiversity preservation). The third perspective in Fig. 10 shows that, if everyone on earth lived like the author, it would require 3.7 earths. In another area of the website you can find that globally we are exceeding the earth's carrying capacity by 20% (as of the year 1999).

Students are assigned to visit the website, use this calculator for their current lifestyle, and then to compare it with the U.S. average and the average available worldwide. Many students experiment to see what behaviors they can change and how it impacts the EF estimate. They learn that it is quite challenging in the U.S. to

Fig. 10. Estimated ecological footprint for the author.

approach the 4.5 acres that is the worldwide average available.

Coupling the previous IPAT relation and future trends with the global EF estimate that we exceed global carrying capacity by 20% results in the observation that, in order not to exceed global sustainable capacity by 2050, society will need to improve technological efficiency by a factor of 5 to 9. The author impresses upon students that this, though challenging, presents excellent opportunities for, indeed requires, engineering innovation and entrepreneurship. It is put into perspective by estimating that the overall efficiency of producing useful light by burning coal in a power plant to light a fluorescent light is about 2–4% overall. Similarly, moving a person around with a typical car, considering that all one needs to do is move one's self, is about 1–2% efficient. Clearly, increases by a factor of 10 are within the realm of possibility.

Summary of other topics and resources

There are several other green design topics and resources used in the course. These are summarized in Table 1. It should be evident that significant time and attention are devoted to teaching students about green design and its relevance to engineering practice. The next to last topic in the table, oil peak and future, just arose this past semester and provoked a lot of discussion, since oil is anticipated to be effectively gone in the students' lifetimes. Connecting to larger timely issues helps to engage students and further demonstrate the relevance of green design. The last topic in the table, sustainability and popular culture, is also meant to get students to identify course themes with their larger lives. Encouraging them

Table 1. Summary of other green design topics, resources, and assignments

Topic/Issue	Resources	Activity
Products of green design	*Sustainable design* [21]: A 21-minute video describing three products—the Smart Car, a wind-up radio, and a pencil made from recycled polystyrene. The wind-up radio is significant because it was originally designed for use in developing countries.	Students watch video and discuss afterwards. Two products with the wind-up feature, a flashlight and radio, are demonstrated.
Eco-effectiveness: natural principles	1. *The Next Industrial Revolution* [22]: A 55-minute video featuring Bill McDonough and Michael Braungart. Includes principles and corporate examples of green design. 2. *The Next Industrial Revolution* [23]: An article describing eco-effectiveness and natural principles. A good summary of their book, *Cradle to Cradle* [3].	Students read paper and watch video, followed by a class discussion. A two-page paper is required summarizing what they learned from the video, article, ecological footprint exercise, and the "Computers" article.
Product life-cycle	"Computers", a chapter from *Stuff: The Secret Lives of Everyday Things* [24]: Discusses the life-cycle environmental issues of personal computers.	See previous.
Green buildings	*Lessons Learned* [25]: A 30-minute video that describes the integrated design process that led to a LEED gold building, PA Department of Environmental Protection's Cambria Office Building (on which the author consulted).	Students view video, followed by a class discussion.
Renewable energy	*PA Energy* [26]: A 30-minute video describing renewable energy technologies for Pennsylvania including biofuels, wind, solar, ground-source heat pumps, photovoltaics, and energy efficiency.	Students view video, followed by a class discussion.
Oil peak and future	1. "The Long Emergency" [27]: An article that is based on the new book of the same title that claims peak oil production will be soon and that dire consequences will follow. 2. "Oil End Game" [28]: An article also claiming oil production will peak soon but with a much more positive, pro-technology stance.	Students read both articles and write a two-page paper for each.
Sustainability and popular culture	1. *I Heart Huckabees* [29]: A recent comedy movie that has a wide-ranging plot with the central character being a young environmentalist. One of the author's favorite movies. 2. Popular music: Students are invited to bring songs (with lyrics) that they like to class and relate to the green design themes and topics. The author initiated this with the song "Comfort Eagle" by Cake, which he believes is about consumerism as the new religion.	Free-ranging discussion after the movie and songs that are contributed by students.

to listen to their music with an ear to recognizing messages relevant to the course was reasonably successful and will be further developed in future semesters.

CONCLUSIONS

Green design has evolved over the last 15 years into a reasonably mature discipline, at least in principle. By incorporating published principles, along with nature as a model and context, the following definition was developed by the author:

> Green design means practicing engineering with the inclusion of natural systems, both as a model and as a fundamental consideration, for the improvement of the quality of all life.

The challenge now is to incorporate green design into all of the engineering disciplines. To demonstrate the importance of green design, it should be taught throughout undergraduate engineering education, yet only a few schools have implemented this for first-year students.

In the first-year engineering design course at Penn State, the author has developed new introductory projects emphasizing green design. One project involves producing a working prototype of cardboard furniture for residence halls, and the other is a redesign of a loudspeaker. In both projects, material selection is the focus, incorporating streamlined life-cycle assessment. Students learn to make estimates and to use SLCA analyses in selecting materials. Lessons learned in the first more structured project are applied to the second, more open-ended industry-sponsored project.

A wide range of other topics and resources are used that relate to the principles of green engineering and the definition of green design proposed above. By continually exposing students to videos, readings, and related discussions and homework assignments, the author demonstrates the importance of green design in engineering practice and in their larger lives.

REFERENCES

1. *Green Products by Design: Choices for a Cleaner Environment*, Office of Technology Assessment, OTA-E-541 (September 1992).
2. www.epa.gov/oppt/greenengineering.
3. W. McDonough and M. Braungart, *Cradle to Cradle: Remaking the Way We Make Things*, North Point Press, New York (2002).
4. http://www.ce.cmu.edu/GreenDesign/.
5. *Our Common Future: World Commission on Environment and Development*, Oxford University Press, New York, NY (1987).
6. Green engineering: Defining the principles, Engineering Conferences International, Inc., Sandestin, FL (18–22 May 2003).
7. T. Graedel and B. Allenby, *Industrial Ecology*, 2nd edition, Pearson Education, Upper Saddle River, NJ (2003).
8. J. Benyus, *Biomimicry: Innovation Inspired by Nature*, HarperCollins, New York (1997).
9. R. Hesketh, C. Slater, M. Saveleski, K. Holler and S. Farrell, A program to help in designing courses to integrate green engineering subjects, *International Journal of Engineering Education*, **20**(1) (2004), pp, 113–123.
10. J. Kampe and T. Knott, Exposing first-year students to green engineering, 2002 American Society for Engineering Education Annual Conference, Montreal, Quebec, Canada (June 2002).
11. Gilbane Gold [videorecording], National Society of Professional Engineers, Alexandria, VA (1989).
12. C. Slater, R. Hesketh, D. Fichana, J. Henry and A. Flynn, Expanding the frontiers in green engineering education, 2005 American Society for Engineering Education Annual Conference, Portland, OR (June 2005).
13. B. Sukumaran, J. Chen, Y. Mehta, D. Mirchandani and K. Hollar, A sustained effort for educating students about sustainable development, 2004 American Society for Engineering Education Annual Conference, Salt Lake City, UT (June 2004).
14. http://bridgecontest.usma.edu/pdfs/appendc.pdf.
15. S. Garrett and J. Heake, Hey kid! Wanna build a loudspeaker? The first one's free, Annual Convention of the Audio Engineering Society, New York, NY (10–13 October 2003).
16. M. Ogot and G. Kremer, *Engineering Design: A Project-Based Introduction*, Trafford Publishers, British Columbia, Canada (2004).
17. P. Ehrlich and J. Holdren, Impacts of population growth, *Science*, **171** (1972), pp. 1212–1217.
18. United Nations Population Division, World population prospects: The 2002 revision population database, http://esa.un.org/unpp/ (2003).
19. W. Rees and M. Wackernagel, *Our Ecological Footprint: Reducing Human Impact on the Earth*, New Society Publishing, British Columbia, Canada (1996).
20. N. Chambers, C. Simmons and M. Wackernagel, *Sharing Nature's Interest: Ecological Footprints as an Indicator of Sustainability*, Earthscan Publications, London (2001).
21. Sustainable design [videorecording], Classroom Video, Warriewood, N.S.W. (2001).
22. The next industrial revolution [videorecording], Earthome Productions, Stevenson, MD (2001).
23. W. McDonough and M. Braungart, The next industrial revolution, *Atlantic Monthly* (October 1998).
24. J. Ryan and A. Durning, *Stuff: The Secret Lives of Everyday Things*, Northwest Environment Watch (1997).

25. Lessons Learned [videorecording], Penn State Public Broadcasting Media Solutions, www.mediasales.psu.edu (2003).
26. PA Energy [videorecording], Penn State Public Broadcasting Media Solutions, www.mediasales.psu.edu (2004).
27. J. Kunstler, The long emergency, *Rolling Stone* (13 April 2005).
28. A. Lovins, E. Datta, O. Bustnes, J. Koomey and N. Glasgow, Winning the oil end game: Executive summary, http://www.oilendgame.com/ExecutiveSummary.html (2005).
29. *I Heart Huckabees* [movie], Twentieth Century Fox Home Video (2005).

Andrew S. Lau is Associate Professor of Engineering, Coordinator of First-Year Seminars for the Penn State College of Engineering, and Associate Director of the Center for Sustainability at Penn State. Professor Lau received a B.Sc. in mechanical engineering (1977) from Penn State and an M.Sc. in mechanical engineering (1983) from the University of Wisconsin–Madison. He has been a faculty member at Penn State since 1984. He is a founding member of the Green Building Association of Central Pennsylvania and a partner in the 7Group, a green building consulting firm.