What works? Sustainability Grand Challenges in Engineering Curricula via Experiential Learning

Amy E. Landis[1], Claire L. A. Dancz[2], Kristen Parrish[3], Melissa M. Bilec[4]

[1]Colorado School of Mines, USA

[2]Clemson University, USA

[3]Arizona State University, USA

[4]University of Pittsburg, USA

Abstract

Today's complex global problems necessitate engineering solutions that not only consider sustainability, but include elements of design and creativity. Unfortunately, many engineering programs do not train students to think in terms of multiple contexts and at various scales. We often constrain students' creativity to think within the narrow parameters of their specialization. Engineering educators face a difficult task of training students with both technical competencies and sustainability consciousness to tackle 21st century challenges. If we are to positively contribute to society, then we need to fundamentally change the way scientists, social scientists, and engineers are educated (Bielefeldt 2013).

Two successful models for implementing sustainability grand challenges into engineering curricula have emerged in practice and in literature: stand-alone courses versus modules that are integrated into many courses. Engineering programs implement the stand-alone course-based model by establishing one to two distinct courses designed to address sustainability grand challenges and design in depth. One example of this is senior design. Conversely, engineering programs implement the modular-based model by integrating sustainability grand challenges and design throughout a host of existing courses and weave student exposure throughout the curriculum. These modules can be via ready-made modules, but more often than not faculty develop their own modules. The goal of this research was to evaluate the two models for implementing sustainability and to provide succinct recommendations and lessons learned for engineering programs tasked with integrating sustainability into their curricula.

We review the implementation results of three sustainability courses, fourteen sustainability-themed modules, and senior design. We track progress towards responding to ABET Program Criterion related to sustainability and Civil Engineering Body of Knowledge 2nd edition (BOK2) Outcome 10: Sustainability. Results compare outcomes of students' senior design project from universities implementing the two different approaches. And finally, we present the results of a formative and summative surveys of hundreds of students who participated in classes implemented throughout the project as well as faculty perceptions and barriers to implementation.

Introduction:

The proposed activities incorporate recommendations from the National Research Council (NRC) for enhancing education in science, technology, engineering, and mathematics (STEM) disciplines by developing new experiences that facilitate diverse pedagogical approached, including project-based and active learning. The NRC recommendations include providing engaging laboratory, classroom and field experiences; teaching large numbers of students from diverse backgrounds; improving assessment of learning outcomes; and informing science faculty about research on effective teaching (Fox et al. 2003, Donovan et al. 2005, Bransford et al. 2006). Research suggests that team based projects can also enhance student learning in STEM fields since it promotes active and collaborative learning while simultaneously promotes individual accountability, personal responsibility, and communication skills (Allen et al. 2006).

The over-arching goal of this project was to train students to think outside the box, connect their learning to the real world, and prepare these students to tackle the engineering challenges of a global economy. Through this National Science Foundation funded project, we developed 14 modules and 3 courses that utilize experiential learning on topics related to sustainability grand challenges. We implemented these modules and courses in the curricula in our nine partner institutions, Arizona State University (ASU), Mesa Community College (MCC), University of Pittsburgh (UPitt), Community College of Allegheny County (CCAC), Chandler-Gilbert Community College (CGCC), Laney College (LC), Clemson University, Fresno City College, and Colorado School of Mines (Mines). We also evaluated the effectiveness of the modules and classes on student, faculty, and program performance. All materials developed (courses, modules, etc.) employed well-known experiential learning pedagogies and build on the teams' sustainability engineering educational expertise. Flexibility was built into the stand-alone course materials and modules to accommodate the resources of different faculty and facilitate the adoption of these courses across different universities.

The three stand-alone sustainability courses can be adapted for different levels of the undergraduate curriculum. We aimed to produce all of the materials that an instructor needs to begin teaching these courses, including: syllabus with ABET outcomes, sample course schedule, description and instructions for conducting experiential learning activities, lecture slides, homework assignments, sample course projects, exams, and pre- and post- course assessments. Some of the experiential learning activities in the stand-alone courses will utilize the modules that we will develop in our module approach; however, each course has unique experiential learning activities integrated throughout much of the entire class, often over the course of many weeks.

The modules were designed with the flexibility for faculty to utilize them in a number of different courses at different levels. Modules were designed to fit into approximately one week of lecture content. The modules designed in this project aim to provide everything an instructor needs for implementation: a summary of learning objectives (including ABET outcomes), lecture slides and notes, recommended readings, a homework assignment, experiential learning activity instructions, an example you-tube video to provide guidance on conducting the experiential learning activity, and module pre- and post- assessments. Modules were also designed to fit into a wide range of different engineering courses, from freshman engineering classes, to engineering ethics and business practices. The modules are: critical resources, energy audit, food desert, game design, IR for building physics, life cycling thinking, model UN, packaging, power grid, sustainability metrics, technology evolution, waste audit, and water footprinting. The modules are available on our website (www.sustainableengineeringed.org).

The engineering programs at each institution integrated sustainability into their curricula to different degrees. In addition to our original partner institutions (UPitt, ASU, MCC & Laney), we also implemented courses and modules into curricula at other schools, such as Clemson University, Colorado School of Mines, Chandler-Gilbert Community College (CGCC) and

Fresno City College. CCAC was also provided access to the green building course. UPitt implemented all three stand-alone sustainability courses (Y1, all three courses; Y2, all three courses; Y3, all three courses; Y4, all three courses, except GB moved to a graduate course; year 5, all three courses, except GB moved to a graduate course). The modules used in the courses were (**Table 1**): food desert, life cycle thinking, energy audit, game design. UPitt and ASU implemented all three courses, while Laney implemented the GB course. Modules were implemented at several institutions: Sustainable metrics module at ASU, the water footprint module at Chandler-Gilbert Community College and MCC, and the power grid, food waste, and food dessert module at Clemson, water footprint and sustainable metrics at Fresno City College. Numerous modules were used in the Civil Engineering Department at Clemson University. And LCA was taught at Mines. In addition, faculty outside of our institutions have implemented these modules. For example, we highlighted our modules in a workshop at AEESP in 2017; over 20 faculty at that workshop took our modules to use at their home institutions.

Table 1. Description of New Modules to be Developed in this Project
***Several modules have multiple, distinct variations**

Module	**Description**	**Variations**
Model UN	A card game guides students through a model UN. One card describes the country, a set of cards identifies strategies, and events cards that the UN must address are held by the instructor.	Cards will be created that address topics of feeding 9 billion people, C sequestration, managing the N cycle, information security
Life cycle thinking (LCT)	Students are given a product in class and asked to take it apart. Students then create a process flow diagram that includes life cycle flows of energy, materials, emissions.	Any type of product can be used (e.g. candy bar, small electronic, etc), enabling LCT in nearly any class related to materials, products. Advanced levels can quantify process flows.
Sustainability Metrics*	Students are asked to bring a green product to class. Students investigate what metrics make it green, how to quantify and benchmark metrics, how green metrics influence design	Any type of product with a green label can be used: students can bring them to class or faculty can provide to students. Assignment can be modified to evaluate metrics, redesign products
Energy-supply, demand, and transmission	Students are given M&Ms to represent a unit of energy. Students calculate energy conversions, losses during transmission as energy (M&Ms) moves from the resource to the point of use.	Students can practice multiple skills by using Matlab to solve and graph information from their game. Different types of energy production systems can be included, including renewables. Activity can evaluate changes in supply and demand.
Energy-renewables	Students play the flash game Super Energy Apocalypse by Lars A Doucet. Groups are tasked with different energy strategies for	Students can play remotely and tweet their progress. The module will also be designed to use the board game,

	developing the new world, and they must assess their impacts.	Power Grid by Rio Grande Games for a more tactile experience.
Packaging	Students disassemble packaging for a line of products, weigh and catalogue the different materials, evaluate the effect of packaging on product safety, transportation, and materials use.	Packaging can be from a variety of products (cookies, DVDs, etc.). Students can redesign the packaging, calculate emissions and costs of shipping, and optimize product packaging and delivery.
Technology Evolution	Students create a timeline of a products' evolution. The cell phone is a classic example: students identify the major changes in technology over time and predict the next generation.	The timeline can address the connections between social values and design decisions, the systems connected to the designs, the evolution of emerging technologies.
Sustainable Waste Management*	Students conduct a visual waste audit (e.g. watch and document what is disposed of in campus dining hall) and quantify how much waste ends up in different streams. Students determine where their waste goes, compare to alternatives.	The activity can be conducted either in or out of class to differing degrees of complexity; from simply discussing implications of waste management to calculating emissions from different manners of disposal (e.g. landfill, incineration)
C, water footprinting	Students use existing online tools to calculate either their carbon or water footprints. Students learn about embedded water, solutions for minimizing C and water emissions.	Students can be asked to compare the results from different tools, with the aim of critically evaluating information. Students can run the tool to test improvements.

Assessment and Evaluation

We divide measurable outcomes into three categories for evaluation: (i) Student-centered evaluation of learning outcomes for each module and course, (ii) Evaluation of faculty and institutional outcomes for the two different methods of course integration and (iii) Evaluation of outcomes from the four-year duration of the project. Outcomes from the classes and modules (outcome type i) were evaluated by comparing formative and summative survey responses from implementation of the proposed TUES 2 project to the survey responses from prior classes and to control classes (i.e. classes not using modules). In order to evaluate the use and effectiveness of the stand-alone course method and the module method (outcome type ii), we evaluated student performance in the individual courses and modules. We also compared products from students matriculating through the five engineering programs, from freshman course projects to senior design course projects. Finally, we will evaluate the success of our TUES 2 program (outcome type iii) by quantifying the continued use of our modules within faculty classes via faculty surveys.

The implementation of these courses and modules impacted the education of thousands of undergraduate students at our partner institutions as well as at many other universities who have adopted these modules. Key findings from the pre- and post-assessment module and course surveys found that students are motivated to learn about sustainability and engineering grand challenges. Faculty experienced significant barriers to including more sustainability and engineering grand challenges in their course content. Some common barriers include time constraints to fit in new material, balancing the dilution of course fundamentals with the new material and resources to aid non-experts in sustainability.

Results from this work have been published in several journals, and we summarize the cumulative work in this presentation. First, evaluating the "Active Experiential Sustainable Engineering Module for Engineering Education," results indicate students performed best cognitively when terms were given explicit definitions rather than implicitly, and signify one of the important components of the module is the use of active and experiential learning through with engineering students explores sustainability concepts of design for end-of-life, design for disassembly, and sustainable metrics by hands-on office chair disassembly (Dancz et al. 2017). "Assessment of Students' Mastery of Construction Management and Engineering Concepts through Board Game Design" established the use of a Game Design Module as a way to assess students' mastery of course content where students modify existing board games to teach players –i.e. their classmates– course content (Dancz et al. 2017). The results indicate that students can demonstrate mastery of concepts through design of their own board game and that instructors can assess student mastery through these student-designed games. Results show that using board game design as a method for assessing student retention of concepts improved student performance and increased student satisfaction. Next we look at "Utilizing Civil Engineering Senior Design Capstone Projects to Evaluate Students' Sustainability Education Across Engineering Curriculum (Dancz et al. 2017)." This paper presents the development of a novel, holistic sustainability rubric and application to civil engineering senior design capstone projects to evaluate students' sustainability knowledge at two institutions using a stand-alone course method to integrate sustainability into engineering curriculum. Rubric evaluation of student reports revealed that students' performance in senior design projects is primarily driven by their instructor's expectations; if sustainability is not a major deliverable, then students are less likely to integrate sustainability concepts that they learned from prior classes in their reports. To make sustainability a priority, the authors suggest that senior design project requirements should be updated to explicitly require holistic sustainability applications. In addition, instructors could approach raising sustainability expectations by engaging a sustainability expert as an advisor to the senior design course and/or utilizing a sustainability expert as project mentor. Results from the paper "Sustainable Engineering Student Cognitive Outcomes: Examining Different Approaches for Curriculum Integration" represents the culmination of our research comparing the stand-alone course approach to the module approach to teaching grand challenges and sustainability in Engineering (Ketchman et al. 2017). This study compares results from the application of a comprehensive holistic sustainability rubric assessment tool to three years of student projects in two stand-alone sustainable engineering courses and two senior design courses, intended to assess dissimilarities in student outcomes and locate causality, in the context of sustainability. T-test results indicate student projects in the stand-alone courses exhibited higher levels of cognition, a 119% increase in achievement of application, 330% increase in use of quantitative methods, and improved linkage of the three pillars of sustainability: economic, environment, and society. The authors present four potential factors contributing to discrepancies in student outcomes, offering strategic approaches to overcoming these barriers institutionally and nationally.

We also investigated faculty barriers and perspectives to adopting new sustainability curriculum (Burke et al. 2018). "Faculty Perspectives on Sustainability Integration in Undergraduate Civil and Environmental Engineering Curriculum." This paper elucidates and explores faculty perceptions about the importance of sustainability in civil and environmental engineering (CEE) education as well as methods for and barriers to its incorporation in CEE courses. Specifically, it presents results of a survey administered to faculty at two institutions as well as to attendees at an Association of Environmental Engineering and Science Professors (AEESP) preconference workshop. Findings show that most sustainability content is currently taught in the later years of undergraduate students' education while most faculty continue to employ traditional lecture-based teaching methods.

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