Teaching Sustainable Engineering and Industrial Ecology using a Hybrid Problem-Project Based Learning Approach

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Abstract

Recently there has been an increased societal awareness of the environmental impacts of industrial activities. Many universities have included courses in sustainable engineering and industrial ecology in their engineering/technology curriculum to better prepare tomorrow's engineering professional. A unifying thread that runs through such courses is a "life cycle" based holistic approach to product, process and infrastructure design. Application of appropriate pedagogy is key to active student engagement in the learning process and to the application of concepts to the solution of technical problems. In this paper a hybrid problem-project based pedagogical approach to teaching sustainable engineering and industrial ecology is described. Problem based learning was used to promote self- directed student learning of key course concepts in which teams of students solved problems in product or process design. These problems typically were related to the lecture topic that was to be covered for the day. Project based learning was used as a central organizing principle for the course and to enable students to apply the principles of life cycle assessment (LCA) of environmental impacts of a product. The project, which was assigned early in the semester and due at the end, drove all of the learning activities for the semester. Based on the assessment of student learning in 2015 and 2016, the pedagogical strategies adopted are promoting the comprehension and application of sustainable engineering and industrial ecology toward the development of environmentally sound products and processes.

Introduction

In 2008, the National Academy of Engineering (NAE) released a report that outlined 14 grand challenges for engineering in the 21st century. These challenges if met would improve our lives. The 14 Grand Challenges were divided into four categories. The first category is sustainability—maintaining air and water quality, protecting freshwater quantity, preventing sea level rise, keeping forests and other ecosystems in good condition, and minimizing artificially triggered climate change [1]. The Royal Academy of Engineering in a report warns "we are exceeding the capacity of the planet to provide many of the resources we use and to accommodate our emissions" [2]. These reports underscore an increased societal call for professionals across government, industry, business and civil society to be able to solve problems related to climate change and sustainable development as part of their work [3].

Professor Robert Socolow of the Princeton Environmental Institute suggested that a greater emphasis on environmental issues called for a change in engineering education [1]. Lord Broers, President of the Royal Academy of Engineering suggests that with infrastructure and engineering products becoming increasingly complex, engineers need to integrate consideration of whole-life environmental and social impacts – positive as well as negative – with the mainstream and commercial aspects of their work [2]. In response to these recommendations many universities have included courses in sustainable engineering and industrial ecology in their engineering and engineering technology (ET) programs.

What to teach?
Thus, sustainability is a key pedagogical theme for higher education. Many institutions are attempting in different ways to embed the principles and practice of sustainability within their teaching missions [4]. However, since the term sustainability is very broad in scope it is worth exploring what sort of topics and concepts are typically being included in sustainability oriented courses in engineering and ET programs.

Allenby and his colleagues offer the following clarification of key terms that must be addressed before proceeding to actually identify the contents of such courses. Accordingly, "sustainable engineering may be thought of as the operational arm of industrial ecology: first use the methodologies of industrial ecology, such as life-cycle assessment, materials flow accounting, or product or process matrix analysis, to determine relevant social and environmental considerations; then use sustainable engineering methods to integrate that knowledge into product, process, and infrastructure design and life-cycle management [5]. This important relation between sustainable engineering and industrial ecology is echoed by Ehrenfeld who states that the concept of industrial ecology is a promising new paradigm that enables industry and society to approach sustainability [6].

Accordingly, in this study a graduate course entitled TECH 5382 – Sustainable Engineering and Industrial Ecology was created and offered primarily to majors in engineering technology. The course content is divided into three major parts. The first part deals with foundational material such as introduction to industrial ecology and sustainability, a comparison between the inherently efficient biological ecology and industrial ecology and the current status of resources. The second part deals with life cycle analysis (LCA), including the what, why and how of LCA. The last part addresses different facets of Design for Environment including product design, process design, material selection, energy use, product transportation, product use, and end of life recycling.

How to Teach?
The first few times the authors offered TECH 5382, it was mostly offered as a lecture based course with a final project. The final project was on a topic of interest to the student that related to sustainability. Thus, the research involved mostly a summary of other researcher's findings. The authors found that while this approach was adequate from standpoint of exposing students to sustainable engineering and industrial ecology, it did not promote deep learning nor lead to the development of application skills. Other researchers such as Kagi and Dinkel report that a lecture based approach to teaching LCA allowed theoretical knowledge transfer, but did not allow to address and exercise all the questions and pitfalls that one would face in real LCA projects. Real LCA projects involved situations in which engineers would have to provide solutions despite all the data gaps and other problems like such as making reasonable estimates and identifying uncertainties [7].

In teaching industrial ecology to graduate students, Marstrander and his colleagues recommend that pedagogy should engage students in a holistic and life cycle oriented view of products, processes, and their interactions with the environment implemented through project work [8]. Bessant and her colleagues recommend problem based learning (PBL) as means to engender "transformative sustainability education" which in turn would lead to shifts in perspectives, values and attitudes of learners and create action-oriented, sustainability-literate “change agents” [4]. Wiek and his colleagues report that there is some convergence that academic sustainability programs would benefit from using problem and project based learning (PPBL) approaches in their curricula and courses [9].

Some researchers have also made the case for combining elements of PBL and Project Based Learning (PrBL). Donnellly and Fitzmaurice suggest that PBL and PrBL are part of a continuum and that in application the line between PBL and PrBL is blurred. Further, they add that the two are applied in combination and play complementary roles [10]. Yasin and Rahman advocate hybrid forms of PBL and PrBL in the context of sustainability education [11]. Pitfalls associated with the sole application of one these approaches is avoided in using the hybrid approach. That is, both the risk of getting caught in the knowledge first trap by endlessly analyzing problems as well as prematurely proceeding to the solution without sufficient problem framing and analysis is averted [12], [13].

Based on the forging analysis of prior work, the authors adopted a hybrid PBL and PrBL based approach to learning in TECH 5382. Both PBL and PrBL, use the constructivist and experiential learning approaches [14] that promote deep learning by offering students the opportunity to work with real world sustainability problems and placing emphasis on research. Thus, this change in pedagogy in TECH 5382 represented a shift from lecture based, instructor centric, passive learning to student centered, active learning that included a research based project.

Implementation Details

The course is a core course for graduate students in engineering technology. In addition, graduate students in business administration, engineering, education, geography and the physical sciences may opt to enroll in this course as an elective choice. This diversity of background helps to promote discussions in the class in which multiple perspectives are offered. In addition, most PBL teams features students with a mix of discipline based background, as an example, a team of three that includes one from each of the following disciplines – engineering technology, business management and education.

The key objective of the course is to enable students to approach the design of sustainable industrial products from a life cycle perspective. The topics covered in the lecture include: introduction to industrial ecology, biological ecology, current status of resources (with emphasis on technologically desirable resources), life cycle analysis, design for environment to include product design, process design, material selection, energy efficiency, product transportation, product use and end of life recycling. In order to promote self-directed student learning and a collaborative learning environment in which team members benefit from a multiplicity of perspectives, PBL activities were assigned to coincide with each major lecture topic. The teams typically included 3-5 students. Each team was presented with a problem and asked to present solutions at the next class meeting time when the lecture that pertained to the PBL topic was delivered. Typically, the student teams presented their solutions at the beginning of the class. The problem and the solution were tangible and dealt with specifics rather than generic material. One of the many assigned problems in the PBL activity on manufacturing processes is as follows: *Forging is one method of producing turbine blades for jet engines. Study the design of such blades and referring to relevant technical literature, prepare a step-by-step procedure for* *making these blades. Comment on any difficulties that may be encountered in this process, including environmental concerns.* Another example is the following PBL activity in product design: *Aluminum beverage can tops are made from 5182 alloy, while the bottoms are made from 3004 alloy. Study the properties of these alloys and explain why they are used for these applications.* It should be noted that each of the many teams is assigned a different problem. So during the first 30-45 minutes of the class (duration 3 hours) students present many specifics and particulars as pertains to the lecture topic for the day. Thus, during the lecture the general principles are provided. Most of these principles were already "discovered" by the students in course of their PBL activities. Thus, the PBL activities promoted inductive learning.

At the beginning of the semester (in fact in the very first meeting period) the students were issued their term project assignment. The key instructions from the project assignment are captured in the following. *For the final project choose a product that you are familiar with and of modest complexity. Then perform a Life Cycle Analysis (LCA) including the following:*

1. *Provide an analysis of the product, i.e. the assemblies, subassemblies, parts, components and materials that constitute the product (provide a drawing or model as appropriate).*
2. *Provide an analysis of the processes that are used to manufacture or construct the product (use process flow chart as appropriate).*
3. *Conduct a Life Cycle Inventory and Life Cycle Impact analysis. Based on the analysis discuss the strengths and weaknesses of the current product from an environmental impact standpoint.*
4. *Propose at least two alternate designs that would obviate the weaknesses identified in step 3 above.*

The project was worth 30% of the semester grade and represented the single most consequential assignment in the course. As may be expected, most students were not familiar with principles of LCA and its detailed inventory and impact analysis methodology at the start of the semester. However, the project served as the central organizing principle and drove all of the learning activities for the semester. While the PBL activities helped students with self-directed learning of the key concepts of the course the PrBL activity served as a "glue" in illustrating the synthetic application of the many topics toward a life cycle approach to the design of products. Students were required to turn in a one-page proposal within two weeks of the project assignment as to their choice of the product and the deliverables that they planned to include in the final project report. Roughly from the mid-point in the semester (about 6-7 weeks from the start) each student presented their project progress to the entire class. The presentations were to last roughly 20 minutes (15 minutes of formal presentation with 5 minutes for Q&A). Topics covered during the presentation include their choice of functional units and system boundaries as well as an indication of databases and other sources for estimation of life cycle inventory and impacts. The feedback received from the instructor and peers during and after the presentation helped students to make the necessary changes to their project. Thus, the presentation served as a midterm formative assessment of their project.

Student Products
Since the project is the organizing principle of the course the discussion on student products will be confined to project details. During Summer 2016 offering the following student projects were undertaken.

Table 1 – Student projects Summer 2016

Student #	Project title
1	LCA of high carbon steel fishing hooks
2	LCA of hot rolled steel coils
3	LCA of a car tire
4	LCA of polylactic (PLA) cup
5	LCA of silver coin production in the U.S.
6	LCA of a dowel pin

The following illustrate the results from life cycle impact analysis.

Table 2 – Impact (acidification potential) analysis example (Courtesy Joshua Kingston, Life Cycle Assessment of High Carbon Steel Fishing Hooks Manufactured for Saltwater Fishing, Term Paper, Texas State University, August 2016)

Acidification	**Anode at Plant (Kg)**	**Die Casting Total (Kg)**	**Emission Total (Kg)**	**Functional Unit (Kg)**	**Emission Total / Funct. Unit (Kg)**
Emissions					
SO x	3.22E-03	3.35E-03	6.57E-03	300	1.97E+00
NO x	1.10E-04	1.80E-03	1.91E-03	300	5.73E-01
HF	2.30-e05	0	0.00E+00	300	0.00E+00
NH4	1.50E-07	0	1.50E-07	300	4.50E-05
SO2-4	2.30E-05	0	2.30E-05	300	6.90E-03
H2SO4	4.40E-06	0	4.40E-06	300	1.32E-03
Total AP / Funct. Unit (SO_2e / Kg)			**2.3804046**		

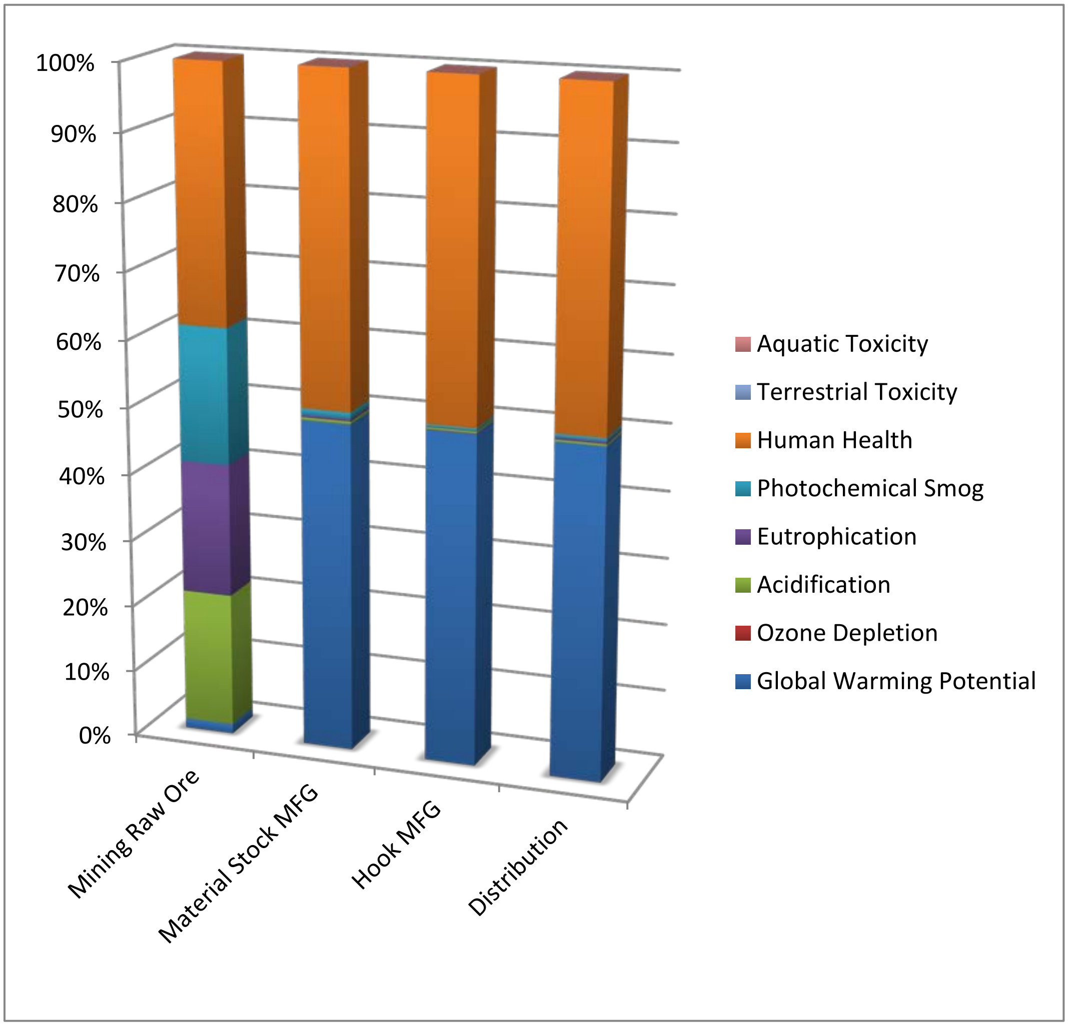

Figure 1 – Total Life Cycle Impacts (Courtesy Joshua Kingston, Life Cycle Assessment of High Carbon Steel Fishing Hooks Manufactured for Saltwater Fishing, Term Paper, Texas University, August 2016)

Learning Assessment

In order to assess student learning, learning outcomes were identified that covered the entire gamut of Bloom's learning taxonomy. These outcomes are listed below. Outcomes 1 and 2 address *knowledge* and *comprehension* levels of the taxonomy. Outcomes 3, 4, 5 and 6 address the *application* level. Outcome 5 and 6 also address the *analysis* and *synthesis* levels. Outcome 7 addresses the *evaluation* level. Taken together these outcomes help assess student learning in industrial ecology and sustainability engineering in a comprehensive fashion.

1. I understand the similarities and dissimilarities between biological and industrial ecologies and am able to apply this knowledge toward sustainable development of products and processes.
2. I can apply the concept of design for environment (with regard to product design, process design, material selection etc.).

3. I can establish system boundaries in regard to a LCA.
4. I can determine what functional unit should be used in a LCA.
5. I can conduct a life cycle inventory analysis.
6. I can conduct a life cycle impact assessment (based on impact factors such as GWP, eutropification, acidification etc.)
7. I can apply the LCA process for technical decision making.

Unlike a course in finite element analysis or field theory, sustainability is a term and concept that is very actively employed and understood in the lay community. To be basically versed in sustainability does not require a student to have had a prior course in this area. Also, given the fact that this is a graduate class and the fact that students have had a healthy multiplicity of background in terms of their undergraduate studies, it was important to establish baseline levels of prior knowledge in each of these outcomes before proceeding to assess the same at the end of the semester. Thus pre and post surveys were conducted that probed student accomplishment level on each of the seven learning outcomes. Each outcome was assessed on a Likert scale from 1-5; where 1 indicated "strongly disagree" and 5 indicated "strongly agree". Based on this design of learning assessment surveys, the data was collected in the summer and fall 2016 offerings of the class and the scores are reported below.

Table 3 – Summer 2016 course offering

Learning Outcome	Pre test score	Post test score
1	2.1	4.3
2	1.7	4.0
3	1.3	4.0
4	1.1	3.8
5	1.0	3.7
6	1.0	4.0
7	1.4	4.0

Table 4 – Fall 2016 course offering

Learning Outcome	Pre test score	Post test score
1	1.7	4.25
2	2.67	4.14
3	1.4	4.0
4	1.47	4.56
5	1.35	4.13
6	1.17	3.63
7	1.35	4.25

The scores reveal consistent gains in student learning. Offerings of this course prior to 2016, did not feature substantial discussions on the "how to" of LCAs. Thus, as indicated earlier the term projects completed by most students prior to 2016 included term papers that reviewed or summarized prior research on a topic of interest to student, such as a review of prior research on sustainability of concrete pavements. The following are some project titles from 2014.

Table 5 – Student projects Summer 2014

Comparison of Life Cycle Assessment Software for Cement Industry
Literature Review on LCA/Environmental Impact for Ready Mix Concrete
Current State of Research on the Life Cycle Analysis and Environmental Impact of Concrete Masonry
Life Cycle Assessment of Cement Production Methods, US and EU Improvement Potentials and Comparison of the Chinese LCAs to ISO Standards
A Comparison of the Commercial LCA Software for Concrete

Most, if not all involved a report on prior research. There was no "doing" that involved LCA. Thus students did not have to go through choice of system boundaries and functional units or search databases to obtain inventory and impact data. Specifically they did not go through the struggle of dealing with incomplete and sometimes imprecise data. In addition, until 2016 detailed learning outcomes were not assessed as indicated above. Therefore, it is not possible to evaluate enhanced learning that occurred upon the introduction of the hybrid PBL and PrBL pedagogy. In conjunction with the instructor decision to include substantive discussions on the "how to" of LCAs, term projects that included actual LCA work or "doing LCA" was also required and formal pre and post surveys were conducted. Thus, it is possible to demonstrate learning gains from a comparison of the baseline pre survey scores to post survey scores in order to establish the effectiveness of the hybrid approach.

Lastly, the post survey instrument in Fall 2016 probed students as to their preference of four different pedagogical methods. The preference was indicated on Likert scale of 1-5, where 1 indicated "strongly disagree" and 5 indicated "strongly agree". Student preferences are indicated as shown in the table below:

Table 6 – Student preference for various pedagogical methods

Pedagogical method	Description of pedagogical method	Score
1	Lectures delivered by the Professor	4.6
2	In-class group activity (PBL)	4.27
3	In-class presentation by the student	4.13
4	Semester long term project (PrBL)	4.40

Students have rated all four pedagogical methods quite highly. The first, i.e. lectures delivered by professors received the highest score, but may not be treated as an entirely objective validation of in-class lectures. The instructor is a 26 year teaching veteran, that had received over five university, state and national teaching awards. The remaining scores may be treated with considerable validity for there was no mitigating influences. Method 4, PrBL received the highest score. In fact, in the comment section for this method students wrote many favorable comments such as "The term project was fun and it really solidified my understanding of LCA", and "excellent learning". The PBL based group activity also received a good preference rating. The lowest rating was for in-class presentation. This was possibly occasioned by some student's degree of discomfort with public speaking. One of the objectives of the presentation and term report was to improve communication skills, especially oral and written skills. Thus, students' also perceive the PBL and PrBL activities as being preferred pedagogical approaches and that they promote learning gains.

Conclusions

The complexity of industrial products and systems and the increased societal awareness of the environmental impacts of such products and systems have led to the life cycle approach to the design of engineered products and systems. In turn, this had led to a call for the inclusion of sustainable engineering concepts in the engineering curriculum. This paper presented the study of a graduate course in Industrial Ecology and Sustainable Engineering, the purpose of which was to train students in the life cycle approach to the design of sustainable products and processes.

In order to promote active, self-directed learning and ability to apply LCA to the development of sustainable products and processes, a hybrid PBL and PrBL learning approach was adopted. In the summer and Fall 2016 offerings of this course students completed term projects that required them to engage in the ”doing” of LCA and the application of Design for Environment concepts. A comparison of the projects accomplished prior to the adoption of the hybrid pedagogy to those after the adoption indicate that students were able to apply LCA to development of environmental sound products and processes. Student pre and post surveys indicate significant gains in seven key learning outcomes that encompass the breadth of application of LCA and Design for Environment. Student response to surveys that probed the choice of pedagogy revealed strong preference for both the PBL and PrBL approaches. Taken together, these results suggest that a hybrid approach to teaching industrial ecology and sustainable engineering is effective in improving student learning.

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