Bringing Environmental Sustainability to Undergraduate Engineering Education: Experiences in an Inter-Disciplinary Course

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Abstract

This paper chronicles the development of a unique interdisciplinary course in environmentally conscious design at Kettering University, a technologically focused Midwestern university. Funded by the National Science Foundation, a team of six faculty members at Kettering University adapted work done by Ford Motor Company to educate undergraduate STEM students about the subject of environmental sustainability. The authors describe their modular approach and use of active learning techniques in achieving significant learning outcomes for their students. Assessment results demonstrate the course's impact on student learning and achievement of learning objectives.

Introduction and Motivation

There are a growing number of calls for the inclusion of environmental sustainability in undergraduate engineering education. In February of 2008, the National Academy of Engineering announced a set of "Grand Challenges for Engineering. In their document, the NAE stated:

> As the population grows and its needs and desires expand, the problem of sustaining civilization's continuing advancement, while still improving the quality of life, looms more immediate.

In an earlier report the NAE stated that the growing environmental crisis means that "Engineering practices must incorporate attention to sustainable technology, and engineers need to be educated to consider issues of sustainability in all aspects of design and manufacturing" (NAE, 2004). ABET outcomes also speak to the need for sustainability education in outcomes (h) and (j) in its Engineering Accreditation program outcomes (ABET Engineering Accreditation Commission, 2007). These outcomes deal with: (h) "the broad education necessary to understand the impact of engineering solutions in a global and societal context" and (j) "a knowledge of contemporary issues."

Mulder writes of a crisis that the engineering profession faces in Western society. With the number of engineering graduates and the status of the profession in decline, there is a need to see sustainable development as a new paradigm. Mulder writes:

> However, the traditional top-down technocratic approach will not cope with the challenge of sustainable development. Democratizing technological decision making and increasing the participation of stakeholders will be important to prevent the failures of the past. Are engineers fit for the job? The basic features of most engineering training programs (the application of basic science and mathematics to technological problems) have not been changed since engineering schools were established. However, this approach is not a solid base from which to solve society's modern problems, as environmental problems are intimately connected to social and political issues. (Mulder, 2004)

Against this backdrop, an interdisciplinary group of faculty at Kettering University (the Kettering Industrial Ecology Team or KIET) set out in 2005 to develop a new course in environmental design. KIET's work came about after these faculty members observed that many engineering programs like Kettering's offer relatively little instruction in environmental sustainability. Content that does exist frequently focuses on air, water, and soil pollution rather than environmental sustainability in manufacturing and product design (Powers 2002). Kettering's curriculum has long focused on engineering and manufacturing, especially of automobiles, but has not focused on the environmental impact of these activities. KIET seeks to rectify this situation and to disseminate the results of our work freely with peer institutions. Funded with an NSF grant (DUE-0511322), the group created a new course (IME540 Environmentally Conscious Design) that brings together relevant knowledge from multiple disciplines and encourages active learning pedagogy. Notably, KIET adapted work done by Ford in their Partnership for Advanced Studies (PAS) project for high school students and shaped it for use at a university level (Poledink, 2004).

In addition, the KIET team sought broader impacts from this project. In particular, we want to make our curriculum attractive and meaningful to female students. Environmental engineering is more popular than any other engineering discipline for female and minority students (ASEE, 2003; Beder, 1989; Tietjen, 2004). The university has employed the industrial ecology coursework, for example, to attract these students to summer programs that in turn lead to full-time study. Additionally, KIET started a student led society named GEO (Green Engineering Organization) that organizes speakers and various "green" projects around campus.

Kettering University's co-op partners provide another clear signal of the need for coursework in industrial ecology. Historically, Kettering has deep roots in the manufacturing sector, especially among automotive firms. Concerns over the life cycle of automobiles and related legislation in the EU are examples that demonstrate the importance of the topic (Kimberley, 2004). Other industries with Kettering University ties have highlighted a need to focus on industrial ecology. For example, Michigan based furniture manufacturers have supported a need to focus on industrial ecology and have participated on the KIET advisory board. The demand for this type of education has led tothe class to broadening into a continuing education class for practicing professionals.

Comparison to Peer Schools

A review of the literature and comparison to peer schools reveals the uniqueness of KIET's course. This uniqueness shows in two related dimensions: the focus on engineering design and the holistic approach taken in teaching the subject. The former comes naturally from the institution's history as an engineering school. As noted above, ABET outcomes (h) and (j) taken together make a compelling argument for teaching students to design environmentally sustainable products. The need for a holistic approach became apparent to KIET as we worked with our industry advisory board. Environmental sustainability in product design is typically not a singular goal in modern corporations. Firms need to view "green" in the context of corporate social responsibility and the firm's business model.

Kettering University's efforts to provide inter-disciplinary education in sustainable design came early in a more general movement among engineering schools to do the same. A review of peer schools reveals a number of comparisons:

1. Rose Hulman began a "Home for Environmentally Responsible Engineering" program in the 2011–2012 year. Their efforts include residential living and specialized versions of composition and design courses (Rose-Hulman, 2011).
2. Renesselaer Polytechnic Institute implemented an elective residential program in the fall of 2011 and has a minor in sustainability courses based on courses in its Sciences and Technology area (Renesselaer Polytechnic Institute, 2011).
3. California Polytechnic State University has a "Sustainability Across the Curriculum" initiative that catalogs some 170 courses in multiple majors and minors includingsustainability content (California Polytechnic State University, 2011).
4. Lawrence Technological University has identified sustainability content across its curriculum and has incorporated these courses in a series of certificates (Lawrence Technological University, 2011).

Kettering University's efforts in the KIET initiative differ from those of their peers in several ways. First, KIET is unique in the strength of its inter-disciplinary focus on environmentally sound design for engineering students. The six-member KIET team collaborated in teaching a single course. Unlike peers who have tended to catalog and modify existing courses to embrace sustainability, the KIET effort involved the creation of a new course based on industrial input. In addition, Kettering University has incorporated active learning in an online environment.

Module Content

The KIET developed coursework for IME540 (Environmentally Conscious Design and Manufacture) in modules. Each module is further broken down into topics, as shown in Table 1 in the Assessment section below. This division allows for maximum reuse of the course material in other venues. The seven modules are as follows:

1. Technology, the environment and industrial ecology
2. Life-cycle concepts and assessment
3. Material selection strategies and requirements
4. Process design and improvement
5. End-of-use strategies
6. Environmentally responsible management
7. Green chemistry

We organize students into groups of three to four students at the beginning of the course. Each group picks or is assigned to work on a single product throughout all modules of the course. Examples of products studied include cell phones, printer cartridges, high-heeled shoes, toasters, and coffee makers. The objective of the course is for the students to redesign their chosen product from various environmental viewpoints using material learned in each module.

Although originally intended as a course for graduate and upper division undergraduate students, the material is readily adaptable for industry and other groups. Since KIET's creation, its members have shared modules with such diverse groups as business schools (the environmentally responsible management module) and environmental chemists (green chemistry). Modules from our class were incorporated at the community college level into a sustainability course, and at the high school level the material was incorporated in to a chemistry course.

Module 1—Technology, the environment and industrial ecology

In this module, the instructor introduces students to the historical implications of the industrial revolution on environmental sustainability. The class also considers the ethical and social dimensions of industrial activity on the environment. Next, the class introduces the notion of industrial ecology and sustainable business practices premised on the need to move to a more sustainable world. The instructor introduces students to environmental performance metrics and basic environmental science. Relevant readings required in this module include the classic "Tragedy of the Commons" by Garrett Hardin (1968).

Module 2—Life-cycle concepts and assessment

The immediate goal of Module 2 is to provide students with tools useful in determining the overall environmental impacts associated with a product. The long-term goal for the module is that the student will use the tools to develop products and processes that have a measurably lower impact on the environment. The module covers the concept of a product life cycle, including mining/processing of materials, manufacturing, transportation, use, and disposal. Students also learn about the types of environmental impacts associated with human activity and examples of the complexity of trying to determine the environmental impact of a product. As an in-class activity, students take an on-line quiz to gauge their personal environmental impact (Global Footprint Network, 2011). The key lesson for most U.S. students is that their lifestyle would not be sustainable if everyone on the Earth lived as they did.

Life Cycle Assessment (LCA) methodologies are introduced through a screening LCA method called Okala Ecological Design (IDSA, 2007). In a screening LCA, students learn to reduce all the environmental impacts of each material and manufacturing process to a single impact number (or factor). Students sum the factors for all of the materials and manufacturing processes used during a product's life cycle to determine the total environmental impact for a product. A lower total score indicates a lower environmental impact.

Module 3—Material selection strategies and requirements

The goal of the material selection module is to give the students tools to conduct material selection that reduces the environmental impact of a product while meeting functional requirements and targeted material costs. The instructor presents office furniture as an opening case study. Office furniture is an ideal topic because of the high amount of embodied energy (the quantity of energy required by all of the activities associated with a production process) inherent to the product when compared to other items in the built environment, such as concrete, steel, and carpeting. The students then apply the techniques presented to their assigned product.

Properties of materials are introduced, along with the impact each of the materials hase on the environment at each stage of the life cycle, including end of life and recyclability. After the first class, the instructor challenges students to use their intuition to determine the "best" material for their assigned product. In this assignment, students discover that they have to know the characteristics of the product they are developing. As part of their work, students access the Cambridge Engineering Software (CES) database of materials and material properties.

Students then determine the best material for their assigned product using the Weighted Properties Index (WPI) method (Lewis, 1990). First, students assign weighting factors to each of the properties. Students compare their intuition obtained from the homework with a pair-wise comparison and with Saaty's scale comparison methods for assigning weighting factors (Saaty, 1980). Students then scale the properties of their choosing and calculate the WPI. The students apply the performance index equation to the WPI method to determine the material best suited overall for the performance requirements.

Module 4—Process design and Improvement

The content in this module describes how new processes, such as those found in a manufacturing plant, can be designed to be sustainable and how existing processes and facilities can become more sustainable. The goal of module four is to introduce students to material and energy balances through a waste and energy audit of an industrial facility. Students also learn about environmentally sustainable product packaging and delivery. Based on assessment results from early offerings of the course, the instructor added LEED certification as a topic.

The case study for this module comes from the Global Engine Manufacturing Alliance (GEMA) in Dundee, Michigan. GEMA is a joint venture of Chrysler, Mitsubishi, and Hyundai Motors. Early in the plant's life, the leadership of GEMA committed themselves to sustainability in building the plant and developing the manufacturing processes. Because the facility is new, GEMA considered many potential sustainable options. In the first session, students review both successful and unsuccessful options, as well as GEMA's joint venture concept. Students study concepts of waste, waste streams, and waste audits, as well as energy audits, with the common wastes of an engine plant used to illustrate the concepts. Students understand the concept of "zero waste to landfill" as demonstrated through GEMA's efforts. GEMA is one of very few plants to attain "zero waste to landfill" in all of its processes.

Following the GEMA case study, students take a tour of Kettering University's heating and air conditioning facilities. The instructor assigns students to complete a waste and energy audit of a building or a portion of the university facilities. Student present to the class their waste and energy audit findings.

In addition, the instructor covers the basic concepts of LEED certification. This includes sustainable sites, water efficiency, energy, material, indoor environmental quality, and innovation. The instructor explains the requirements of Silver, Gold, and Platinum certification and provides students with the layout and basic specifications of university buildings.

Module 5—End-of-use strategies

In this module, students focus on the end-of-life disposition of products that are no longer useful, functional, and/or desirable for the user. The module begins with defining the "end of life" of a product as really the "end of use." There are times when a product is still functional but no longer desirable. Some examples include a well-made chair that has gone out of style or a working computer that has become technologically obsolete. Students define the possibilities for disposal of a product that is at the end-of-use stage in its product life cycle. Possibilities include solid waste landfill, hazardous waste landfill, incineration, recycling with disassembly, recycling without disassembly, refurbishment through remanufacturing, and reuse through service. The instructor also covers the history of sanitary landfills and the trend to generate power from methane, a by-product of landfills. The module concludes with the idea that landfills are not a sustainable solution for waste.

Module Five includes a tour of a local electricity generating landfill. The students experience first-hand the inner workings of a solid waste landfill. They view the heavy equipment, hear the machinery, smell the aroma, and walk the paths between working cells. This experience is memorable and educational. Students consider waste-to-energy as an idea while viewing an electricity generating station that sells power to the local power company.

During this module, the students propose a redesign alternative for a sustainable cradle-to-cradle design and evaluate the end-of-use disposition of the new design. Evaluation of the redesigned product includes both environmental impacts and cost ramifications for the redesigned product.

Module 6—Environmentally Responsible Management

In this module, students view environmental sustainability from an economic perspective. The KIET advisory board has repeatedly reminded the authors that "green business models" have to be both "green" and "business models" in order to be successful. The goal of the module is to introduce students to "best practices" in environmental sustainability that all firms can employ. Best practices covered include the triple bottom line, green supply chains, environmental management systems (ISO 14000), cap and trade approaches, life cycle cost accounting, and creating a culture of sustainability.

Module 6 includes several learning activities such as readings, cases, video/audio content, and a simulation game. The module starts with a case study on the popular Starbucks coffee business. Students learn to balance the classic goal of the firm (profit maximization) and the concept of enlightened self-interest. Students study green logistics in following the Starbuck's supply chain. They also consider alternative regulatory approaches such as cap and trade while playing a simulation game. In a case study called "How Shall We Wash Our Hands," students apply life cycle costing approaches. Finally, using a case study on HP, the class considers how organizations can create a culture of sustainability.

Module 7—Green Chemistry

KIET added and expanded green chemistry in later offerings of the course. It was neither part of the original set of modules proposed for the course nor a part of the Ford PAS curriculum. However, Graedel (1999) shows green chemistry to fit into the context of industrial ecology. This module consists of two sessions. In the first session, the instructor introduces students to the 12 Principles of Green Chemistry (Anastas, 1998). The students apply these principles as they synthesize biodiesel from oil using a transesterification reaction. During the synthesis, students compare biodiesel to the synthesis of petroleum-based diesel (Thompson, 1996). The students then analyze the product using Infrared Spectroscopy. In the next session, students run the biodiesel on a jet engine and analyze its efficiency compared to petroleum-based diesel. The student reactions to this module have been overwhelmingly positive. One student stated, "Students who are normally not exposed to much chemistry are able to see the challenges and benefits of green chemistry." During the assessment of the class by the advisory board, most respondents agreed or strongly agreed that Green chemistry should be part of this course.

Pedagogical Methods

KIET designed the course to create a learning environment that incorporates knowledge-, learner-, and assessment-centered perspectives. The need for these foci is evident in many sources, including the National Research Council report on connecting educational theory with educational practice: How People Learn: Brain, Mind, Experience and School (NRC, 2000). It cites the need to incorporate innovative pedagogical teaching methodologies to ensure that U.S. graduates have mastered course material beyond memorization, the first level of Bloom's Taxonomy. Active, exploratory learning is necessary for the student to integrate the topics to the level of deep learning.

Therefore, the team incorporated active learning strategies and activities into this course. The course consists of a set of self-contained modules. Generally, each module contains a set of common elements: (1) a case study to motivate student interest, (2) learner-appropriate content, (3) active learning content and strategies, and (4) opportunities for student participation in formative and summative assessment (Barr, 1995; Richards, 1995; Frechtling, 2002).

The course development includes activities that correspond with different learning styles discussed by Felder (1998), specifically the categories of "sensory/intuitive," "theories/principles," "visual/verbal," "inductive/deductive," "active/reflective," and "sequential/global." In the course modules developed, the instructors included a balance of real and virtual experiments that provide physical data for sensory reasoning while also illuminating high-level concepts for intuitive reasoning. The instructors outline and dissect known sustainability theories, as well as many underlying principles governing applications. The course module presentations by both the instructors and the students utilize significant visual content such as pictures and graphs. Verbal content such as discussions and assigned readings also offer individual perspectives. While deductive content is typically present in most classes, students experience field trips for inductive and experiential learning. The course content is very active in nature, but also encourages open-ended assessment for reflective learning. Case studies from industry are used throughout the course to demonstrate the applicability of industrial ecology and to facilitate learning (Bocker, 1987; Kenney, 2001; Banning, 2003).

Course Offerings

The KIET team has offered IME540 five times since the initial launch in 2007. Figure 1 below shows the level of enrollment for each offering. The KIET offered the first three offerings live in a traditional classroom. In the winter of 2009 KIET switched to an online offering that is more accessible to students both on-campus and off-campus. The KIET offers the online course using BlackBoard and incorporates a rich blend of video lecture, hands-on exercises, and discussion forums. The course is offered over one 11-week academic term, with each module consisting of three 2-hour lectures.

Assessment Results

To provide comprehensive assessment and evaluation, the KIET developed and delivered a multifaceted assessment plan with the assistance of an external consultant. This plan included student, faculty, and industrial advisory board input for the purpose of formative and summative feedback. The team developed a measurement rubric for each stakeholder for periodic evaluation. The assessment instruments included weekly strength/improvements/insights (SII) assessments for faculty performance improvement, semester pre and post tests for documenting student knowledge gains, and surveys for yearly advisory board member counsel.

KIET enlisted an Advisory Board composed of experts from both industry and academia. The kick-off meeting provided KIET with insight as they formulated the development of the project goals and the content of the modules. Once the team developed modules, the Advisory Board acted as external sounding boards regarding whether the students were learning what they needed to know to be productive employees upon graduation. Further, the Advisory Board provided recommendations for the future direction of the larger project. The Advisory Board members' personal and firms' support of this endeavor is illustrated by the fact that they made time to travel to the regular meetings, offered some financial assistance, provided technical expertise as guest speakers on campus, and completed the assessment instruments illustrates. Figure 2 shows the assessment results from an advisory board survey documenting that the team met the course learning objectives.

Figure 3 provides a brief overview of pre and post knowledge survey results for the six modules of the course. Table 1 provides a detailed summary of the 31 topics included in the six modules, along with student pre and post test knowledge survey results for each topic. In the comparison of the pre and post knowledge survey, the students self-reported significant increases in their environmental sustainability knowledge. Using a four point Likert scale with 1 corresponding to "very little knowledge" and 4 corresponding to "very familiar," students' initial knowledge averaged 1.6 and finished at an average score of 3.3.

SII assessments by faculty peers and students provided feedback for performance improvement. This leveraged the multidisciplinary strength of the faculty team and gave students the opportunity to take ownership of their own learning. One example of this came when one semester's cohort of students provided feedback on the Green Chemistry lab. The students

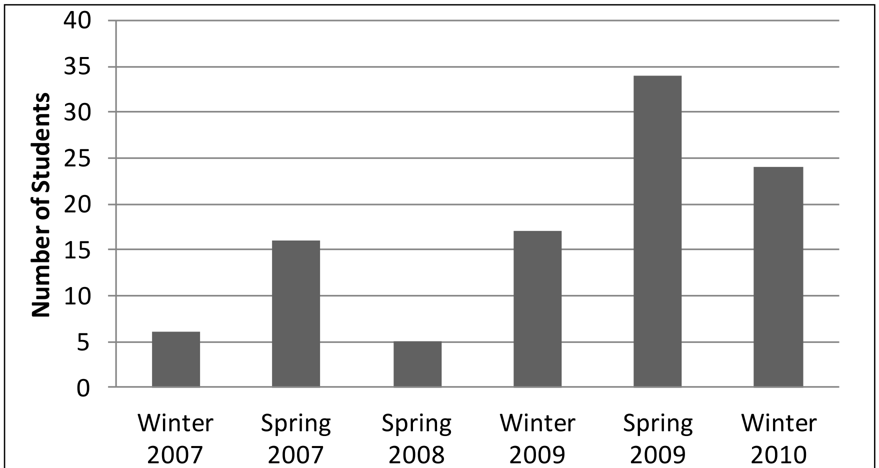

Figure 1. Enrollment in IME540-Student Enrollment in IME-540 class since 2007. Note the class was offered on-line in Winter of 2009

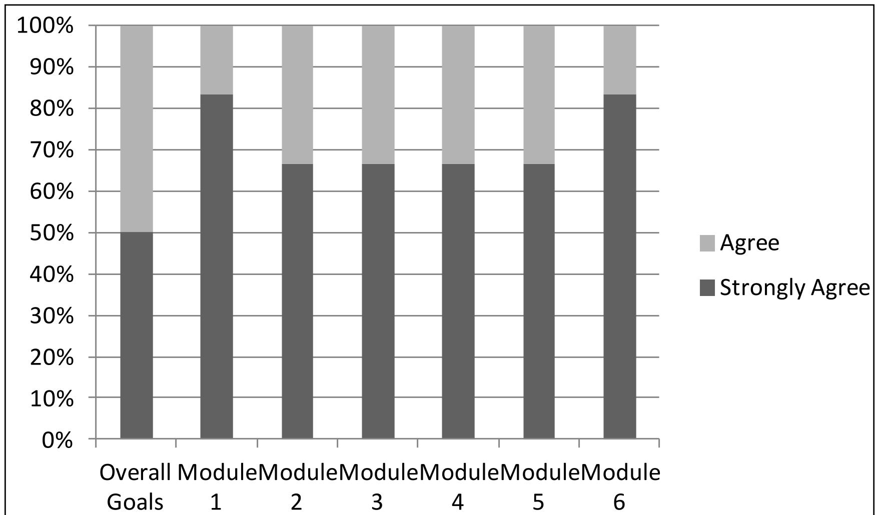

Figure 2. Advisory Board Assessment-The advisory board consisting of academic and industry professional assessed the class to determine if the class reached the learning objective for each module. (Sample size 6)

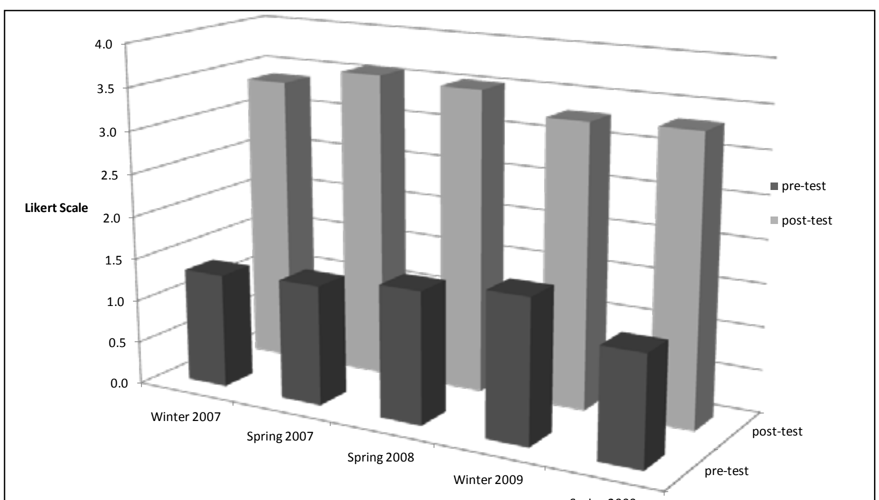

Figure 3. Student Pre/Post Assessment-Pre- and Post- Test results for five offerings of Environmentally Conscious Design.

Module 1:

- The history of the environmental impacts of industry.
- The history of the social/ethical impacts of industry.
- Environmental Ethics - moral and ethical dimensions of our interaction with the natural environment.
- The meaning of terms like "the tragedy of the commons", "social responsibility", and "sustainability".
- The meaning of "industrial ecology" or "green engineering/design".
- How to assess the basic environmental and social impacts of everyday products -- i.e. the basic categories by which products are broken down into components to assess their environmental and social impacts.
- Specific knowledge of the full range of environmental and social impacts of one article of clothing or everyday object that most people use.
- The social, historical, and environmental impacts of textile production, specifically cotton cloth (t-shirts).

Module 2:

- Life cycle stages
- Life cycle assessment (LCA); approach and current challenges
- Alternative approaches to LCA

Module 3:

- Life Cycle impact of materials (i.e. plastics and metals)
- Weighted Property Index method
- Saaty's Scale for Pair-Wise comparison of materials
- Performance Indicies as applies to selection of materials
- Cambridge Engineering Selector software (CES)
- Exchange Value functions

Module 4:

- Process flow: inputs, outputs and wastes
- Material and energy balances
- Environmental impact minimization
- Product delivery

Module 5:

- Eliminate, reduce and re-use
- Remanufacturing
- Design for recycling and recycling processes
- Workings of a landfill

Module 6:

- Economic and regulatory approaches to environmental control such as "cap and trade"
- Identifying and managing competing interests in economic and environmental sustainability
- Environmental management systems including ISO 14000
- Green supply chains
- Total (or life cycle) cost accounting
- Developing environmentally responsible organizational cultures

Table 1: Learning Objectives for Each Module

reported understanding from the lab how organic material such as vegetable oil can serve as a type of fuel. However, to understand the process fully they asked to use the fuel they developed in the lab to run an engine. Because KIET faculty consisted of not only a biochemist but also a mechanical engineer with expertise in the engine dynamometer lab, the students were able to witness that their lab-developed biofuel could run a retrofitted jet engine. This allowed students to participate in active learning experiences in the visual learning and psychomotor domains, as well as providing an exciting memory for all concerned.

Conclusion

In this paper, the authors have chronicled the development of a course in environmentally conscious design in a predominantly-undergraduate engineering institution. The project employs an interdisciplinary teaching approach using six faculty members and active learning techniques to reach students. Assessment results demonstrate significant learning and accomplishment of learning objectives. The KIET project team has evolved the course from a traditional class offering to an online course to attract a growing number of students. KIET is pursuing additional funding for expanded work to add environmental sustainability topics to multiple courses and a group of partner institutions.

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