

Integrating Sustainability Grand Challenges and Active, Experiential Learning into
Undergraduate Engineering Education

by

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ABSTRACT

Engineering education can provide students with the tools to address complex, multidisciplinary grand challenge problems in sustainable and global contexts. However, engineering education faces several challenges, including low diversity percentages, high attrition rates, and the need to better engage and prepare students for the role of a modern engineer. These challenges can be addressed by integrating sustainability grand challenges into engineering curriculum.

Two main strategies have emerged for integrating sustainability grand challenges. In the stand-alone course method, engineering programs establish one or two distinct courses that address sustainability grand challenges in depth. In the module method, engineering programs integrate sustainability grand challenges throughout existing courses. Neither method has been assessed in the literature.

This thesis aimed to develop sustainability modules, to create methods for evaluating the modules' effectiveness on student cognitive and affective outcomes, to create methods for evaluating students' cumulative sustainability knowledge, and to evaluate the stand-alone course method to integrate sustainability grand challenges into engineering curricula via active and experiential learning.

The Sustainable Metrics Module for teaching sustainability concepts and engaging and motivating diverse sets of students revealed that the activity portion of the module had the greatest impact on learning outcome retention.

The Game Design Module addressed methods for assessing student mastery of course content with student-developed games indicated that using board game design improved student performance and increased student satisfaction.

Evaluation of senior design capstone projects via novel comprehensive rubric to assess sustainability learned over students' curriculum revealed that students' performance is primarily driven by their instructor's expectations. The rubric provided a universal tool for assessing students' sustainability knowledge and could also be applied to sustainability-focused projects.

With this in mind, engineering educators should pursue modules that connect sustainability grand challenges to engineering concepts, because student performance improves and students report higher satisfaction. Instructors should utilize pedagogies that engage diverse students and impact concept retention, such as active and experiential learning. When evaluating the impact of sustainability in the curriculum, innovative assessment methods should be employed to understand student mastery and application of course concepts and the impacts that topics and experiences have on student satisfaction.

DEDICATION

This work is dedicated to my mother and father, Ann Louise Antaya, M.S., and Timothy Allen Antaya, Ph.D., whose love of nature and dedication to education instilled in me the motivation to study the problem of integrating grand challenges like sustainability into engineering education and to the memory of my grandfather, Douglas Edward Martyn, whose adoration for all beings I carry with me to this day.

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Chapter 1

INTRODUCTION: SUSTAINABILITY AND GRAND CHALLENGES IN ENGINEERING EDUCATION

The next generation of engineering professionals must be prepared to solve complex and multidisciplinary problems in a sustainable and global context. Engineering education can provide students with the tools to approach these grand challenges of the 21st century while considering aspects that are key for designing sustainable systems [1]. Despite this, engineering education faces several challenges, including, but not limited to, addressing low diversity percentages, high attrition rates, and the need to better engage and prepare students for the role of a 21st century engineer [2].

Since the 1970s the representation of women in Science, Technology, Engineering and Mathematics (STEM) occupations has grown unevenly from 3% to 26% [3]. While the percent of women in math and science has continued to grow, growth in engineering has stagnated around 13% since 1990 [3]. Also, the number of bachelor's degrees awarded in science and engineering has increased, while the percentage of women earning bachelor's degrees in computer science and engineering has decreased in the last 10 years [4]. In addition, while underrepresented minorities represent more than 30% of the total United States' workforce, only 12% are enrolled in science and engineering undergraduate degree programs and 16% are employed in some STEM occupations [3, 4]. The President's Council of Advisors on Science and Technology (PCAST) and relevant research recommend that creating an educational experience where students have a connection to their degree and a connection to their technical community can contribute to increasing diversity in STEM. Sustainability is one theme

that can create this connection for many students. Research indicates that students who hope to address sustainability issues related to energy, water, and the environment demonstrate increased interest in pursuing engineering degrees; increasing the connection between sustainability and engineering could broaden participation of underrepresented populations, including women [5].

Furthermore, fewer than 40% of students enrolled in STEM majors complete their degree [2, 6]. There are many reasons for a student to move from STEM to another discipline, including intellectual compatibility and institutional support [7]. However, according to a recent National Academy of Science report, *Changing the Conversation*, one of the most significant contributing factors to high attrition rates is that courses no longer appeal to our youth [8, 9].

Youth are seeking careers that can make a difference, thus strategies for engineering education need to bring exciting topics and engaging methods into the classroom to motivate students toward goals that matter to them. Sustainable engineering offers a solution to these pressing challenges by providing context for the role of a modern engineer in solving to 21st century problems. Sustainability topics in engineering curriculum can address many of the underlying factors facing diversity and retention of students that otherwise leave STEM majors due to lack of engagement and/or motivation [5].

The National Academy of Engineering (NAE) developed and issued the Grand Challenges for Engineering, with five of the fourteen directly related to sustainability (solar energy, carbon sequestration, nitrogen cycle, clean water, and infrastructure) [10]. The Grand Challenges offer a framework for exposing engineering students to the role of

an engineer in modern society. Adoption of these challenges within engineering curricula has been cited to engage a diverse array of interested students by establishing contextualized linkages between course content and the contributions an engineer makes to solve global issues through systems-thinking innovation [11].

Engineering programs across the country have not determined the most effective strategy for merging sustainability and NAE Grand Challenges for Engineering throughout the schools' curriculum. Two main strategies have emerged from universities attempting to integrate grand challenges and sustainability into the curriculum; termed herein as the *stand-alone course method*, and the *module method*. In the stand-alone course method, engineering programs establish one or two distinct, stand-alone courses that address sustainability grand challenges in depth. In the module method, engineering programs integrate sustainability grand challenges throughout a host of existing courses. Neither method has been critically evaluated within the literature.

The goal of this research is to apply best practices from engineering education, including active and experiential learning pedagogies, to inform methods for integrating sustainability and grand challenges into engineering curricula. This research develops new sustainability course modules and develops methods to evaluate the modules' effectiveness on student cognitive and affective outcomes. This research also evaluates the stand-alone course method for integrating sustainability into curriculum. Senior capstone projects were used to evaluate students' ability to apply sustainability learned throughout their academic career to a culminating project. A novel rubric for evaluating sustainability in student projects was developed and tested.

This research has three main research objectives and related tasks, shown in Table 1 and described in detail in the next section. They include the evaluation of two modules that employ active and experiential learning: the Sustainable Metrics (SusMet) Module to teach sustainability concepts (objective 1) and the Game Design Module to assess student knowledge (objective 2). Objective 3 is to evaluate students' cumulative sustainability knowledge through the analysis of senior design capstone projects at two institutions, Arizona State University (ASU) and University of Pittsburgh (UPitt) using a mixed-methods assessment of novel rubric and survey developed in this thesis. Each objective results in a peer-reviewed journal publication, which is also identified in Table 1.

Table 1. Summary of Research Objectives, Related Tasks, and Publications.

Research Objectives	Related Tasks	Publication Title and (Chapter)
1 Determine the effectiveness of sustainability modules on student perceptions of sustainability and student learning outcomes (addresses the module method)	1.1 Develop and refine sustainability module 1.2 Develop and refine formative and summative survey and rubric assessment 1.3 Implement module and assessments at ASU; collect and analyze data. 1.4 Identify and evaluate improvements to make the module easily transferable to other institutions.	Incorporating Sustainability into Engineering Education Through An Active and Experiential Sustainable Engineering Module (Chapter 2) Antaya et al. (2015). <i>Redesign of a Sustainability Experiential Learning Module for Transferability and Portability</i> . ASEE 2015, Seattle, WA. (Chapter 2.8)
2 Determine the effectiveness of an active learning module using games to reinforce course concepts and enhance instructor's ability to evaluate student performance (active learning module)	2.1 Develop and refine games module for use as a semester-long project assignment 2.2 Develop summative survey and rubric assessment 2.3 Implement module and assessments at ASU; collect and analyze results.	Assessment of Students' Mastery of Construction Management and Engineering Concepts through Board Game Design (Chapter 3)
3 Evaluate students' cumulative sustainability knowledge across engineering curriculum via assessment of senior design capstone projects to inform educational assessment strategies for sustainability (addresses the stand-alone course method)	3.1 Develop survey to assess sustainability affective outcomes in senior design capstone experience 3.2 Develop rubric to evaluate sustainability cognitive outcomes from senior design capstone reports 3.3 Implement survey and rubric at ASU and UPitt senior design for three semesters; collect and analyze data.	Utilizing Civil Engineering Senior Design Capstone Projects to Evaluate Students' Sustainability Education Over Engineering Curriculum (Chapter 4)

Objective 1: Evaluate effectiveness of sustainability modules on student affective and cognitive outcomes

Objective 1 evaluates the module method of integrating sustainability into curriculum. The module was developed in 2008 by Drs. Landis and Bilec at the University of Pittsburgh; the research team called this module the 'chair lab' because the active learning component involved students dismantling and reassembling different chairs. The module is formally called herein the Sustainable Metrics (SusMet) Module.

The SusMet Module covers concepts of design for end-of-life and design for disassembly and implicit concept of sustainable metrics through active and experiential learning in the disassembly of office chairs, including a chair that is labeled as ‘green’. The module was further developed and refined for this thesis (Task 1.1). The development and refinement was published in a peer-reviewed conference proceedings of the American Society for Engineering Education (ASEE) [12]. The learning objectives for the SusMet Module include the following: 1) Explain the basics of design evolution and 2) Define end-of-life, design for disassembly, design for environment, sustainable metric, and environmental sustainability. This module was developed for the freshman-level, to introduce sustainability concepts to engineering students that they can employ for the rest of their engineering education. One of the benefits of introducing this module to freshman is that it exposes students early to the interrelation of sustainability and engineering. The module fits into approximately one week of lecture content. The module package includes everything an instructor needs for implementation: a summary of learning objectives, lecture slides and notes, recommended readings, a homework assignment, and an active, experiential learning activity instructions. The module is explained in further detail in Chapter 2.

In order to evaluate the effectiveness of the SusMet module, formative and summative survey and rubric assessment were developed (Task 1.2) to assess student affective and cognitive outcomes. A module-specific rubric was developed and applied to student homework assignments to assess student retention of learning objectives. The survey to assess student affective and cognitive outcomes was distributed digitally and contained questions, formatted on a Likert scale, that are related to student’s cognition of

the module learning objectives and their perceptions of sustainability concepts [13]. The survey was distributed prior to (formative) and after (summative) the SusMet Module; in the comparison course a duplicate survey was implemented. The rubric assessed student cognitive performance by comparing post-module assignments of two groups of students, one group with the hands-on experience of the chair disassembly and one without (comparison), by analyzing the assignment for frequency of sustainability concept usage.

In task 1.3, results from the module survey and rubric were analyzed to evaluate cognitive and affective outcomes from the module and retention of learning objectives through the rubric assessment. The SusMet Module and subsequent assessments were implemented at ASU in eight sections of FSE 100: Introduction to Engineering courses and one section of FSE 394: Engineering Projects in Community Service (EPICS) Gold II.

While the SusMet module has been very successful with instructors at ASU, it relies on the use of large chairs that are expensive and not easily transported across campus. Task 1.4 outlines a method for redesigning the module so that it is more portable while still achieving the same learning objectives and student experience. This work has already been published in ASEE's peer-reviewed conference proceedings [14].

Objective 2: Evaluate effectiveness of an active learning module using games to reinforce course concepts and enhance instructor's evaluation of student performance

Objective 2 addresses a modular approach to active learning using student-developed games to reinforce course concepts and enhance the instructor's ability to evaluate student performance. The Game Design Module involves student creation of

board games that utilize their course content. The module is a semester-long project, but is intended to take the place of (or supplement) a final exam. The learning objectives for the Game Design Module include the following: 1) Demonstrate knowledge core course concepts and 2) Show application of core course concepts, including building materials, methods and equipment that students would experience on an industry job site. One of the merits of exposing students to creative game design in the classroom is that it asks students to begin thinking critically about the content that they should have learned. In addition, the game framework asks students to think about their educational experience in a new way, as they design games with the aim of teaching their peers the content that they learned in class. The module fits into approximately one week of lecture content and includes everything an instructor needs for module implementation: a summary of learning objectives, lecture slides and notes, a homework assignment, and an active, experiential learning activity instructions.

The game module was refined (Task 1.1) after each implementation and assessment (Task 2.2). A module-specific summative survey and journaling activity was developed to assess student affective and cognitive outcomes. In addition, a module-specific rubric was developed to assess cognitive outcomes from the work turned in by students. Learning outcomes and student cognitive performance was evaluated using the rubric by comparing the frequency and accuracy of use of course concepts in student games. In order to evaluate the effectiveness of the Games Module, student performance was compared to a comparison project. The Game Design Module was implemented in three sections of CON 252: Building Construction Materials, Methods, and Equipment (BCMME) at ASU. The Game Design Module could also be applied to sustainability

courses/content however this thesis was intended to assess the effectiveness of the active learning module for demonstrating students' mastery of course concepts.

Objective 3: Evaluate students' cumulative sustainability knowledge across engineering curriculum via a novel sustainability rubric used in senior design capstone

Objective 3 evaluates the stand-alone method by analyzing senior design projects at ASU and UPitt. Both ASU and UPitt require students to take at least one stand-alone sustainability class during their academic career. A novel sustainability rubric was developed in order to understand whether students are able to apply what they've learned during their curriculum (i.e. the stand-alone sustainability class) in their culminating senior design projects. Task 3.1 developed a survey to assess sustainability affective outcomes in senior design capstone projects, while the rubric was developed in Task 3.2 affective outcomes relate to students' perceptions of sustainability in engineering [13]. The rubric built on best practices in the literature (e.g. McCormick et al 2014, Bielefeldt 2013, and Anderson et al 2001) and assesses students' projects for evidence of sustainability concepts and grand challenges, linkages between sustainability concepts and level of Bloom's taxonomy [15-18].

Task 3.2 aims to inform educational assessment strategies for sustainability, and utilizes the results from the assessment of senior design capstone projects to begin to inform program impact on student learning outcomes related to sustainability. The results were also used to make recommendations for program-wide curricula change, pointing out factors that determine success. Examples of success include increased student retention of sustainability concepts, increased student reporting of their perceptions of the

visibility of sustainability in engineering, and increased acknowledgment that sustainability and engineering are interrelated.

Intellectual merit

This research applies best practices from engineering education, including active and experiential learning pedagogies, to inform methods for integrating sustainability and grand challenges into engineering curricula and methods for assessing student knowledge of sustainability grand challenges during their undergraduate career. The research activities directly addresses many of the issues facing Science, Technology, Engineering, and Mathematics (STEM) education as cited by the National Research Council (NRC), such as assessing instructional strategies for faculty incorporating new topics into their courses, providing approaches for evaluating student learning outcomes related to these new topics, and providing methods to approach curriculum-wide transformation [19]. Findings from this research will guide how present and future engineering educators address the incorporation of sustainability and National Academy of Engineering (NAE) Grand Challenges for Engineering by analyzing the module and stand-alone course methods for integrating sustainability into engineering curricula [20]. In order to evaluate the effectiveness of the stand-alone and module method, new mixed-method assessments were developed to evaluate the effect of sustainability and active learning in modules (Chapter 2), in classes (Chapter 3), and in curriculum (Chapter 4). Through the implementation and monitoring of these strategies at Arizona State University (ASU) and University of Pittsburgh (UPitt), recommendations for methods to integrate sustainability and grand challenges were created to address program-wide curricula change.

Broader impacts

This research develops 10 ready-to-use modules on sustainability grand challenges and 1 assessment tool for understanding engineering students' knowledge and application of sustainability concepts for instructors to utilize within engineering classes and throughout curriculum. The modules employ engaging activities on sustainability and NAE Grand Challenges for Engineering using active and experiential learning pedagogies that have been shown to improve student learning outcomes and satisfaction [21-24]. The modules are packaged for ease-of-use and are freely available on ASU and UPitt websites. The SusMet module has been implemented in classes at ASU other than engineering, including K-12 teachers classes in Mary Lou Fulton Teachers' College, sustainability classes in Julie Ann Wrigley Global Institute of Sustainability, and design classes in Herberger Institute for Design and the Arts. It has also been utilized at other institutions, including Chandler-Gilbert Community College and Mesa Community College. Overall, this project improves the capabilities of engineering educators and future engineers to tackle some of society's most imminent challenges.

Background and Literature Review

This thesis covers many topics, from sustainability and National Academy of Engineering Grand Challenges for Engineering, to active and experiential learning, to game-based learning and assessment, to sustainability assessment across a curriculum. The background and literature review provides a summary of recent research and findings in these areas relevant to this thesis.

The state of sustainability in engineering curriculum

Incorporating sustainability into traditional courses provides students with a meaningful way to connect more personally to their courses. In addition, sustainable engineering can often bring more rigor to curriculum. Despite this, a disconnect exists between engineering programs across the country in the adequate merging of sustainability throughout the schools' curriculum. Universities recognize the importance of integrating sustainability into curriculum, but many struggle with how to best update curriculum and overcoming faculty barriers to teaching new concepts. A 2010 workshop on incorporating sustainability into the civil and environmental engineering (CEE) curriculum co-organized by Drs. Landis and Bilec during the National Civil Engineering Department Heads Conference showed that the average CEE curriculum had three courses with significant sustainable engineering content, 11% of programs reported no sustainable engineering course content and only 12% of CEE faculty reported researching or teaching in sustainable engineering area [25]. An ASU CEE faculty survey conducted in November 2011 found that about half of faculty attempt to integrate sustainability and that there are varying degrees of faculty understanding of sustainable engineering. Zhang et al found that engineering faculty identified that the major challenges for the integration of sustainability in engineering education to fall into four categories, which they defined during a 2012 workshop as 'shifting paradigms,' 'rigidity of existing curricular structure,' 'the need for new methods,' and 'insufficient resources' [26]. Faculty cited that sustainability necessitates transformations in culture and thinking, requires non-traditional interdisciplinary collaborations and the integration of practical, hands-on activities within current and future courses. Faculty felt particularly challenged by

unfamiliarity with sustainability concepts and applications, not knowing how to integrate these concepts without diluting and/or sacrificing existing course content, and a general lack of materials, resources and time to support their efforts for course reform.

NAE Grand Challenges of Engineering

The National Academy of Engineering (NAE) developed and issued fourteen Grand Challenges for Engineering. Five of fourteen challenges directly relate to sustainability, including “restore and improve urban infrastructure,” “provide access to clean water,” “make solar energy economical,” “develop carbon sequestration methods,” and “manage the nitrogen cycle” [20]. In response to the pressing challenges, over the next decade 122 schools across the country have pledged to graduate at least 20 students specifically trained in solving large-scale problems like the grand challenges [27]. Many of the Grand Challenges have also been identified by the White House Strategy for American Innovation and the United Nations Millennium Development Goals as global challenges that will require diverse, innovative solutions [28, 29].

Methods for integration of sustainability and grand challenges into curriculum

While disparate strategies and methods have been employed to integrate grand challenges such as sustainability into the curriculum, the two predominating methods have been generalized herein as: the stand-alone course method, and the module method. In the stand-alone course method, a program establishes one or two distinct, stand-alone courses into the students’ curriculum that focus on the grand challenges. In the module method, engineering programs integrate grand challenges throughout a host of existing

courses by threading individual sets of course skills together in an effort to reach higher levels of intellectual behavior via interdisciplinary concept connection [30]. Modules can be designed to fit into one lecture or over a series of lectures. Modules typically include everything an instructor needs for implementation: a summary of learning objectives and module activities, lecture slides and notes, recommended readings, and an assignment for students. In the proposed project, our modules will also include instructions, grand challenges discussion questions, an example you-tube video for conducting the experiential learning activity, and an assessment of student learning and module effectiveness.

Two large programs in the US have compiled resources for integrating sustainability (but not experiential learning) based on the two methods. The Center for Sustainable Engineering (CSE) has created a peer-reviewed repository for stand-alone sustainability courses, accessible at: <http://www.csengin.org> [31, 32]. The UT-Arlington Engineering Sustainable Engineers (ESE) program has taken the module approach; the program has implemented 11 non-active learning sustainability modules in Civil Engineering (CE), Industrial Engineering (IE), and Mechanical Engineering (ME), accessible at: <http://www.uta.edu/ce/ese/index.htm> [33, 34]. No institutions yet employ the module method program-wide.

Active & experiential learning

Active learning places the responsibility of learning on learners themselves and can establish students' ability to exercise lifelong learning by shifting away from instructor-centered instruction towards student-centered instruction [35, 36]. Compared to

traditional lecturing, active learning has been shown to increase student performance in STEM courses regardless of class type, size and distributions of students' personalities (e.g., introvert/extrovert) [23, 37-39]. This suggests that replacement of traditional lecturing with active learning could contribute to increases in number of students receiving STEM degrees, particularly for students whom perform at or below average in traditional lecturing classrooms [23, 24]. Active learning also increases long-term retention of learning objectives beyond the semester timeframe of a course [24, 40].

Experiential learning involves constructing meaning from direct experience and involves the learner in a real, rather than abstract experience and is defined by the interaction among four learning modes: two grasping experiences of concrete experience and abstract conceptualization and two transforming experiences of reflective observation and active experimentation [41-43]. Experiential learning, or creating knowledge through the process of experience, has been cited to positively impact non-traditional student learners, including underperforming students, and increase overall student retention and completion of programs of study [21, 22].

Game-based learning

Game-based learning (GBL) is a recognized pedagogy for teaching students a defined learning outcome. Games used in GBL have been classified many different ways, however tend to fall into one or more of the following genres: action, adventure, fighting, role-playing, simulations, sports, and strategy [44]. Games that promote education in addition to providing entertainment value are described as serious games [45]. Digital games predominate serious games in the GBL literature and have been instrumental in

the creation of new social and cultural worlds [46, 47]. The use of non-digital games, such as board games, offer many of the same community interactions as digital games without requiring the use of computers, making them accessible to a wide variety of classrooms [48]. The Energy Choices (EC) game exemplifies sustainability content taught through GBL pedagogy; the EC game is a board game designed to introduce middle school students to the important role that personal energy choices play in their daily lives in order to prime students for energy lessons that follow [49].

Assessment methods

There are several established ways to assess student progress towards learning goals. Traditional assessment methods *within a course* include, but are not limited to, quizzes, papers, projects, reports, exams, surveys, and journal entries while methods for assessing retention of learning outcomes *across a curriculum* include student portfolios and capstone design projects [50]. Although active and experiential learning pedagogies have been cited to positively impact non-traditional learners and engage a broad spectrum of students, sustainability assessments *within a course* using active and experiential pedagogies are limited in the literature [51, 52]. In addition, while sustainability and grand challenges have been cited to engage and motivate diverse sets of students in engineering, methods for assessing students' sustainability knowledge *across a curriculum*, rather than a course content-based assessment, are limited the literature [53].

While game-based learning with the use of serious games and their ability to help students learn is explicit in the literature, little research has been conducted on student-developed games to assess student learning *within a course*. The closest example is in

computer science courses that allow students to modify an existing computer game by program changes into the game to receive immediate feedback on effective code execution [54]. When compared to writing code in a traditional programming assignment, the students that practiced the learning objectives within a game environment outperformed students who participated in the traditional assignment [54].

Strategies for assessing student sustainability knowledge and application within engineering are limited to a few studies. The strategies include what students should be assessed and how to assess them, including defining learning objectives related to assessing understanding of sustainable development via critical, holistic thinking and assessing the number of times a student mentions sustainability concepts, whether or not a student links three pillars of sustainability (environmental, economic, social), utilizing instructor-created rubrics on course content or available assessments such as Sustainability in Higher Education Assessment Rubric (SHEAR) [16, 17, 55-57]. Designed for ease of use and adaptability, SHEAR outlines eight categories of assessment, including awareness and knowledge, skill development, application in diverse settings, reflection, responsibility, diverse interactions, partnerships, and life-long learning, and rates a course's performance within each category on a four-point scale from 0 (none)- 3 (strong) [58]. To compliment SHEAR, the sustainability assessment survey (SAS) was developed to gauge changes in students' knowledge, skills, attitudes and behaviors towards sustainability concepts and applications as a result of taking a course via pre- and post-assessment surveys [59].

Sustainability in higher education assessments often lack details indicative of interdisciplinary knowledge transfer necessary for learning sustainability, thus

researchers have recently adopted a concept mapping approach of assessing students. This approach compliments the nature of current global issues, which are complex and interconnected, and gauges whether students can rationally infer interactions between and within human and natural systems [60].

Current efforts to measure the progress of incorporating sustainability in higher education have employed cross-institutional assessments [61]. A number of benefits for this methodology have been cited, including the potential for open dialoging of goals, experiences and methods, benchmarking of influential players and best practices and construction of metrics that are quantitative, comparable and transparent across multiple stakeholders [61]. Analysis of more than two dozen institutional sustainability assessments, however, revealed that measuring progress is critically disadvantaged by the relative lack of empirical data and comparable metrics to judge across curricula incorporating concepts and applications from this new field [61-63]. Many of the indicators are not relevant at a university scale and those that may be useful for university adoption are likely too resource-intense to manage or present uneven foci, with heavy emphasis on economic sustainability and little emphasis on social or environmental [62, 63]. There is a need for stakeholders to pioneer a universal assessment tool or, at the very least, agree on a minimal set of metrics to assess advancements in incorporating sustainability in higher education and evaluating engineering students' sustainability knowledge *across a curriculum* [64].

Development of sustainability grand challenge modules

To address content for incorporating sustainability and grand challenges into engineering curricula ten modules, presented in Table 2, were developed with the support from the National Science Foundation Transforming Undergraduate Education in STEM (TUES) Type 1 program (formerly Course, Curriculum, and Laboratory Improvement CCLI)- Award No. 0942172/1242325, Venture Well (formerly National Collegiate Inventors and Innovators Alliance NCIIA) Course and Program Grant Award No. 5120-07, the University of Pittsburgh Innovation in Excellence Award (IEA), the ASU Gary and Diane Tooker Professorship for Effective Education in STEM, and the National Science Foundation Transforming Undergraduate Education in STEM (TUES) Type 2 program- DUE Award Nos 1323719 and 1323190, and Arizona State University NASA Space Grant Fellowship.

The modules cover topics of carbon footprinting, water footprinting, renewable energy, energy supply and demand, life cycle thinking, future of food, metrics to assess sustainability, and the evolution of technology, all of which demonstrate the relationship between engineering design and sustainability [12]. Two modules, shown in bold, were explored in depth in this dissertation; the Sustainable Metrics Module introduces students to sustainability concepts of design for end of life, design for disassembly and sustainable metrics and the Game Design Module assesses student knowledge through student creation of board games that demonstrate the interaction of core course concepts, such as climate, water, energy, and food.

The modules are available for free download (accessible at www.stemed.engineering.asu.edu) and contain everything an instructor needs to

implement them, including: a summary of learning objectives, lecture slides and notes, a homework assignment, and an active, experiential learning activity instructions.

Table 2. Summary of Modules Developed.

Blue rows with bold text denote the modules that were the focus of this research.

Module	Description	Notes
Carbon, 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.
Energy-renewables	Students play the flash game Super Energy Apocalypse by Lars A Doucet. Groups are tasked with different energy strategies for developing the new world and they must assess their impacts.	Students can play remotely and tweet their progress. The module will also be designed to use the board game, Power Grid by Rio Grande Games for a more tactile experience.
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.
Game Design	Students create board game utilizing existing course content to demonstrate mastery of course concepts	Game design can be modified from three game days to two games days, depending on format of the course.
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, and emissions.	A variety of products are applicable (e.g. candy bar, small electronic, etc), enabling LCT in a wide array of classes. Advanced levels can quantify process material and energy flows.
Model United Nations (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 address topics of feeding 9 billion people, Carbon sequestration, managing the Nitrogen cycle, and information security
Sustainable Metrics	Students are asked to bring a green product to class. Students investigate what metrics make it green, how to quantify and benchmark metrics, and how green metrics influence design².	Any 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 or redesign products
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.

Dissertation chapters

With these overarching concepts in mind, this dissertation investigates the stand-alone course and module methods for integrating sustainability into curriculum. The thesis document describes the development of two modules, one that teaches

sustainability and one that uses GBL to assess student learning. Finally, the stand-alone method is evaluated by developing a novel sustainability rubric to assess student learning across a curriculum. Each chapter in this thesis is organized as a series of peer-reviewed journal papers; each of which address one of the three main research objectives described in Table 1. To address the first research objective, determine the effectiveness of sustainability modules on student perceptions of sustainability and student learning outcomes, Chapter 2 presents the development and implementation of the Sustainable Metrics (SusMet) Module to teach sustainability concepts to engineers through active and experiential learning, including the redesign of the module for transferability and portability. To address the second research objective, determine the effectiveness of active learning modules using games to reinforce course concepts and enhance instructor's ability to evaluate student performance, Chapter 3 presents the use of student-developed board games as a method to assess student mastery of construction and engineering concepts through the development and implementation of Game Design Module. To address the third research objective, evaluate students' cumulative sustainability knowledge across engineering curriculum via assessment of senior design capstone projects to inform educational assessment strategies for sustainability, Chapter 4 concludes the thesis with the development of a rubric for evaluating students' sustainability knowledge acquired during their undergraduate engineering courses; the rubric is applied to senior design capstone projects and evaluates two institutions' senior design projects for students' use of sustainability and reflects on the use of an engineering-focused design project as the place for evaluating sustainability.

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Chapter 2

INCORPORATING SUSTAINABILITY INTO ENGINEERING EDUCATION THROUGH AN ACTIVE AND EXPERIENTIAL SUSTAINABLE ENGINEERING MODULE

This chapter is broken into two parts. Part one evaluates the module method of integrating sustainability into curriculum and utilizes a mixed-methods assessment of student survey on cognitive and affective outcomes and rubric evaluation to assess the impact of the module activity on student retention of learning concepts. Part two presents a method for redesigning the module so that it is more portable while still achieving the same learning objectives and student experience.

Abstract

Background Engineers of the future must be prepared to address complex, multidisciplinary grand challenge problems in sustainable and global contexts. However, engineering programs across the country offer no consensus on the approach for adequate merging of sustainability throughout engineering curriculum. This paper explores the cognitive and affective outcomes of integrating an active, experiential learning sustainability module into existing engineering courses. The Sustainable Metrics (SusMet) Module covers explicit concepts of design for end-of-life and design for disassembly and implicit concept of sustainable metrics through active and experiential learning in the disassembly of office chairs, including a ‘green’ chair.

Purpose/Hypothesis The objective of this research is to establish the impact of the module on student comprehension of learning objectives and to understand the effect of the module activity on student retention of module learning objectives.

Design/Method The SusMet Module was implemented in a total of nine courses (318 total participants): eight freshman-level Introduction to Engineering courses and one

junior-level Engineering Projects in Community Service course at Arizona State University. The research design included one course where students completed the entire module and one comparison course in which the active learning portion was removed; both courses included a follow-on design assignment two weeks after module implementation. The SusMet Module was assessed using a mixed-methods approach of anonymous digital pre-and post-module surveys to test affective and cognitive outcomes and a rubric assessment to test the activity portion on learning objective retention.

Results The activity portion of the module had the greatest impact on student cognition and retention of learning objectives; students that experienced hands-on disassembly of the chairs retained concepts students tended to struggle with, i.e., design for end-of-life (explicit) and sustainable metric (implicit), to a greater degree than students in the comparison course that did not experience hands-on chair disassembly. Students performed best cognitively when terms were given explicit definitions rather than implicit, and Junior-level students were more capable of providing correct definitions for implied terms than Freshman-level students. Junior-level students consistently outperformed the Freshman-level students despite increases in Freshman student confidence, implying that Freshman-level students may overestimate their abilities and Junior-level students may have greater understanding of their capabilities, an affective finding.

Conclusions The results signify that one of the important components of the SusMet 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.

Introduction

Engineers of the future must be prepared to address complex, multidisciplinary problems in sustainable and global contexts. The National Academy of Engineering Grand Challenges of Engineering provide context for future challenges that require engineering intervention [1]. Engineering education can provide students with the tools to approach these grand challenges while considering design aspects necessary for creating and maintaining sustainable systems [2].

Incorporating sustainability into traditional courses provides students with a meaningful way to connect more personally to their courses. In addition, sustainable engineering can often bring more rigor to curriculum. Despite this, a disconnect exists between engineering programs across the country in the adequate merging of sustainability throughout the schools' curriculum. A survey from the 2010 civil and environmental engineering (CEE) department chair workshop showed that the average CEE curriculum had three courses with significant sustainable engineering content, 11% of programs reported no sustainable engineering course content and only 12% of CEE faculty reported researching or teaching in sustainable engineering area [3]. Faculty cited that sustainability requires the integration of practical, hands-on activities within current and future courses and the challenge faculty face is unfamiliarity with sustainability concepts and applications, not knowing how to integrate these concepts without diluting and/or sacrificing existing course content, and a general lack of materials, resources and time to support their efforts for course reform [4].

One way to infuse sustainability into engineering curricula is for faculty to adopt ready-to-use sustainability modules. Modules can be designed to fit into one lecture or

over a series of lectures. Modules typically include everything an instructor needs for implementation: a summary of learning objectives and module activities, lecture slides and notes, recommended readings, and an assignment for students. Using modules to teach sustainability concepts reinforces the broader applicability of sustainability to all engineering disciplines by connecting traditional engineering to impacts to, and solutions for, society, economy, and environment [5]. The best-known use of modules to integrate sustainability into traditional engineering courses is the University of Texas- Arlington (UT-Arlington) Engineering Sustainable Engineers (ESE). The ESE program has implemented eleven non-active learning sustainability modules in Civil Engineering, Industrial Engineering and Mechanical Engineering, accessible at: <http://www.uta.edu/ce/ease/index.htm> [6, 7]. No institution yet employs sustainability modules for integration into engineering curricula program-wide.

Experiential learning involves constructing meaning from direct experience and involves the learner in a real, rather than abstract experience and is defined by the interaction among four learning modes: two grasping experiences of concrete experience and abstract conceptualization and two transforming experiences of reflective observation and active experimentation [8-10]. Experiential learning, or creating knowledge through the process of experience, has been cited to positively impact non-traditional student learners, including underperforming students, and increase overall student retention and completion of programs of study [11, 12].

Active learning places the responsibility of learning on learners themselves and can establish students' ability to exercise lifelong learning [13]. Compared to traditional lecturing active learning has been shown to increase student performance in STEM

courses regardless of class type and size [14, 15]. This suggests that replacement of traditional lecturing with active learning could contribute to increases in number of students receiving STEM degrees, particularly for students whom perform at or below average in traditional lecturing classrooms [14, 16]. Active learning also increases long-term retention of learning objectives beyond the semester timeframe of a course [16, 17].

This paper explores the cognitive and affective outcomes of integrating a ready-to-use sustainability module into existing engineering classes. This paper evaluates the effectiveness of one module called the Sustainable Metrics (SusMet) module. The SusMet Module utilizes experiential learning to teach concepts of design for end-of-life (EOL), design for disassembly, and sustainable metrics, all of which are at the interface between engineering design and sustainability [18].

Methods

The methods section first describes the Sustainable Metrics (SusMet) module, including module learning objectives, module lecture and hands-on activity. Following, the methods provide a description of the courses where the module was implemented in Fall 2013 and Spring 2014 semesters at Arizona State University. And finally the methods present the module assessment utilizing a mixed-methods approach. The mixed-methods assessment includes an anonymous pre- and post-module survey on cognitive and affective outcomes and a rubric assessment to determine the impact of active, experiential learning on retention of learning objectives in a design assignment following the module.

Module Description

The SusMet Module is an active and experiential learning module that explores topics of design for environment, disassembly, end-of-life and sustainable metrics through the disassembly of traditional and green office chairs. The module's explicit learning objectives state that students will be able to 1) explain the basics of design evolution, 2) apply design evolution concepts to analyze the office chairs from recent decades in terms of their "green" quality or design for the environment, 3) determine the feasibility of end-of-life recycling of the materials comprising the chair and 4) examine and assess the green design properties of chairs from mid 1900's versus a 21st century chair touted as green [19]. Students' knowledge of sustainable metrics is actually an implicit learning objective of the SusMet Module, despite the module's name. Among instructors, the SusMet Module is called the 'Chair Lab' due to the disassembly of the chairs as the in class activity. Thus, students are not told that they will be learning about sustainable metrics, but rather that they will complete the 'Chair Lab' in class.

The SusMet Module lecture and activity is presented in Figure 1. The instructor begins the SusMet Module with a 10-minute presentation to prepare students for the module activity. The presentation introduces students to decades of office chairs, including a 1950's chair, early 1990's chair, late 1990's chair and a 'green' 2000's chair advertised for its ease of disassembly and materials usage [18]. The entire module, including lecture slides, sample homework assignment, and activity instructions are available on www.stemed.engineering.asu.edu. Through a class discussion the students then explore the history of designing for X, where X can represent design for end-of-life (EOL) and design for disassembly by connecting these concepts to the common office

chair. Students are then put into teams of 4-5 to review the manufacturer's brochure that accompanies the 'green' chair for the presence of design for EOL, disassembly and sustainable metrics concepts. The instructor asks students to construct a hypothesis regarding the claims made by the manufacturer of the 'green' chair. Students predict how the other chairs will perform compared to the 'green' chair designed specifically for EOL and disassembly. The students also determine what metrics they will need to document in order to compare the chairs design for EOL, disassembly and sustainable features.

The module activity begins with timed competition to disassemble the office chairs using common household tools. During the 30-minute disassembly, students record metrics that they brainstormed, often including the number of parts and materials used in the chairs and the percent disassembly reached in allotted time. The teams present their findings in a class discussion comparing the ease of disassembly and metrics recorded during disassembly, including sustainable metrics, between the office chair evolutions. Students then switch chairs with another team to experience the reassembly of a different chair design. For the next 30 minutes the teams record reassembly metrics related to the new chair experience. The module concludes with a final class discussion comparing the disassembly experience with the team's original chair to the reassembly experience with a new chair. The teams present their findings regarding design for EOL, disassembly, and sustainable metrics and connect their findings to the brochure associated with the 'green' chair.

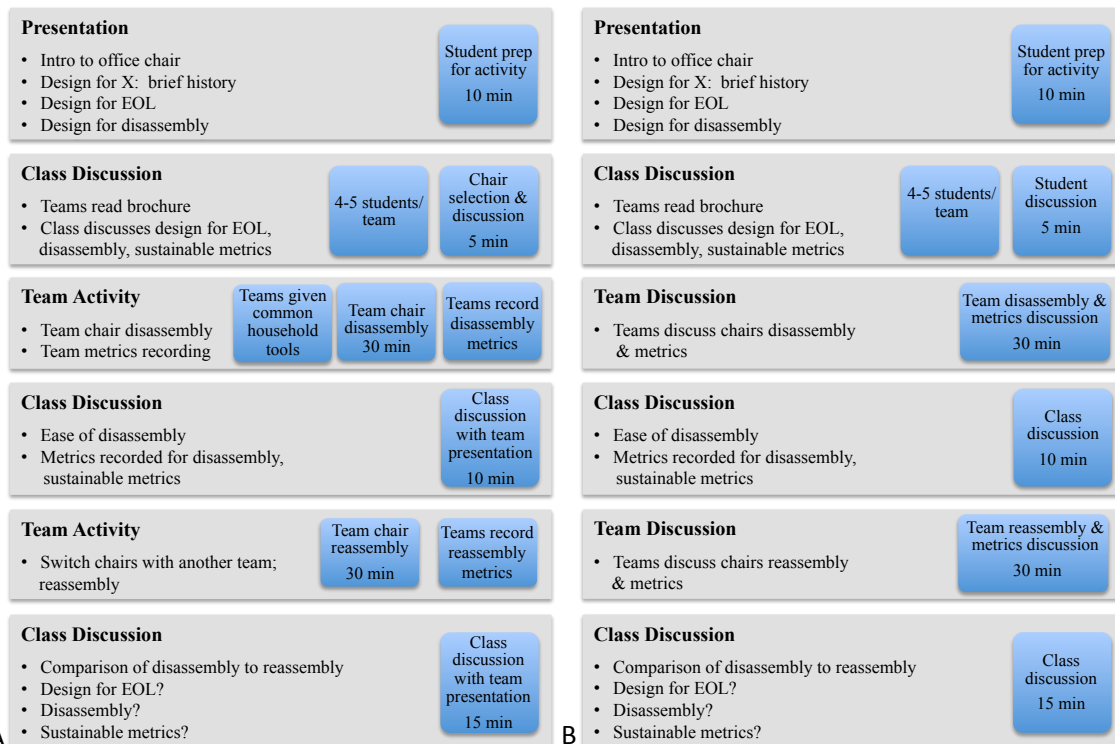


Figure 1. Sustainable Metrics (SusMet) Module Flow Chart With Activity (A) and Without Activity (B).

(A) The SusMet Module with activity is conducted in six stages. The module begins with a presentation on key concepts and learning objectives and transitions to a class discussion on the presence of key concepts in a ‘green’ chair brochure as sustainability claims. Students actively test the claims by dismantling decades of different chairs. After which the instructor facilitates a class discussion on student findings. Students then reassemble the chairs and the module concludes through team presentations and discussion relating module learning objectives to comparison of chair designs. (B) In the SusMet Module without activity students participate in the same lecture and class discussions while the activity portion of the module is replaced with team discussions of chair disassembly, reassembly and metrics.

Online, the module has sample assignments with different variations for different levels of student. For this study the online module assignments were not given to students in the SusMet classes. However, a design assignment was given to one intro class and a comparison class to evaluate retention of concepts; this assignment and analysis is described later in the *Retention of Concepts* Section.

Module Test Courses

The modules were implemented in six Freshman Intro to Engineering courses and one Junior course called EPICS at ASU, summarized in Figure 2. Introduction to Engineering courses at ASU introduce approximately 40 freshman students per section to the engineering design process through lecture and laboratory exploration of engineering concepts. ASU divides Introduction to Engineering courses into three tracks: civil engineering/construction management, mechanical/electrical engineering and computer science/industrial engineering [20]. (The difference between these tracks is the laboratory portion; students receive the same content in the lecture portion of the class while exploring different disciplines of engineering in the laboratory portion. In addition to introducing freshman to engineering, this course also prepares students to work in teams through a semester project that features a design competition to build engineering models such as water wheels (civil/construction focus), solar cars (mechanical/electrical focus), or maze design (computer/industrial focus). Students work in teams of five on the course project and practice communication skills via written reports and oral presentations. Introduction to Engineering at ASU are taught by several instructors; as of 2014 ASU offers 45 sections in the Fall and 12 sections in the Spring. The SusMet Module was implemented in six sections of Introduction to Engineering (called herein Intro A-F) taught by three different instructors shown in Figure 2. The instructors were given a packet of module materials which included lecture slides, description of activity, and discussion questions. All three instructors watched the module implemented by another instructor prior to teaching it in their own course for this study.

Engineering Projects in Community Service (EPICS) courses at ASU utilize a service-learning approach to explore engineering topics through applied community service projects [21]. In 2013-2014, EPICS courses at ASU were split between three levels: EPICS Gold I, Gold II and Gold III with a total enrollment of 126 students in 2013-2014 school year. Gold I was a freshman-level course and focuses on the project feasibility and planning phases of the engineering design process. Gold II was a junior-level course focusing on engineering design and building phases. Gold III was a senior capstone experience taken in addition to the engineering senior capstone design course and students use this additional semester to finish their project. As of Spring 2014, a single instructor taught approximately 40 students each of the EPICS I-III courses at ASU. The SusMet Module was implemented in the EPICS Gold II (EPICS II) junior-level course to compare junior engineering responses to that of freshman engineering students in Introduction to Engineering shown in Figure 2.

Retention of Concepts: Comparing the Comparison Course to an Intro Course

To understand the impact of active learning within the SusMet Module on retention of learning objectives, a comparison class without the activity (called ‘comparison’ in Figure 2) in another section of Intro to Engineering was compared to an Intro to Engineering class with the activity (called ‘Intro + Ret’ in Figure 2). The SusMet Module was implemented in one additional Introduction to Engineering (Intro + Ret) section; the module implementation was the same as the other Intro to Engineering classes and the EPICS II class. In the Comparison class, only the lecture portion of the SusMet Module was implemented into an Introduction to Engineering Comparison

course. Students in the Comparison course participated in the SusMet Module, but the activity portion of the module was removed. Students in the Comparison course did not utilize the chairs. Instead, the instructor gave the exact same module lecture and discussion to the students.

Two weeks after the module was implemented in the Intro + Ret course and the Comparison course, the students were given a design assignment. The assignment, called 'Engineering Design Process Lab,' asked students to apply the engineering design process to create a conceptual design [20]. In this design assignment students defined the problem in a problem statement, used brainstorming techniques to generate design alternatives and applied a decision matrix to select best design based on design criteria. For this particular design, students were asked to design a combined desk-chair to be utilized in a classroom setting. This design assignment had individual and team components; students submitted individual problem statements but discussed design requirements and utilized the decision matrix to determine the best design as a team. The final design was submitted as a team. The design assignment was part of Introduction to Engineering curriculum and not the online SusMet Module.

	SusMet Module	SusMet Module + Design	SusMet Module - Activity + Design
Freshman Level	<div style="display: flex; flex-wrap: wrap; justify-content: space-around;"> <div style="border: 1px solid black; padding: 5px; margin: 5px;">Intro¹ A</div> <div style="border: 1px solid black; padding: 5px; margin: 5px;">Intro¹ B</div> <div style="border: 1px solid black; padding: 5px; margin: 5px;">Intro¹ C</div> <div style="border: 1px solid black; padding: 5px; margin: 5px;">Intro¹ D</div> <div style="border: 1px solid black; padding: 5px; margin: 5px;">Intro² E</div> <div style="border: 1px solid black; padding: 5px; margin: 5px;">Intro³ F</div> </div>	Intro + Ret ³	Control ¹
Junior Level	<div style="border: 1px solid black; padding: 10px; width: fit-content; margin: auto;">EPICS II⁴</div>		

Figure 2. Summary of SusMet Module Implementation.

The Sustainable Metrics (SusMet) module was implemented in six freshman-level Introduction to Engineering courses (Intro A-F, taught by instructors 1-3) and one junior-level Engineering Projects in Community Service Gold II course (EPICS II, taught by instructor 4). The SusMet Module was also implemented in one intro-level course (Intro + Ret, taught by instructor 3) where students participated in the entire module and one comparison course (Comparison, taught by instructor 1) where the activity portion of the module was removed. Both the Intro + Ret and Comparison courses completed a design retention assignment two weeks after the module to understand the impact of the activity on retention of learning objectives.

Mixed-Methods Assessment

The SusMet Module was assessed using a mixed-methods approach combining pre- and post-module surveys and rubric evaluation of student work. The rubric was used to assess retention of concepts and evaluate how the experiential portion of the module impacted student-learning outcomes.

Survey Assessment

The pre- and post-module questions, shown in Table 3, included single-response, Likert-scale and open-ended questions [22]. All students took the pre-module survey prior to the module lecture and the post-module survey after the module discussion. Questions 1-4 on the pre-module survey and 1-3 on the post-module survey assessed *cognitive outcomes*; students respond to term recognition prior to the module and then

provide definitions for the explicit learning outcomes including design for EOL, design for disassembly, and one implicit learning outcome including sustainable metrics. Questions 5 and 6 on the pre-module survey assessed an *affective outcome*, student-perceived confidence related to module content and application of module content. The affective questions ask students about their perceived confidence in their ability to apply design for EOL and disassembly principles and identify and use sustainable metrics. Corresponding post-module questions 5 and 6 asked students to respond to the same pre-module affective questions and an additional question 4 regarding students' perceived ability to challenge green claims. This survey research was approved exempt under IRB protocol #1206007924 at Arizona State University and #PRO10010207 at the University of Pittsburgh.

Table 3. Pre- and Post-Module Survey Questions.

Question	Possible Response
Pre Survey	
1. I have heard of the term "design for end-of-life" before this class	Yes or No
2. I have heard of the term "design for disassembly" before this class	Yes or No
3. I have heard of the term "sustainable/sustainability" before this class	Yes or No
4. I have heard of the term "metric" before this class	Yes or No
5. Please identify your confidence in your ability to apply "design for end-of-life" and "design for disassembly" principles to improve a product or process	Very Unconfident, Unconfident, Neutral, Somewhat Confident, Very Confident
6. Please identify your confidence in your ability to identify "sustainable metrics" and use them to describe the sustainability of a product or process	Very Unconfident, Unconfident, Neutral, Somewhat Confident, Very Confident
Post Survey	
1. Please define the term "design for end-of-life" to the best of your ability	Open-ended
2. Please define the term "design for disassembly" to the best of your ability	Open-ended
3. Please define the term "sustainable metric" to the best of your ability	Open-ended
4. Please identify your confidence in your ability to challenge "green claims" made by someone with the use of clear reasoning supported by evidence	Very Unconfident, Unconfident, Neutral, Somewhat Confident, Very Confident
5. Please identify your confidence in your ability to apply "design for end-of-life" and "design for disassembly" principles to improve a product or process	Very Unconfident, Unconfident, Neutral, Somewhat Confident, Very Confident
6. Please identify your confidence in your ability to identify "sustainable metrics" and use them to describe the sustainability of a product or process	Very Unconfident, Unconfident, Neutral, Somewhat Confident, Very Confident

Responses to all surveys were anonymous. Pre-survey questions 1-4 and post-survey questions 1-3 assessed cognitive outcomes where as pre-survey questions 5 and 6 and post-survey 4-6 assessed affective outcomes. Definitions were coded on a binary scale as correct/incorrect based on the definitions provided.

Pre, post and total survey responses are shown in Table 4. A total of 318 students participated in the classes and were surveyed during Fall 2013 and Spring 2014. The average pre-survey response rate was 81% and average post survey response rate was 72%. Survey responses for the open-ended post-module questions 1-3 were coded for definition accuracy by the authors. Definitions were coded as correct or incorrect based on the definitions provided in the module; design for EOL was defined as a design that enables design user to identify proper dispose streams for product after original use is no longer needed or possible and design for disassembly was defined as a design that

enables the average consumer or user of product to easily disassemble the design into its pieces [23, 24]. The implied definition for sustainable metrics was a measurement that assesses the sustainability of a design and can be quantified to compare one design against another [25]. The authors performed a t-test on the survey responses to compare students' pre- and post-module understanding for each question.

Table 4. Summary of Surveys and Response Rates.

Survey Name	Semester	Survey Response Rate (%)	
		Pre	Post
¹ Intro A	Fall 2013	67%	59%
¹ Intro B	Fall 2013	90%	83%
¹ Intro C	Fall 2013	85%	90%
¹ Intro D	Fall 2013	75%	78%
² Intro E	Fall 2013	97%	97%
³ Intro F	Spring 2014	67%	62%
³ Intro + Ret	Fall 2013	92%	90%
¹ Comparison	Spring 2014	80%	65%
⁴ EPICS II	Fall 2013	80%	25%
Total Survey Responses		262	240
Average Survey Response Rate		81%	72%

The pre- and post-module survey was administered in students in six sections of freshman Intro to Engineering (Intro A-F, taught by instructors 1-3), one section of junior Engineering Projects in Community Service Gold II (EPICS II, taught by instructor 4), one test freshman Intro to Engineering retention test section (Intro + Ret, taught by instructor 3) and one control freshman Intro to Engineering section (Comparison, taught by instructor 1) digitally via Survey Monkey (318 total participants) during Fall 2013 and Spring 2014 semesters at Arizona State University.

Rubric Assessment

To understand the impact on retention of learning objectives, students in one Introduction to Engineering section (Intro+Ret) and one Comparison course, also an Introduction to Engineering section, were given a design assignment two weeks after the SusMet Module implementation. Students utilized the engineering design process to design a desk with attached chair as part of their intro curriculum. The design assignment

was collected from students in both sections and evaluated using a rubric. The rubric evaluated SusMet Module learning objectives; design for end-of-life and design for disassembly (explicit) and sustainable metrics (implicit). The rubric looked for four elements: design for end-of-life, design for disassembly, sustainable metrics, and other-materials. Design for end-of-life looked for designs that identified recyclability and/or method of disposal, Design for disassembly looked for designs that included ease of disassembly and use of commonly available tools for disassembly. Sustainable metrics looked for designs that included some sort of number or metric that the students incorporated their drawing. For example, a student might have integrated sustainable metrics by describing reductions in energy required to make their chair. The final element, other-materials, was included to cover designs that considered material selection. For example, students may have chosen a material that was recycled or recyclable for use in their design; the rubric accounted for students who address materials selection without design for end of life. Student designs were scored on a binary scale; a design that had an element received a 1 where a design without an element received a 0. Each design could score a maximum of 4, meaning the design had elements of design for end-of-life, design for disassembly, sustainable metrics, and other- materials. The authors performed a t-test on the rubric responses to compare Intro+Ret and Comparison students' post-module design assignments.

Results and Discussion

The SusMet Module was assessed using a mixed-methods approach of pre- and post-module surveys and a comparison experiment to assess the impact of the

experiential portion of the module on student-learning outcomes. Cognitive and affective module outcomes from the pre-and post-module survey are presented in Figures 3-8. Results from the comparison experiment to assess the experiential portion of the module using an unrelated post-module assignment are presented in Figure 9. Results indicate that there was no significant difference between the three Introductions to Engineering instructors in terms of cognitive or affective outcomes.

Students' cognitive learning of the term "design for end-of-life" is presented in Figure 3, which summarizes the results from pre- and post-module survey. Prior to introduction to any module materials students were given the anonymous digital pre-module survey via Survey Monkey. Pre-module students responded to having heard of the term "design for end-of-life" before this class with a "yes" or "no" response options. Post-module students were asked to define the term "design for end-of-life" to the best of their ability. When comparing the pre- and post-module surveys for the "design for end-of-life" term all classes showed statistically significant improvement and understanding of the term at p-value of 0.01, with the exception of Intro F, which was significant at a p-value of 0.1 due its smaller sample size. The results show that 19% of Introduction to Engineering, 25% Introduction + Retention and 19% of Junior EPICS Gold II students, and 22% of Comparison students on average, had heard of "design for end-of-life" prior to the module. Post-module an average of 72% of the Introduction to Engineering students and 66% of Introduction + Retention students correctly defined "design for end-of-life," compared to 64% of Comparison students and 100% of Junior EPICS Gold II students. There was no single instructor whose students consistently reported knowing more or less pre-module nor was there any single instructor whose students performed

consistently better or worse post-module. Junior-level EPICS students outperformed freshman-level students on definition accuracy. The common factors in the correct written definition among all students included concepts related to the useful life of a product, for example “*a design that considers what will happen to the product when it is no longer useful.*” The most common incorrect definition focused on designing a product that lasts forever, for example “*a design that will last a long time.*” Providing students with an explicit, rather than implicit, definition to "design for end-of-life" may have a direct impact on definition accuracy post-module. The most common incorrect definition indicates that the term definition could use further clarification; while designing a product to last a long time could impact the product's EOL, it is not does not guarantee EOL was considered in the design.

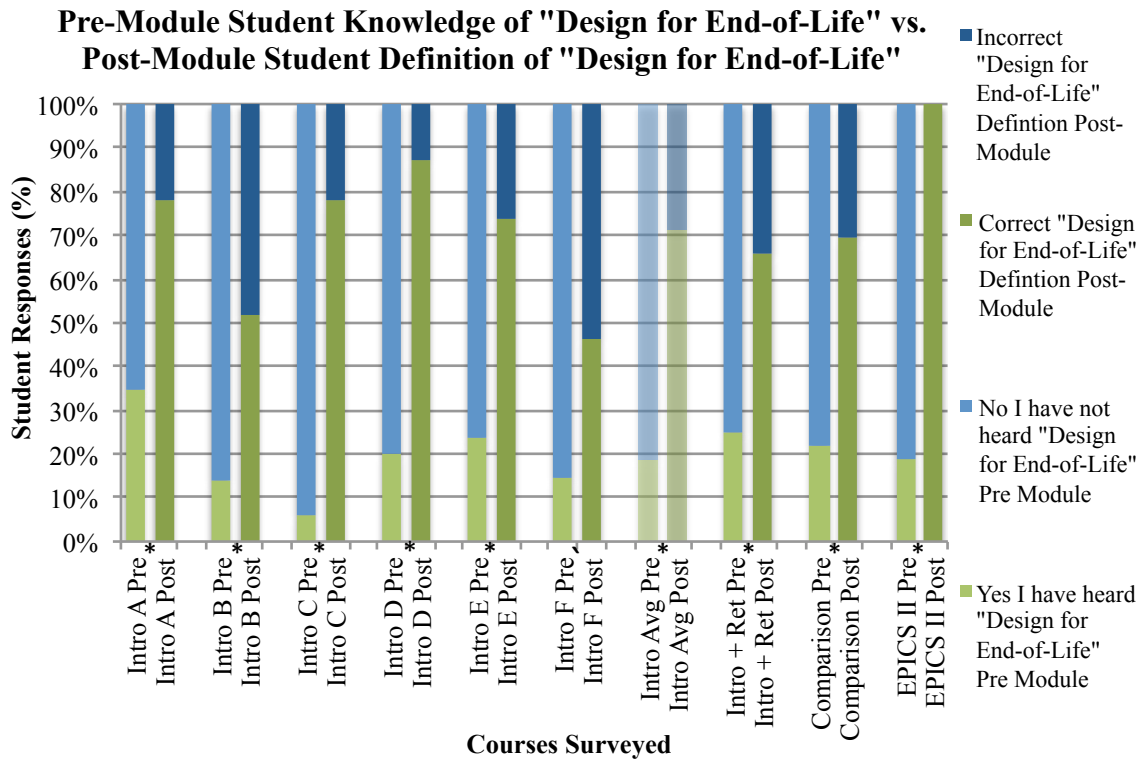


Figure 3. Pre- and Post-Module Student Survey Responses for “Design for End-of-Life” Definitions. The Sustainable Metrics (SusMet) module was implemented in six freshman-level Introduction to Engineering courses (Intro A-F) and one junior-level Engineering Projects in Community Service Gold II course (EPICS II). The SusMet Module was also implemented in one intro-level course (Intro + Ret) where students participated in the entire module and one comparison course (Comparison) where the activity portion of the module was removed. Students in all nine courses completed anonymous pre- and post-module surveys. Question one on both pre- and post-module surveys assessed cognitive outcomes; pre-module students responded to having heard of “design for end-of-life” term and post-module students defined the “design for end-of-life” term. * = statistical significance at p-value 0.01, ^ = statistical significance at p-value 0.05 and ` = statistical significance at p-value 0.1 between pre- and post-module student responses. All of the classes showed statistically significant improvement and understanding of the term “design for disassembly” and its definition at p-value of 0.01, except Intro F, which was significant at p-value of 0.1.

Similar to cognitive learning of design for EOL, pre- and post-module student knowledge of the term "design for disassembly" results are presented in Figure 4. Students responded to having heard of the term "design for disassembly" before the module with “yes” or “no” response options. Post-module students were asked to define the term "design for disassembly" to the best of their ability. When comparing the pre- and post-module surveys for the "design for disassembly" term all classes showed

statistically significant improvement and understanding of the term at p-value of 0.01. The results show that 32% of Introduction to Engineering students, on average, had heard of the term prior to the module while 25% Introduction + Retention, 38% Comparison and 25% of EPICS Gold II students had heard of “design for disassembly” prior to the module. Post module, Introduction to Engineering students correctly defined "design for disassembly" an average of 93% of the time compared to 89% Introduction + Retention course, 85% Comparison and 100% of EPICS Gold II students. Definition accuracy results indicate that compared to “design for end-of-life,” also an explicit module definition, “design for disassembly” concept was easier for freshman-level students to understand. The resulting difference between these two explicit concepts may be due to hands-on experience with design for disassembly compared to the hands-off experience with design for end-of-life. Students actually disassemble an office chair during the module. Students don’t actually experience end-of-life but they may see different parts that can be recycled or landfilled. The common factors in the correct written definition for design for disassembly among all students included concepts related to the parts of a product, for example “*a design that can be easily broken down into its different parts.*” The most common incorrect definition focused on designing a product that is recyclable, for example “*a design that is recyclable.*” Providing students with an explicit, rather than implicit, definition to may contribute to definition accuracy post-module. The most common incorrect definition indicates that the term definition could use further clarification; while designing a product to be recyclable could impact the product’s disassembly, it is not does not guarantee that the product’s design considered disassembly options.

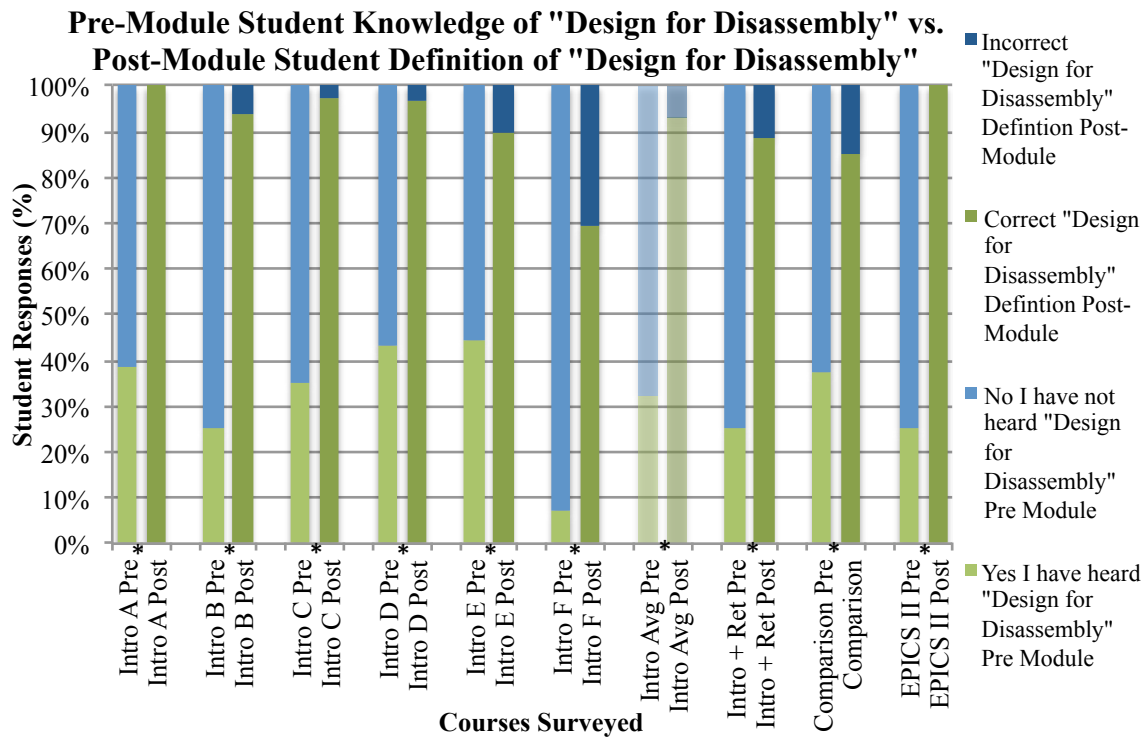


Figure 4. Pre- and Post-Module Student Survey Responses for “Design for Disassembly” Definitions. The Sustainable Metrics (SusMet) module was implemented in six Introduction to Engineering courses (Intro A-F) and one Engineering Projects in Community Service Gold II course (EPICS II). The SusMet Module was also implemented in one intro-level course (Intro + Ret) where students participated in the entire module and one comparison course (Comparison) where the activity portion of the module was removed. Students in all nine courses completed anonymous pre- and post-module surveys. Question two on both pre- and post-module surveys assessed cognitive outcomes; pre-module students responded to having heard of “design for disassembly” term and post-module students defined the “design for disassembly” term. * = statistical significance at p-value 0.01, ^ = statistical significance at p-value 0.05 and ` = statistical significance at p-value 0.1 between pre- and post-module student responses. All of the classes showed statistically significant improvement and understanding of the term “design for disassembly” and its definition at p-value of 0.01.

The final learning objective, “examine and assess the green design properties of chairs from mid 1900’s versus a 21st century chair touted as green”, was related to the implicit term “sustainable metrics”. Students are likely to have knowledge of the term sustainability and metric as separate terms as well as the combined term in the learning objective. In order to understand students’ incoming knowledge, the pre-survey asked students’ recognition of the term sustainable/sustainability separate from metric. Results for student knowledge of the implied term, “sustainable metric,” are shown in Figure 5.

When comparing the pre-module surveys for student knowledge the "sustainable/sustainability" and "metric" and post-module defined the term "sustainable metric" term none of the classes showed statistically significant improvement and understanding of the term. This is likely due to high recognition of the terms pre-module and low accuracy of term definitions post-module. Prior to the module an average of 96% of Introduction to Engineering students, 89% Introduction + Retention, 84% Comparison, and 100% EPICS Gold II students had heard of the term "sustainable/sustainability." An average of 83% Introduction to Engineering students, 75% Introduction + Retention, 81% Comparison, and 88% EPICS Gold II students had heard of the term "metric" prior to the module. Post module, students were asked to provide a definition for the combined term sustainable metric; 52% of the Introduction to Engineering students provided an accurate definition while 31% Introduction + Retention, 46% of Comparison students, and 80% EPICS Gold II students answered correctly. Junior EPICS Gold II students' post-module definitions were more accurate than freshmen. The common factors in the correct written definition for sustainable metric among all students included concepts related to the measurement of sustainability, for example "a *measurement by which the sustainability of a product can be determined.*" The most common incorrect definition focused on method of producing a sustainable product, for example "*method of producing an environmentally-friendly product.*" Based on definitions provided by the students it was clear that the "sustainable metric" term should be reviewed with the class post-module to explicitly define the term. In classes where less than a quarter of students did not recognized terms and concepts pre-module, students demonstrated learning the concepts post-module. When the majority of students reported recognizing terms and concepts pre-

module, in fact less than half of students were able to demonstrate that they learned the concept. The results may indicate that students who have high confidence and recognition of terms and concepts prior to a class are less likely to consider definitions presented in class, even if they are explicit. The concept of sustainable metrics may also be a more difficult concept to grasp; similar to the difference between disassembly and end of life, students only partly experienced sustainable metrics as they counted parts and collected times for disassembly. An accurate definition of sustainable metrics is still very abstract, despite providing explicit definitions.

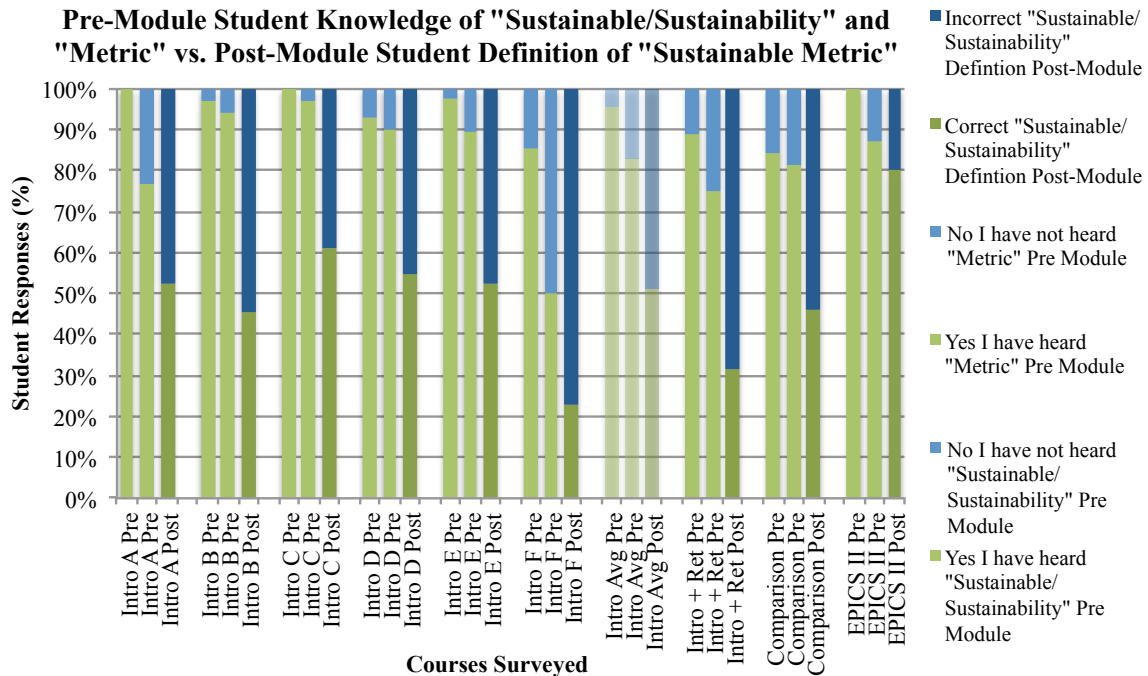


Figure 5. Pre- and Post-Module Student Survey Responses for “Sustainable/Sustainability,” “Metric,” and “Sustainable Metric” Definitions.

The Sustainable Metrics (SusMet) module was implemented in six Introduction to Engineering courses (Intro A-F), one Engineering Projects in Community Service Gold II course (EPICS II), one intro-level course (Intro + Ret) where students participated in the entire module, and one comparison course (Comparison) where the activity portion of the module was removed. Students in all nine courses completed anonymous pre- and post-module surveys. Question three and four on the pre-module survey and question three on the post-module survey assessed cognitive outcomes; pre-module students responded to having heard of “sustainable/sustainability” and “metric” terms and post-module students defined “sustainable metric.” * = statistical significance at p-value 0.01, ^ = statistical significance at p-value 0.05 and ` = statistical significance at p-value 0.1 between pre- and post-module student responses. None of the classes showed statistically significant improvement and understanding of the terms “sustainable/sustainability,” “metric,” and “sustainable metric” and their definitions.

Student cognitive and affective learning outcomes of sustainable metrics were also evaluated through questions about product’s green claims. Student confidence in their ability to challenge “green claims” made by someone with the use of clear reasoning supported by evidence are presented in Figure 6. Students identified their confidence pre- and post-module, indicating on a Likert scale whether they felt “very unconfident,” “somewhat unconfident,” “neutral,” “somewhat confident,” or “very confident” in their ability to challenge “green claims”. When comparing the pre- and post-module surveys

for "green claims" all classes showed statistically significant improvement and understanding of the term at a p-value of 0.01, with the exception of Intro D and Intro+Ret, which were significant at a p-value of 0.05. Intro F and EPICS II did not show statistically significant improvement due their smaller sample sizes. Introduction to Engineering students' confidence their ability to challenge "green claims" increased from pre- to post-module, shown in Figure 6. Pre-module Comparison students also reported increased confidence after the lecture. Similar to the post-module confidence reported from the explicit learning outcomes, all freshmen reported an increase in confidence in their ability to challenge green claims after the module. Post-module no junior students reported neutral confidence; they either decreased in confidence (very unconfident 6% pre to 20% post) or increased in confidence (very confident 6% pre to 20% post). Despite polarization in junior EPICS students' confidence the junior students performed better in all cognitive evaluations than freshman. This finding is supported in the literature; the engineering works of more senior students are higher quality and consider more alternatives and aspects when compared to freshman students [26]. While challenging "green claims" was not an explicit module learning outcome, students reviewed the 'green' chair's brochure for "green claims" and documented sustainable metrics to verify or dismiss the claims. This disparity in reported confidence may indicate that Junior EPICS students were cognizant of the nuances in challenging "green claims" and therefore needed to know more before they felt confident in challenging these claims.

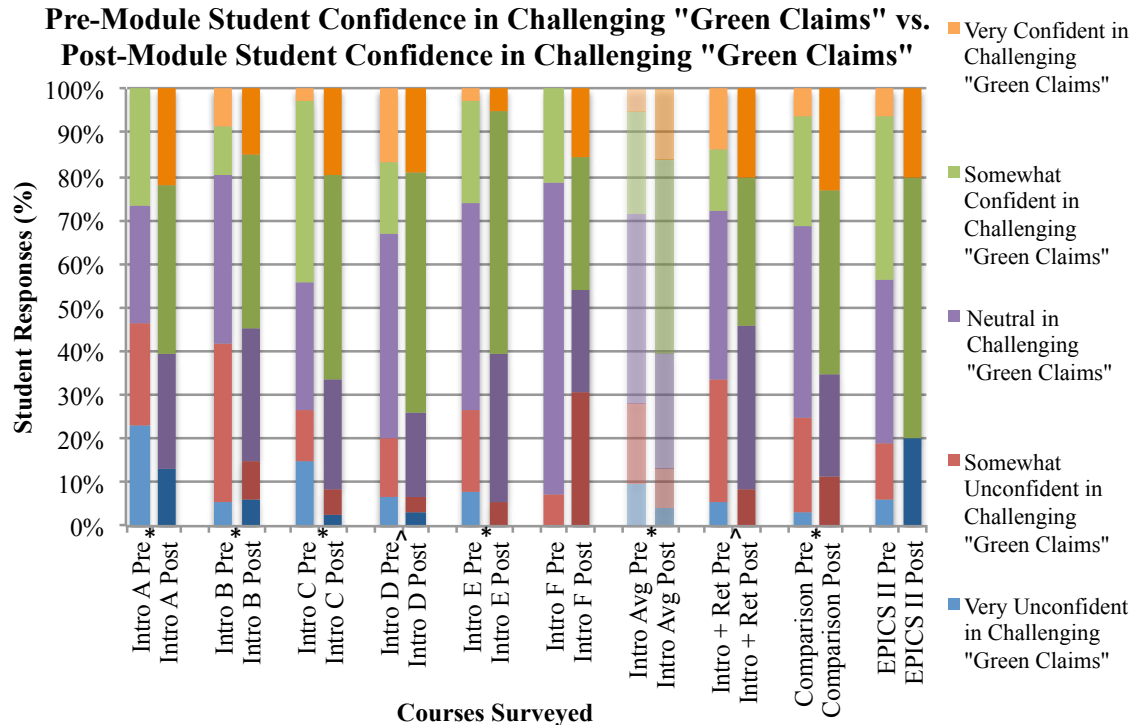


Figure 6. Pre- and Post-Module Student Confidence in Challenging “Green Claims”.

The Sustainable Metrics (SusMet) module was implemented in six Introduction to Engineering courses (Intro A-F), one Engineering Projects in Community Service Gold II course (EPICS II), one intro-level course (Intro + Ret) where students participated in the entire module, and one comparison course (Comparison) where the activity portion of the module was removed. Students in all nine courses completed anonymous pre- and post-module surveys. Question four on the post-module survey assessed affective outcomes; post-module students responded to their confidence in ability to challenge “green claims” made by someone with the use of clear reasoning supported by evidence. * = statistical significance at p-value 0.01, ^ = statistical significance at p-value 0.05 and ` = statistical significance at p-value 0.1 between pre- and post-module student responses. None of the classes showed statistically significant improvement and understanding for "green claims" at a p-value of 0.01, with the exception of Intro D and Intro+Ret, which were significant at a p-value of 0.05. Intro F and EPICS II did not show statistically significant improvement.

Student confidence in ability to apply explicit concepts of "design for end-of-life" and "design for disassembly" principles to improve a product or process are presented in Figure 7. Students identified their confidence pre- and post-module, indicating on a Likert scale whether they felt “very unconfident,” “somewhat unconfident,” “neutral,” “somewhat confident,” or “very confident” in their ability to apply "design for end-of-life" and "design for disassembly" principles [22]. When comparing the pre- and post-module surveys for concepts of "design for end-of-life" and "design for disassembly" all

classes showed statistically significant improvement and understanding of the term at a p-value of 0.01, with the exception of Intro F, which was significant at a p-value of 0.05. EPICS II did not show statistically significant improvement due a smaller sample size. Introduction to Engineering students' confidence their ability to apply "design for end-of-life" and "design for disassembly" principles consistently increased from pre- to post-module as shown in Figure 7. Junior EPICS Gold II also students reported increased confidence from pre- to post-module. No juniors reported feeling neutral or very unconfident in their abilities post-module, while freshmen report a wide range of neutrality and lack of confidence in their abilities post-module.

Comparing students' cognitive performance defining explicit terms "design for end-of-life" and "design for disassembly" in Figures 3 and 4 to student confidence in applying these terms in Figure 7, both Introduction to Engineering and Junior EPICS Gold II students reported low knowledge of terms pre-module and provided high accuracy of term definitions post-module. Students' confidence in their ability to apply these concepts from pre- to post-module also increased.

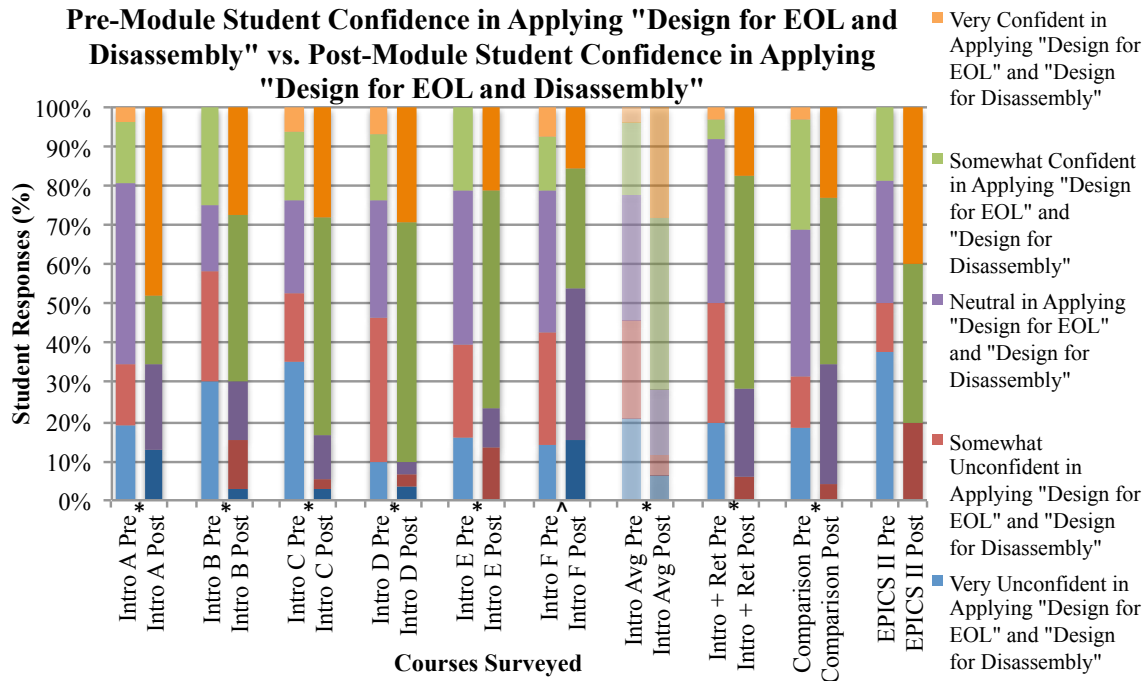


Figure 7. Pre- and Post-Module Student Confidence in Applying “Design for End-of-Life and “Design for Disassembly” Concepts.

The Sustainable Metrics (SusMet) module was implemented in six Introduction to Engineering courses (Intro A-F), one Engineering Projects in Community Service Gold II course (EPICS II), one intro-level course (Intro + Ret) where students participated in the entire module, and one comparison course (Comparison) where the activity portion of the module was removed. Students in all nine courses completed anonymous pre- and post-module surveys. Question five on both pre-and post-module survey assessed affective outcomes; pre and post-module students responded to their confidence in ability to apply "design for end-of-life" and "design for disassembly" principles to improve a product or process. * = statistical significance at p-value 0.01, ^ = statistical significance at p-value 0.05 and ` = statistical significance at p-value 0.1 between pre- and post-module student responses. All of the classes showed statistically significant improvement and understanding of the terms "design for end-of-life" and "design for disassembly" at a p-value of 0.01, with the exception of Intro F, which was significant at a p-value of 0.05. EPICS II did not show statistically significant improvement.

When comparing the pre- and post-module surveys for identification of "sustainable metrics" in Figure 8 all classes showed statistically significant improvement and understanding of the term at a p-value of 0.01, with the exception of Comparison, which was significant at a p-value of 0.05, and Intro A and F, which were significant at a p-value of 0.1. Intro B and EPICS II did not show statistically significant improvement due a smaller sample size. Introduction to Engineering students' confidence their ability to identify "sustainable metrics" increased from pre- to post-module. The majority of

junior EPICS Gold II students reported increased confidence from pre- to post-module. Before the module 31% of juniors were somewhat confident while after the module 80% were somewhat confident. Junior students decreased in their feelings of neutrality (0% post module) and only slightly increased in feeling very unconfident.

Both Introduction to Engineering and EPICS Gold II students reported low confidence in applying terms pre-module and increased confidence applying terms post-module. While no explicit definition was given for “sustainable metrics” in the SusMet Module, the ability of the junior-level students to accurately define this compound term is likely a function of their cognitive differences compared to the freshman students. For the implicit learning objectives, freshmen reported increased confidence after the module and reported recognizing concepts before the module, but they did not demonstrate understanding of the concepts after the module.

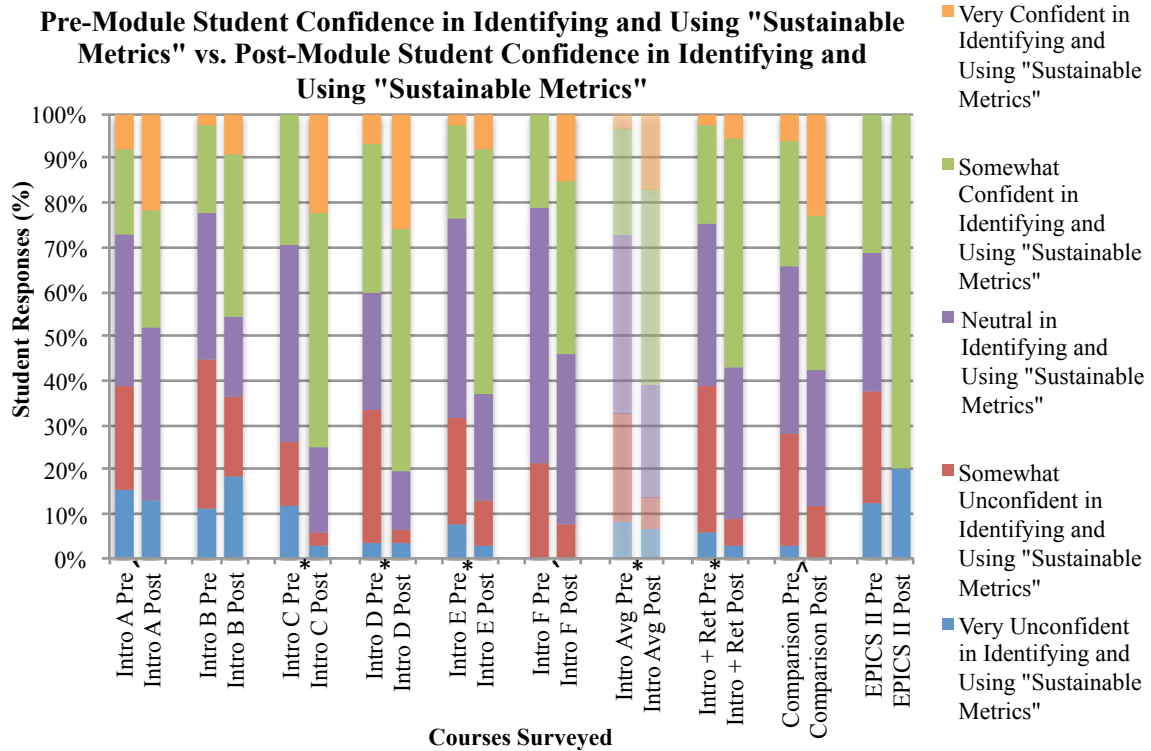


Figure 8. Pre- and Post-Module Student Confidence in Identifying and Using “Sustainable Metrics” Concept.

The Sustainable Metrics (SusMet) module was implemented in six Introduction to Engineering courses (Intro A-F), one Engineering Projects in Community Service Gold II course (EPICS II), one intro-level course (Intro + Ret) where students participated in the entire module, and one comparison course (Comparison) where the activity portion of the module was removed. Students in all nine courses completed anonymous pre- and post-module surveys. Question six on both pre-and post-module survey assessed affective outcomes; pre and post-module students responded to their confidence in ability to identify "sustainable metrics" and use them to describe the sustainability of a product or process. * = statistical significance at p-value 0.01, ^ = statistical significance at p-value 0.05 and ` = statistical significance at p-value 0.1 between pre- and post-module student responses. All of the classes showed statistically significant improvement and understanding for identification of "sustainable metrics" at a p-value of 0.01, with the exception of Control, which was significant at a p-value of 0.05, and Intro A and F, which were significant at a p-value of 0.1. Intro B and EPICS II did not show statistically significant improvement.

In order to investigate student retention of learning objectives related to the hands-on activity in the module, one class (the Comparison) was given the lecture portion of the module without the activity and was compared to a class that received the module (Intro+Ret). The Intro+Ret and Comparison classes were given a design assignment two weeks after the module content; students were asked to design a desk with attached chair

as described in the methods. Two weeks after the lecture portion of the SusMet Module was implemented in the comparison course the students worked on the same chair design assignment. The design assignment was evaluated using a rubric that assessed the four learning outcomes: students' will be able to 1) explain the basics of design evolution, 2) apply design evolution concepts to analyze the office chairs from recent decades in terms of their "green" quality or design for the environment, 3) determine the feasibility of end-of-life recycling of the materials comprising the chair and 4) examine and assess the green design properties of chairs from mid 1900's versus a 21st century chair touted as green. Student cognitive learning was evaluated via the previously described post-module survey, which was collected immediately after the module implementation (refer to Figures 3-5).

When comparing the post-module design assignment for "design for end-of-life", "design for disassembly", "sustainable metrics", and "other-materials" the result in Figure 9 showed a statistically significant difference between Intro+Ret and Comparison classes for "design for end-of-life" and "sustainable metrics" at a p-value of 0.01. The results for "design for disassembly" and "other-materials" were identical for both classes. Student learning outcomes for explicit learning objectives were comparable between the Comparison and module classes. However, the Comparison class performed better with respect to implicit learning objectives. Student performance immediately after the content was discussed were comparable for explicit learning objectives in both the Intro+Ret and Comparison classes; 66% of students in the Intro+Ret class correctly defined "design for end-of-life," 89% correctly defined "design for disassembly." Similarly, 69% of students in the Comparison course correctly defined "design for end-of-life," 88% "design for

disassembly.” The Comparison class performed better on implicit concepts when evaluated immediately after course content; 31% of Intro+Ret students correctly defined “sustainable metric” compared to 46% of Control students. The Comparison class outperformed the Intro+Ret class on defining implicit “sustainable metrics.” This may be a function of the time the Comparison class spent discussing explicit and implicit concepts; since they did not spend time on disassembly (which takes 30 minutes of the 100 minute class) that time was spent discussing implicit module definitions.

Student learning, which was assessed immediately after the module, was similar for the control and other Intro to Engineering classes, but student retention of concepts two weeks later was better for students in the experiential module. Both Intro+Ret and Comparison courses considered design for disassembly and materials usage in the new chair designs, summarized in Figure 9 but the Intro+Ret course also considered design for end-of-life and the implicit learning objective, sustainable metrics. This suggests that concepts students tended to struggle with, i.e., design for end-of-life and sustainable metric, were retained to a greater degree when delivered through experiential learning. This result signifies that one of the important components of the SusMet Module is the hands-on, active learning approach used to explore topics of “design for end-of-life”, “design for disassembly,” and “sustainable metrics”. Despite the Comparison class outperforming the Intro+Ret class on implicit learning objectives immediately after the content was given, students in the experiential learning class (Intro+Ret) demonstrated improved retention of both explicit and implicit concepts.

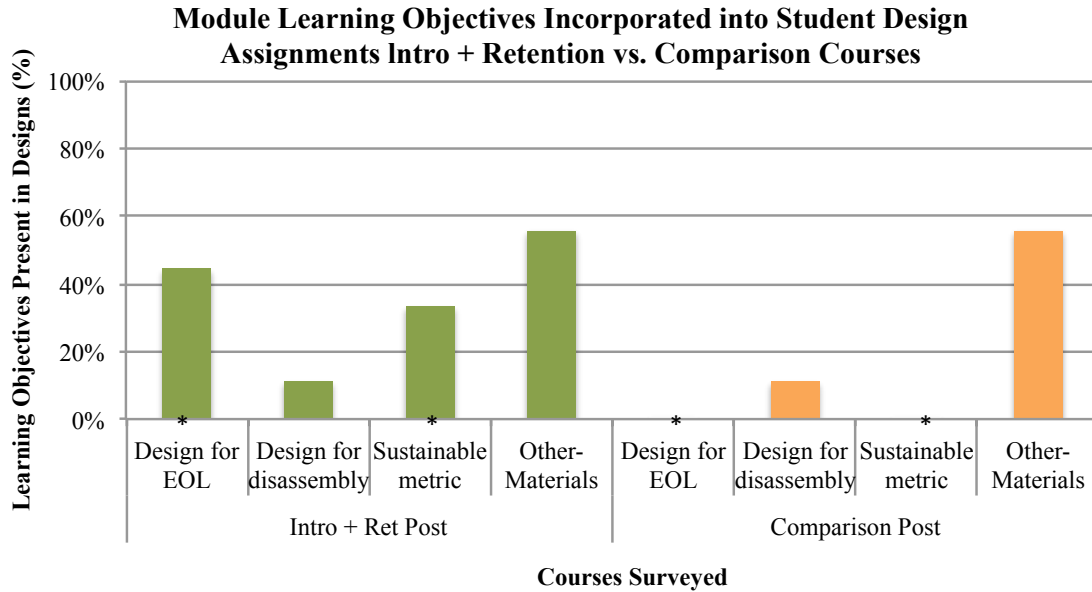


Figure 9. Module Learning Objectives Incorporated into Student Design Assignments for Intro + Retention and Comparison Courses.

Students in the Intro + Ret course participated in the SusMet Module and activity. For students in the Comparison course the activity portion of the module was removed. Students in both the Intro + Ret course and Comparison course completed a design assignment two weeks after the module to understand the impact of the activity portion of the module on student retention of learning objectives. The design assignments for both groups were assessed using a rubric. * = statistical significance at p-value 0.01, ^ = statistical significance at p-value 0.05 and ` = statistical significance at p-value 0.1 between pre- and post-module student responses. All of the classes showed statistical significance for “design for end-of-life” and “sustainable metrics” at a p-value of 0.01 between both classes. The results for “design for disassembly” and “other-materials” were identical for both classes.

Conclusion

This paper presents a modular approach to integrating sustainability into classes via the Sustainable Metrics (SusMet) Module. The module introduced engineering students to explicit concepts of “design for end-of-life”, “design for disassembly,” and the implied concept of “sustainable metrics” through the disassembly of office chairs. The SusMet Module was implemented in six freshman-level Introduction to Engineering courses (Intro A-F) and one junior-level Engineering Projects in Community Service Gold II course (EPICS II). The SusMet Module was also implemented in one intro-level course (Intro + Ret) where students participated in the entire module and one comparison

course (Comparison) where the activity portion of the module was removed. Both the Intro + Ret and Comparison courses completed a design retention assignment two weeks after the module to understand the impact of the activity on retention of learning objectives. The module was assessed using a mixed-methods approach of anonymous digital pre-and post-module survey to test cognitive and affective outcomes and a rubric assessment to test the activity portion on student retention of module learning objectives. The results indicated that no single instructor's students performed consistently better or worse post-module. All Freshmen and Junior students performed best when definitions were explicit ("design for end-of-life" and "design for disassembly" concepts) rather than implied ("sustainable metrics" concept). Junior-level students were more capable of providing correct definitions for implied module learning outcomes than freshman students. Freshman students reported higher confidence in their abilities post-module when compared to Junior students whose accuracy was consistently higher than Freshman students for both explicit and implicit concepts. Retention of learning objectives was most impacted by the activity portion of the module; students that participated in activity and completed an additional design assignment post-module (Intro+Ret class) retained module-learning objectives to a greater degree than students that did not participate in the activity but also completed the design assignment (Comparison class). In addition, concepts students tended to struggle with, i.e., design for end-of-life (explicit) and sustainable metric (implicit), were retained to a greater degree when delivered through experiential learning. This result signifies that one of the important components of the SusMet Module is the hands-on, active learning approach.

Acknowledgements

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Redesign of a Sustainability Experiential Learning Module for Transferability and Portability

This section has already been published in peer-reviewed conference proceedings of the American Society for Engineering Education (ASEE).

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Abstract

In order to teach to the engineering challenges of our global society we have adopted a modular approach to introduce sustainable engineering concepts to traditional civil engineering curricula. This paper highlights lessons learned from the creation, packaging, and distribution of a module that teaches Restore and Improve Urban Infrastructure, one of the fourteen Grand Challenges of Engineering issued by the National Academy of Engineering (NAE). The Sustainable Metrics (SusMet) module is a hands-on activity that engages students in disassembly of a green product and critically reviews the factors that make the product green through the process of discussion and physical disassembly. The SusMet module was packaged for adoption by a wide range of engineering instructors. The complete module package contains: a summary of learning objectives and module activities, lecture slides and notes, recommended readings, detailed description of the experiential learning activity, an assignment, and a pre-and post-module cognitive assessment. The module package was shared through the developers' networks and within the last year was placed online for free download on our engineering education website (STEMed.engineering.asu.edu). Since then, the module has spread to several classrooms across the country and has been used into two senior-

level, interdisciplinary design courses to educate both civil engineers as well as students majoring in sustainability. Since the activity itself requires expensive chairs that can be cumbersome to move around large campuses, the module's transferability and widespread adoption is slightly hindered. This paper presents the decision matrix used to evaluate replacements for the chair to enhance the transferability and portability of this active and experiential learning module.

Introduction

The next generation of engineering professionals must be prepared to solve complex and multidisciplinary problems in a sustainable and global context. The National Academy of Engineering (NAE) developed and issued the Grand Challenges of Engineering, with five (solar energy, carbon sequestration, nitrogen cycle, clean water, and infrastructure) of the fourteen directly related to sustainability [1]. The Grand Challenges offer a framework for exposing engineering students to roles of an engineer in modern society. Adoption of these challenges within engineering curricula engages a diverse array of interested students by establishing *contextualized linkages* between course content and the contributions an engineer makes to solve global issues through systems-thinking innovation [2]. Engineering education can provide students with the tools to approach these grand challenges of the 21st century while considering aspects that are key for designing sustainable systems [3]. Furthermore, according to the National Academy of Science report, *Changing the Conversation*, youth are seeking careers that make a difference [4, 5]. *Sustainable engineering offers a solution to pressing challenges, in conjunction with appealing to our youth.*

The National Research Council (NRC) provides several recommendations for enhancing education in science, technology, engineering, and mathematics (STEM) disciplines. 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 [6-8]. NRC recommendations are met with diverse pedagogical approaches. Experiential learning, which involves constructing meaning from direct experience and involves the learner in a real (rather than abstract) experience [9, 10]. Experiential learning, or learning by doing, has been cited to positively impact non-traditional student learning and increase overall student retention and completion of programs of study [9]. In addition, experiential learning provides students with hands-on experience that can give them an edge in the competitive job market today. 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 [3]. We have adopted an experiential team-based approach in the Sustainable Metrics (SusMet) module.

Incorporating sustainability into traditional engineering courses provides students with a meaningful way to connect more personally to their courses. Through the use of modules, engineering programs can integrate sustainability and experiential learning throughout a host of existing courses by threading individual sets of course skills together in an effort to reach higher levels of intellectual behavior via interdisciplinary concept connection [11]. Modules can be designed to fit into one lecture or over a series of lectures. Modules typically include everything an instructor needs for implementation: a

summary of learning objectives and module activities, lecture slides and notes, recommended readings, and an assignment for students. Using modules to teach sustainability concepts reinforces the broader applicability of sustainability to all engineering disciplines by connecting traditional engineering to impacts to, and solutions for, society, economy, and environment [12]. The authors have developed a host of sustainability grand challenge modules available (STEMed.engineering.asu.edu). The SusMet module has been designed such that it can be adopted into any general engineering course from freshman to senior-level undergraduates.

Module Overview

The SusMet module is a hands-on activity that actively engages students through the disassembly of green and traditional products. Early on in the module, students disassemble a green chair and analyze the metrics that contribute to the chair's greenness. Students critically evaluate the factors that make product's green through the process of comparison to chairs not labeled green, discussion and disassembly.

The SusMet module has been integrated into over 15 classes over the past five years. It was conceptualized in 2009 as a way to introduce civil engineers to concepts of design for environment, design for disassembly, design for end-of-life, as well as assessing sustainable metrics. The module learning objectives have been updated from Antaya et al 2013 and now cover students' ability to 1) explain the basics of design evolution, 2) apply design evolution concepts to analyze the office chairs from recent decades in terms of their "green" quality or design for the environment, 3) determine the feasibility of end-of-life recycling of the materials comprising the chair via disassembly,

material categorizing and weighing and 4) examine and assess the green design properties of chairs from mid 1900's versus a 21st century chair touted as green [13]. Sustainable metrics have been left as an intentional indirect learning objective for this module in order to compare the cognitive outcomes of explicit versus implicit module components across student test groups.

In the activity portion of this module, the instructor begins class with a 10-minute presentation to prepare students for the activity. The presentation introduces the office chair. These chairs represent design evolution; they include a 1950's chair, early 1990's chair, late 1990's chair and a 2000's chair that was advertised as green based on its ease of disassembly and materials. The "green" chair is designed such that it can be fully disassembled in less than five minutes by the average consumer, has multiple options for recycling at the product's end of life, and minimizes energy use over materials, production and transportation phases of the chair's life. All of the chairs used for the SusMet activity are shown in Figure 10. The presentation then uses class discussion to connect the office chair with the history of "design for X" where X is any criteria set for a design, followed up by covering the key module concepts of design for environment, design for end-of-life and design for disassembly. Students are then placed in teams of 4-5 and asked to examine a brochure provided by one of the office chair manufacturers for "green claims" regarding the chair's disassembly and end-of-life. The instructor holds a brief class discussion on the findings in the brochure; the claims of the brochure indicate that the chair can be dismantled in 5 minutes or less into all of its separate parts using common household tools. The instructor asks students to hypothesize whether or not the claims are true, and how the chairs from other decades will perform compared to the

green chair. The students also determine which metrics they will track during the chair disassembly to evaluate their hypothesis.

Each team takes a chair from a different time era and then begins the process of disassembly using common household tools in a timed competition. During disassembly, each team tracks metrics representing design for disassembly and design for end-of-life including, but not limited to, number of parts, number of tools used, number of materials used in the chairs, and recyclability of parts. After 30 to 60 minutes (the time varies based on the length of the class) the instructor stops the disassembly progress and students record the percent of the chair they believe to be disassembled. The teams then switch chairs with another team for reassembly, performing the process in reverse and documenting metrics for their reassembly chair. At the conclusion of the activity, the teams discuss and critically review their hypotheses and evaluation of the sustainability of the chairs based on the metrics collected during the lab. The instructor concludes the class through a 15-minute active discussion on design for environment principles and material selection; this discussion includes how an office chair can be translated to represent many examples of urban infrastructure that require retrofitting and/or redesign. Often, students complete a homework assignment that reflects on the process; the homework assignment varies from class to class. More advanced classes are asked to complete a lab report, while beginners are asked to respond to a set of module-prompted questions.

Module Evolution and Transferability

The SusMet module was first packaged in 2012 and its transferability was tested. Due to high demand, in 2013 the module package was updated with a module description, activity description and readings, sample slides with notes sample assignment for students to exercise research and communication skills, and a pre/post cognitive assessment of the learning objectives to enable additional instructors to adopt it in their classes. In 2014, through sustained interest, we made the entire SusMet module package available at free download on our engineering education website (STEMed.engineering.asu.edu). The digital availability of the module presented new, unanticipated challenges. Despite the success of creating modifications for the module and its contents, many faculty at other institutions are unable to use the module because they do not have the resources to purchase the \$900 green chair. The chairs are not easily transported, so it is difficult to share the modules with the teams' local community college collaborators. However, there was no obvious product with which to replace the chair. There are many key elements that make the chairs in the SusMet module successful, and it was difficult to find all of these elements in one product. Thus, the aim of this paper is to evaluate the factors for module success and update the module with alternative objects to the chairs using a decision matrix, described in the following section.

Methods

Analysis of Module Key Elements

We began our search for objects to replace the chair by breaking down the key elements of the chair that make it the object of choice for the SusMet module. We have determined five key elements, including 1) object access, 2) design evolution, 3) sustainable metrics, 4) design for disassembly and 5) design for end-of-life shown in Figure 10, that need to be met by an alternative object in order to uphold the learning objectives of the module.



Figure 10. Key Chair Elements Representing Object of Choice for the Sustainable Metrics Module.

Element 1: Object access

The success of the SusMet module is due, in part, to the *office chair* through which sustainability and engineering grand challenge topics are explored. The office chair is recognizable object; instructors and students alike have been able to relate to this object through personal experiences. In addition, the office chair is somewhat portable within a campus. Most office chairs are made with casters, rolling the office chair between and around classrooms presents an easy way to transport; however the chairs are not portable outside of a campus. While the chair lab is capable of being used in many classes across a campus, there are scalability issues for larger classes that require more chairs. Typically, the SusMet module needs approximately one chair per five students.

The most limiting factor in the object access element is the affordability of the office chair. While we have reclaimed our 1950s, early 1990s and late 1990s office chairs from university surplus, the “green” chair was purchased at \$1000 per chair, limiting the instructors that can purchase these as supplies. Choosing an affordable object will be the most challenging objective to ensure module transferability.

Element 2: Design evolution

While design evolution is a subtle component of the module, it is critical to showcasing the changes that occur over time for one object. Some of the office chair evolutions include changes in chair structure, manufacturing, material usage and application, chair functions and core movements and ergonomics present in designs. While all of these aspects are present in the chairs we use everyday we have found that presenting students with hands-on accounts of design evolution has a significant impact

on the experience as opposed to having one example of an office chair design. For example, the 1950s chair was simple in its design with only a few parts and a few different materials. The design evolution engages students in discussions of increased functionality at the expense of simplicity and in some cases sustainability. Finding an object with design evolution examples will be easy; most objects have gone through several evolutions in order to appeal to consumers.

Element 3: Sustainable metrics

Sustainable metrics and green claims also make the SusMet module successful. While the 1950s, early 1990s and late 1990s office chairs do not come with brochure material outlining some of the “green” features of the chair, the “green” chair brochure shares these features (e.g., material selection, energy reductions, and emissions reduction procedures). The claims of the “green” chair present a unique case for students to use reasoning supported by evidence to challenge these marketing claims. The claims also enable students to think through what constitutes a “sustainable metric” and how would they apply the metrics to assess the other office chairs present in the module. Locating an object that makes “green” claims will narrow possible alternative to the office chair though it will not be a limiting factor in object selection.

Element 4: Design for disassembly

Design for disassembly is a key-learning objective for the SusMet module. In discovering whether an object has been designed for disassembly students take an active, experiential role as object disassemblers during the module. In addition, the timed

competition makes the module fun for students. Because the object is disassembled every time this module is conducted, it is important to consider the size of the object, sections that can be disassembled, and tools required for disassembly. The chair is ideal for teams of 4-5 students since it allows for multiple students to work on disassembling the chair at once. The chair can be broken down into sections, such as the arms or back, and then students can continue to disassemble the sections individually while contributing to their team. In addition, the smallest parts of the chair are visible and while some screws are very little, the smallest parts compare favorably to that of a smaller objects whose parts become unidentifiable when disassembled. The chairs typically require common household tools for disassembly, which are more readily available to the average instructor. The chair can also be disassembled and reassembled without deconstruction; the alternative object will need to have reassembly capabilities in order to ensure use of the object in multiple classes.

Element 5: Design for end-of-life

The final element of significance to the SusMet module is design for end-of-life. Design for end-of-life, while a key-learning objective, will help to further define the possible objects that will work as alternatives to the office chair. The green office chair is unique because its particular green claims relate to design for end-of-life; it is supposed to be easily disassembled for recycle or remanufacture. The chair parts are easy to distinguish as recyclable and it is possible to group the materials by type. Afterwards, students can explore the various end-of-life avenues for the different materials, from recycle to landfill. In order for this to continue to be a part of the module the alternative

object must not be of singular material by nature and must have a minimum of two different options for its end-of-life for students to explore.

Results and Discussion

Decision Matrix

We identified new objects with the potential to replace the chairs in the SusMet module by brainstorming with researchers, instructors and students. The objects we identified as possible alternatives to the chair include a fan, cell phone, monitor, printer, coffee maker and clock radio. We analyzed these objects with a decision matrix format presented in Table 5. The objects were scored against each of the five chair elements discussed in the previous section using a ternary scale; a score of -1 meant not all design evolutions of the alternative object fit the element, a score of 0 meant some but not all evolutions of the alternative object fit the element and a score of 1 meant that all evolutions of alternative object fit the element present in the chairs. An object can score a maximum of 9 points. The decision matrix revealed that the highly weighted elements of this module are 1: object access, 3: sustainable metrics, and 4: design for disassembly as these elements determine whether the object will work for both instructor access and student group disassembly. Cell phones totaled 0 points; they satisfied elements 1-3 however are not suitable objects to replace the chair due to their small overall size and the size of parts as they are disassembled, which presents a challenge with more than one student to working on them at a time. Monitors performed similarly to cell phones at 4 points; though larger in size they are inherently less affordable. Printers, coffee makers and clock radios, all scoring 8 points, satisfy elements 1-3 and 5, fully satisfying element

4: design for disassembly, however, is difficult with appliances that are inherently small in design. A fan was the only object to satisfy all the elements and score 9 out of 9 points. Fan sizes falls between cell phones and chairs meaning that many students can disassemble a fan at once and fans are also more affordable to purchase, more portable for an instructor to move around campus, and can also be distinguished by ‘green’ features such as energy and material sourcing.

Table 5. Decision Matrix for Alternative Object to Replace Office Chair.

Alternative Object	Key Object Elements									Total
	Element 1: Object access			Element 2: Design evolution	Element 3: Sustainable metrics	Element 4: Design for disassembly		Element 5: Design for end-of-life		
	Recognizable	Portable	Affordable	Designs show change	Makes green claims	Size of object, sections, and smallest parts	Disassemble & reassemble	Parts are distinguishable	Material grouping	
Fan	1	1	1	1	1	1	1	1	1	9
Cell phone	1	1	0	1	1	-1	-1	-1	-1	0
Monitor	1	1	0	1	1	0	0	0	0	4
Printer	1	1	1	1	1	0	1	1	1	8
Coffee maker	1	1	1	1	1	0	1	1	1	8
Clock radio	1	1	1	1	1	0	1	1	1	8

Key: -1= not all evolutions of alternative object fit element, 0= some but not all evolutions of alternative object fit element, 1= all evolutions of alternative object fit element

Conclusion

While it might seem simple to replace the office chair with any product that can be disassembled, the multiple layers of learning outcomes achieved from this particular mix of chairs is quite difficult to replicate. Analysis of five elements present in the office chairs that make them ideal objects for this module, including object access, design evolution, sustainable metrics, design for disassembly and design for end-of-life, revealed

that substituting an alternative object is not a simple task. We utilized a decision matrix to assess alternatives objects of fan, cell phone, monitor, printer, coffeemaker and clock radio against the five elements. Through this process we recognized that the highly weighted elements of this module are object access, sustainable metrics, and design for disassembly; objects need to be affordable, have a “green claim” to test and capable of being disassembled by multiple students at once. Cell phones, monitors, printers, coffee makers and clock radios are all too small despite their affordability and “green claims”. Fans, however, appeal to all elements present in the chair, including size, and could be utilized as an alternative object to replace the chair. Additional object suggestions will be made available via our engineering education website (STEMed.engineering.asu.edu).

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Chapter 3

ASSESSMENT OF STUDENTS' MASTERY OF CONSTRUCTION MANAGEMENT AND ENGINEERING CONCEPTS THROUGH BOARD GAME DESIGN

This chapter explicitly looks at active learning using student-developed board games to reinforce course concepts and enhance the instructor's ability to evaluate student performance. The board games were assessed using a mixed-methods approach of student survey, content analysis of student journals, and instructor rating-scale/rubric.

Abstract

While the use of games to help students learn is explicit in the literature, little research has been conducted on student-developed games to assess student learning. The objective of this research is to establish 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. The Game Design Module uses active and experiential learning as students' develop board games that utilizes course content in game-play. The module was divided into three distinct days, including Intro Game Day where students were introduced to game design and played existing games, Feedback Game Day where students peer-reviewed one another's draft games, and Final Game Day where students played final versions of their classmates' games. To test the module, three variations of the module were implemented into three sections of CON 252: Building Methods, Materials and Equipment at Arizona State University (180 total participants). The module was assessed using a mixed-methods approach of student surveys, reflective journal entries, and rubric evaluation of student work. A Control Activity, called the Glossary Project, represented traditional assessment method for

student mastery of course content. 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. Student performance increased when the instructor provided learning objectives for the game and when students were given the opportunity to improve their games after receiving peer feedback. Overall, students reported greater enjoyment of the Game Design Module than the Control Activity because it involved creativity and teamwork.

Introduction

Undergraduate construction and engineering curricula is faced with several challenges including, but not limited to, providing contextualized classroom and field experiences, teaching students with diverse capabilities, refining students' professional competence, improving students' communication skills, and improving assessments of student learning outcomes [1, 2]. To address these challenges research suggests that team-based projects can also enhance student learning in STEM fields since it promotes active and collaborative learning while simultaneously promoting individual accountability, personal responsibility, and communication skills [3, 4].

Some discussion exists around the construction and engineering education issue of knowledge-based learning versus hands-on learning and their impact on student education. In knowledge-based learning students gain construction and engineering competencies in the classroom setting without the experience of site visits and fieldwork.

A knowledge-based learning environment is described as learner- centric and comprised of three parameters, including learning, knowledge and learners needs [5]. Despite focus on learners provided by knowledge-based learning environments, researchers challenge the notion that the construction and engineering industries can remain theory-based without becoming increasingly experienced-based [6].

To address the issue of education for an increasingly experienced-based industry, many construction and engineering educators are adopting hands-on learning. Hands-on learning has been cited to contribute to the development of students' verbal and written communication skills in addition to their interpersonal and teamwork skills [4]. Many students cite that they choose construction and engineering because fieldwork is involved; hands-on learning gives students insight into practical applications of knowledge in the field during their undergraduate experience [7]. In addition, hands-on learning can address issues with students who struggle with traditional learning and testing methods [7].

Furthermore, a growing number of undergraduate students are characterized as non-traditional students, balancing school life with other roles including, but not limited to, having dependents and/or partial or full-time employment [8]. While these other roles can present significant challenges in non-traditional students' allocation of time for academic study and participation on campus, many non-traditional students are intrinsically motivated to learn, recognizing the value of education and the role it will play in their future [8-10]. The success of instructing both traditional and non-traditional students relies on delivering a diverse suite of high-impact educational methods to reach the spectrum of learners present in the classroom.

Addressing the challenges of teaching diverse sets of learners can be met with the pedagogies of active and experiential learning. Active learning places the responsibility of learning on learners themselves and can contribute to student ability to exercise lifelong learning [11]. Active learning has been shown to increase student performance in STEM (Science, Technology, Engineering, and Mathematics) courses regardless of class type and size and can be a key factor in increasing the number of students receiving STEM degrees, particularly for students whose performance in traditional lecturing classrooms is at or below average [12-14]. Active learning has also been shown to impact long-term retention of learning objectives beyond the semester timeframe of a course [14, 15].

Experiential learning involves constructing meaning from direct experience and involves the learner in a real, rather than abstract experience [16-18]. Experiential learning, or knowledge creation through the process of experience, has been cited to positively impact non-traditional student learners, including underperforming students, and increase overall student retention in and completion of programs of study [19, 20]. Adopting active and experiential learning pedagogies into construction and engineering curricula allows educators to address students' needs via exposure to and interaction with real-world problems that require multidisciplinary teamwork.

Students learn by acting as part of a community, practicing the application of knowledge to situations where there exists shared values and goals [21]. Games afford instructors the ability to simulate a virtual community where students can operate as a resident within constraints defined by the game creators [21]. Game-based learning (GBL) is a recognized pedagogy for teaching students a defined learning outcome.

Games used in GBL have been classified many different ways however tend to fall into one or more of the following genres: action, adventure, fighting, role-playing, simulations, sports, and strategy [22]. Games that promote education in addition to providing entertainment value are described as serious games [23]. Digital games predominate serious games in the GBL literature and have been instrumental in the creation of new social and cultural worlds [21, 24]. The use of non-digital games, such as board games, offer many of the same community interactions as digital games without requiring the use of computers, making them accessible to a wide variety of classrooms [25].

While GBL with the use of serious games and their ability to help students learn is explicit in the literature, little research has been conducted on student-developed games to assess student learning. The closest example is in computer science courses that allow students to modify an existing computer game by program changes into the game to receive immediate feedback on effective code execution [26]. When compared to writing code in a traditional programming assignment, the students that practiced the learning objectives within a game environment outperformed students who participated in the traditional assignment [26].

There are several ways to assess student progress towards learning goals. Traditional methods include, but are not limited to, quizzes, papers, projects, reports, portfolios, exams, attitude surveys, journal entries, and capstone design projects. However, entirely student-designed games as a method for assessing student learning is absent from the literature.

This paper explores the use of student-developed board games as a method to assess student mastery of construction and engineering concepts. This paper describes the development of a Game Design Module and its effectiveness as an assessment method. The Game Design Module utilizes active and experiential learning; students apply the concepts learned throughout the semester in the design of a board game that their peers will play at the end of the class. The Game Design Module enables the instructor to assess student mastery of course content through games design entirely by students.

Methods

The methods section first describes the Game Design Module including module learning objectives, module lecture and hands-on activity. Next, the methods describe the Control Activity, which is called the Glossary project and resembles a traditional form of student assessment. Following, the methods provide a description of the Arizona State University course utilized for module implementation. As the instructor endeavored to improve the class, it was impossible to hold all factors constant. Thus, both the course and the module evolved from 2012 (which acts as our control with no games module) through three module variations implemented in Fall 2013, Spring 2014, and Spring 2015 semesters. Finally, the methods present the module assessment utilizing a mixed-methods approach. The mixed-methods assessment includes an anonymous post-module survey on cognitive and affective outcomes, a reflective journal entry on module experience and a rating-scale/rubric evaluation to assess student cognition of learning objectives. Finally, the authors compare student learning with and without the module as well as with various module implementations.

Module Description

The Game Design Module is an active and experiential learning module where students' demonstrate their knowledge of course content; the module also and builds communication and teamwork skills through the creation of a board game. The module's learning objectives state that students will be able to: remember and explain the vernacular of building design and construction including terminology, units of measure, standard designations, sizes, graduations, testing methods, reference standards, and regulatory codes.

The Game Design Module lecture and activity is presented in Figure 11. The Game Design Module was split into three game days, described herein as Intro Game Day, Feedback Game Day and Final Game Day. On Intro Game Day, held at the beginning of the semester, the instructor began with a 20-minute presentation to prepare students for the module activity. The presentation introduced students to active and experiential learning and gave examples of how these learning pedagogies can be applied through board game design. The instructor then presented the key features of a board game, including learning objectives, materials/board design and instructions/scoring. Students then played an existing game, such as Nano Around The World (available at www.nisenet.org) or previous semester's games such as "Constructionary" (Pictionary with construction terms; a game made by students participating in the Fall 2013 class) for 10 minutes and discussed the pros/cons of the game design as a class [27]. The instructor then introduced the team activity and game design; students are told that, rather than by taking an exam, they would demonstrate their knowledge of the semester's course content by creating a new game or modifying an existing game to teach players the

concepts learned throughout this class. Each game must include number of players, scoring guidelines, instructions for game play, 100 total construction terms (70 bolded construction terms, which represent critical knowledge areas for the construction industry and 30 non-bolded words, less critical terms in the industry), and clear citations for photos or text from external sources to earn full credit. Students broke into teams of 4-5, and spent 20 minutes thinking about their new game design idea and the materials needed for their game; students were given a budget up to \$50 per game, funded from the instructor's discretionary account and/or research grant. The instructor and teaching assistants answered questions and provided feedback on ideas. Intro Game Day concluded with team presentations of their game design idea and a class discussion on new game ideas; afterwards students turned in their game description and material list to the instructor.

Mid-semester, students brought a draft game to class on Feedback Game Day. For 70 minutes, students traded their game with another team and play each other's game for the purposes of identifying features of the game that need improvement. Students provided verbal and written suggestions for improvement to their classmates during game-play. At the end of class students provided feedback on the status of the draft games in an anonymous survey described in the *Mixed-Methods Assessment* section.

On Final Game Day students bring their final games to class at the end of the semester. Similar to Feedback Game Day, students trade games with another team and play each other's game for 70 minutes. At the end of class students provide feedback on the final games in an anonymous survey described in *Mixed-Methods Assessment* section.

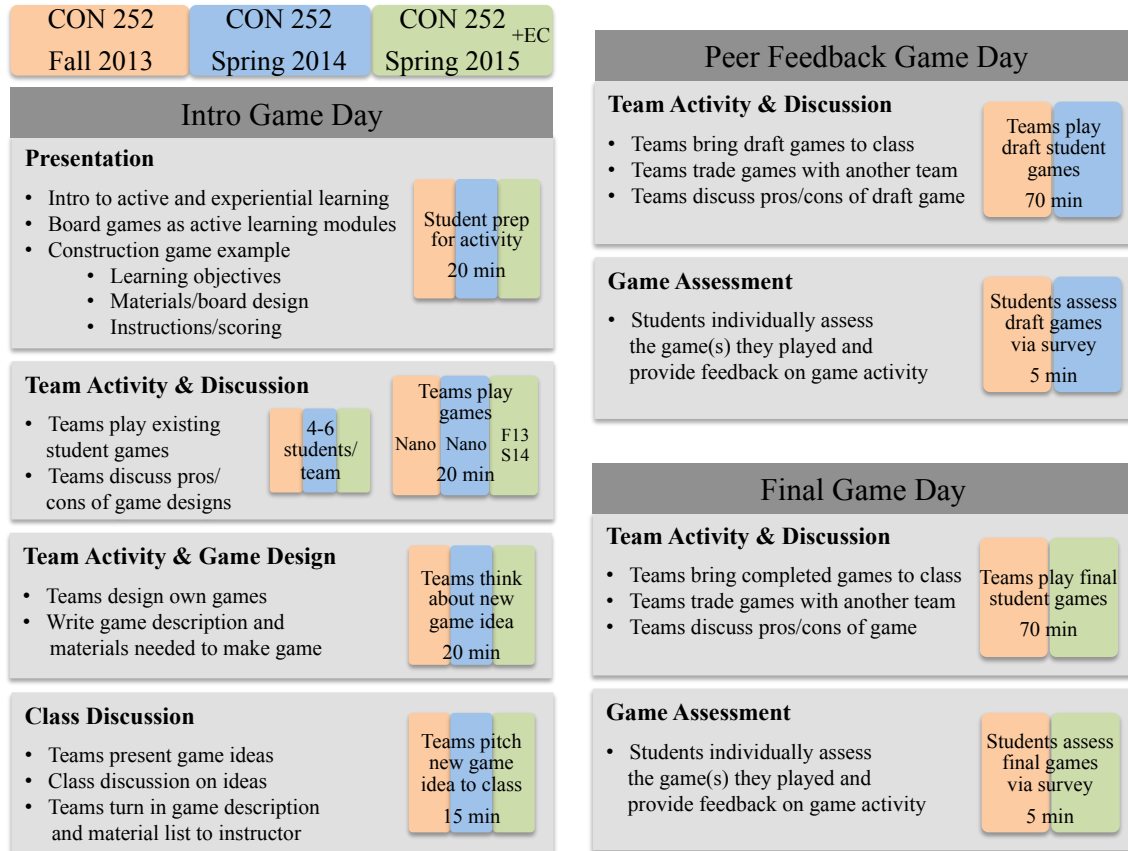


Figure 11. Game Design Module Flowchart.

The Game Design Module was conducted over three days, described as Intro Game Day, Feedback Game Day, and Final Game Day. Three variations of the module were implemented in three semesters of sophomore-level construction class; in Fall 2013 (shown in Orange) students participated all three game days, in Spring 2014 (shown in Blue) students participated in Intro and Peer Feedback Game Days and in Spring 2015 (shown in Green) students participated in Intro and Final Game Days. During Intro Game Day Fall 2013 and Spring 2014 students played a non-construction game called Nano Game (noted as ‘Nano’) while Spring 2015 students played previous semester’s construction board games (noted as F13 and S14 in the figure, which denotes Fall 2013 and Spring 2014 student games). In addition, students in Spring 2015 were given extra credit to create a game that made course content accessible for a younger audience (noted as +EC in the figure, which denotes extra credit).

Control Activity

In the Control Activity, called the Glossary Project, students were given a set of construction vernacular related to their course content and were tasked, as a team, to prepare a glossary booklet comprised of a minimum of 70 bolded and 30 non-bolded words with cited definitions and appropriate corresponding pictures taken by the students.

The bolded words represented critical knowledge areas for the course and the construction industry (e.g., formwork, welded steel, slab on grade), while the non-bolded words represented less critical terms in the industry (e.g., soil nailing, joint sealant). The photography exercise engaged students in a level of active learning as they searched their community for representative images, but did not push students to higher levels of cognition. That is, students could successfully complete the control without ever applying any of the terms they had to report on.

Course

The Game Design Module and the Control Activity were implemented in CON 252: Construction Methods, Materials and Equipment at Arizona State University (ASU), summarized in Figure 11. CON 252 is a sophomore-level construction management course focusing on vertical construction in a ground-up approach: beginning with earthwork information and progressing towards building materials used, various construction methods, and concludes with lessons on installed building equipment. CON 252 focuses on the materials used in building construction and the methods employed to place them on a construction site. The course covers multiple construction materials and methods and aims for students to *identify* and *understand* the most common building construction materials and methods for various building types; the focus of this course is on lower-level of Bloom's taxonomy [28, 29]. Course enrollment is typically between 40-80 students per semester, with 60% of the students being construction management majors, and 40% of the students from other majors.

Three variations of the Game Design Module were implemented in CON 252 in Fall 2013, Spring 2014 and Spring 2015 semesters, as shown in Figure 1; the evolution of the module is detailed in Table 6. In Fall 2013, the module included all three game days where as in Spring 2014 and 2015 the module was modified from three days to two days to assess the differences between Feedback and Final Game Days; in Spring 2014 students participated in Intro and Feedback Game Days and in Spring 2015 students participated in Intro and Final Game Days. The Control Activity was implemented in CON 252 Fall 2012 and Fall 2013. In Fall 2012 students only participated in the Control Activity where as in Fall 2013 students participated in both the Control Activity and the Game Design Module. In Spring 2014 and Spring 2015, students only participated in the game design activity.

Several additional modifications were made to the module throughout implementation as the instructor endeavored to improve the class; the modifications are summarized in Table 6. In Fall 2013 students were not given a single learning objective as described in the *Module Description* section and instead were given the choice of several additional course learning objectives, including a) summarizing the basic processes of designing and constructing a building, b) summarizing and explaining the differences between excavations and building foundation systems, c) summarizing and explaining building structural systems, d) explaining systems to keep structures free from water infiltration, e) summarizing mechanical, electrical, plumbing and vertical transportation systems, f) using teamwork to integrate information, and g) presenting and explaining differences in methods and material options. The students were also free to develop their own learning objectives, provided it was related to one of the course

learning objectives. During Fall 2013 and Spring 2014 Intro Game Days students played a non-construction role playing game called Nano Around the World Game (available at www.nisenet.org) while Spring 2015 students played previous semester's construction board games [27]. In addition, students in Spring 2015 were given extra credit to create a game or game adaptation that made the course content accessible for a younger audience; 100% of students took advantage of the extra credit.

Table 6. Evolution of Module and Control Activity Implementation.

Semester	Module & Control Activity Implementation	Modifications & Rationale	Lessons Learned
Fall 2012	Control Activity only	Control Activity represents traditional assignment to assess students' mastery of course concepts.	Not applicable
Fall 2013	Control Activity + Game Design Module: Intro, Feedback, Final Game Days	Game Design Module added in addition to Control Activity to compare two methods of assessing students' mastery of course concepts and understand student assignment preference.	Performance nearly equal however students preferred module to Control Activity. Control Activity removed. Students also reported that three games days may be too many.
Spring 2014	Game Design Module: Intro and Feedback Game Days only	Game Design Module reduced to two days by removing Final Game Day to understand if peer feedback on Feedback Game Day produces quality games without the need to also hold Final Game Day.	Few students update their game based on peer feedback received on Feedback Game day without expectation of playing final games on Final Game Day.
Spring 2015	Game Design Module: Intro and Final Game Days only	Retained two-day module implementation however Feedback Game Day was replaced with Final Game Day to understand the impact on game quality by requiring students to bring final games to class on Final Game Day.	Few students delivered final-quality games; Feedback Game day seems necessary to ensure quality games are produced and students are afforded time with peer-review process.

Three variations of the Game Design Module were implemented in Fall 2013, Spring 2014, and Spring 2015; in Fall 2013 the module included all three game days where as in Spring 2014 and 2015 the module was modified from three days to two days to assess the differences between Feedback and Final Game Days.

Mixed-Methods Assessment

The Game Design Module was assessed using a mixed-methods approach combining module surveys, reflective journal entries and rubric evaluation of student games. The Control Activity was assessed using assignment criteria and was used as comparison to students' game grades. Each assessment method is described in detail in subsequent sections.

Survey Assessment

The survey questions, shown in Table 7, included Likert-scale and multi-response questions [30]. All students took the anonymous paper survey in class either at the end of Feedback Game Day (Spring 2014: questions 1-8) or Final Game Day (Spring 2015: questions 1-8) or both (Fall 2013: Feedback Day questions 1-2 and 5-9 and Final Day questions 1-2 and 5-8). Questions 1-3, 5, 7-9 on the survey assessed cognitive outcomes; students responded with their degree of agreement with the statement provided for each question, including course concept accuracy, clarity and professionalism of instructions, grammar/typos of instructions, game use in applying course concepts, and identification of game component that were weaknesses, strengths or needed improvement. Questions 4 and 6 assessed affective outcomes; students responded with their perceived game creativity and whether they would recommend the game activity to future semesters of students. A total of 178 students participated in the module. The survey response rate for Fall 2013 Feedback Game Day was 93% and the average response rate on Final Game Day was 73%. The survey response rate for Spring 2014 Feedback Game Day was 81% and the response rate for Spring 2015 Final Game Day was 76%. This survey research

was approved exempt under IRB protocol #1206007924 at Arizona State University and #PRO10010207 at the University of Pittsburgh.

Table 7. Post-Module Survey Questions.

Cognitive/ Affective	Semester				Question	Possible Response
	F13 Feedback	F13 Final	S14 Feedback	S15 Final		
C					1. This game applied course concepts accurately.	Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree
C					2. The instructions for this game were well written, clear, followed a logical progression and were professionally presented and formatted.	Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree
C					3. The instructions for this game were free of grammatical mistakes and typos.	Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree
A					4. This game design was creative. Is a new concept created for game? Are new game mechanics or pieces designed? Are players encouraged to think even more the topic? Are new game strategies or policies introduced?	Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree
C					5. This game help me increase and/or practice applying my knowledge of course concepts.	Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree
A					6. I would recommend this game development activity to other students in future sections of this course.	Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree
C					7. What are the weaknesses of this game?	Instructions, Scoring of Game, Board/Game Piece Design, Application of Course Concepts, Other: please describe
C					8. What are the strengths of this game?	Instructions, Scoring of Game, Board/Game Piece Design, Application of Course Concepts, Other: please describe
C					9. Please provide recommendations to the game creators to improve this game.	Improve Timing, Improve Concept Connection, Improve/Adjust difficulty of Game Pieces, Improve Game Board Design, Improve Scoring

Responses to all surveys were anonymous. Grey cells under the semester column indicate which questions were asked during each semester survey. Questions that cover cognitive outcomes (C) are highlighted in blue cells and affective outcomes (A) are in white cells in the first column.

Reflective Journal Entry

Students completed a reflective journal entry at the end of their game design experience (post-Feedback Game Day for Spring 2014 and post-Final Game Day for Fall 2013 and Spring 2015). The reflective journal entry was intended to gauge students' perceptions on the Game Design Module and provide evidence to the instructor as to whether this experience should be continued in future semesters. In Fall 2013 students were individually asked to respond to three questions, including 1) How do you envision creating and playing games with the CON 252 course content impacting your future career, 2) What did you learn from the experience of creating a game using the course learning objectives and applicable terms, and 3) Do you think the game development activity should be included in CON 252 next semester? Why or why not? In Spring 2014 and 2015, students were asked to prepare a 1-page reflective journal entry on how their game meets learning objectives in their teams. Responses to the reflective journal entries were gathered and reviewed by the evaluator through directed and summative content analysis methods for words/phrases associated with the module learning objective: "reinforce/apply course material" and words/phrases emergent through reading the entries: "competition," "critical thinking," "communication," "creativity," "teamwork," "having fun while learning," "provide context for course material," and "use repetition to learn". Directed and summative content analysis results were generated by the number of times the specified (directed) word/phrase was mentioned within the journal text and reflection of the context in which the word/phrase was discussed (summative) [31]. For example, student journal response of "creating the games in our CON 252 course provoked our inner creativity and it showed us what we can achieve if we try and push

ourselves to be creative and unique” was coded as one example of “creativity” and student journal response of “I envision creating a game that will challenge my thought process in the way that will make me think critically and give me a further understanding of the material” was coded as one “critical thinking” example.

Rating-Scale/Rubric Assessment

The instructor evaluated the Control Activity and games via rating-scale/rubric, shown in Table 8, to assess student cognition of learning objectives for both assignments. The rating-scale utilized in Fall 2013 assessed student games based on accuracy of learning objectives, Bloom’s level evident in the game, and professionalism of final game design [32, 33]. Spring 2014 and 2015 games were assessed via rubric based on the accuracy of learning objectives, clarity and professionalism of instructions, game creativity, and whether or not the game incorporated the minimum number of words after games were turned in on Feedback Game Day (Spring 2014) and Final Game Day (Spring 2015) [32].

Table 8. Rating-Scale/Rubric Assessment Utilized in Instructor Evaluation of Control Activity and Games.

	Semester	Question	Possible Evaluation
Control Activity	F12 & F13	1. Glossary project incorporated minimum number of words with citations and corresponding pictures	Definition accuracy of 70 bolded words, 30 non-bolded words with proper citations and pictures
Game Activity	F13 Final	1. Were the learning objectives accurately incorporated into game play?	High Inaccuracy, Inaccuracy, Neutral, Accuracy, High Accuracy
		2. What Bloom's Level of Intellectual Behavior is evident in this game?	Remembering, Understanding, Applying, Analyzing, Evaluating, Creating
		3. This game's design was professional (i.e. resembled a purchasable game) and effective (i.e. resembled a playable game).	Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree
	S14 Feedback, S15 Final	1. The learning objective expresses construction terminology and is accurately incorporated into game play. (10%)	Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree
		2. The game description/instructions were free of grammatical mistakes and typos. (5%)	Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree
		3. This game's description/instructions and game was professionally presented and formatted. (15%)	Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree
		4. Creativity: Examples = Does the student create a new concept for game, do they design new game mechanics or pieces, do they encourage the player to think even more broadly about construction terms, do they introduce new game strategies or policies? (10%)	Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree
		5. The game incorporate minimum required word count (min. 70 bolded construction terms and 30 non-bolded words) (60%)	Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree
	S15 Final	6. The group's reflective journal clearly describes how the game meets the learning objective. (10%)	Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree
		7. Extra Credit (+10%)	0-10

The CON 252 instructor utilized a rating-scale/rubric, contents of which are shown in this table, to assess all games after the last game day for each semester. Fall 2013 games were assessed based on accuracy of learning objectives, Bloom's level evident in game and professionalism of game design after Final Game Day [33]. Spring 2014 games were assessed based on the accuracy of learning objectives, clarity and professionalism of instructions, game creativity, and the game incorporates min number of words after Feedback Game Day. Spring 2015 games were assessed based on the same criteria as Spring 2014 with the addition of journal entry clarity and extra credit for designing a game adaptable for younger audience. Fall 2013 questions represent a rating-scale and are highlighted in blue cells and Spring 2014 and 2015 represent a rubric and are in white cells.

Control Assessment

The instructor assessed the Control Activity, i.e. the Glossary Project, by reviewing the team projects for the definition accuracy of 70 bolded words and 30 non-bolded words with cited definitions and appropriate corresponding pictures. The Control Activity was assessed using assignment criteria of word count, definitions, and pictures. In Fall 2012 students completed the Control Activity in project teams and in Fall 2013 students completed both the Activity and the Game Design Module in the same project teams. Grades were collected for each project and the instructor's removed all personal identifiers to ensure anonymity.

Results and Discussion

Three variations of the Game Design Module were implemented in three sections of sophomore-level CON 252 Building Materials, Methods and Equipment during Fall 2013, Spring 2014 and Spring 2015 semesters. The Game Design Module was assessed using a mixed-methods approach of post-module survey on cognitive and affective outcomes, reflective journal entry on module experience and instructor evaluation via rubric to determine the effectiveness of the module in assessing student cognition of learning objectives.

Student evaluation of each other's games

During the module implementation, students reported on their peer's accuracy and application of course concepts within games (Figure 12). Students brought draft games into class on Feedback Game Day and final games into class on Final Game Day;

students traded their games with their peers and played each other's games. On both Feedback and Final Game Days students in all three semesters individually completed the anonymous survey at the end of class. Students responded to the statement "this game applied course concepts accurately" and "this game help me increase and/or practice applying my knowledge of course concepts" with "strongly agree," "agree," "neutral," "disagree," or "strongly disagree". The results show that 92% of Fall 2013 Feedback class, 100% of Fall 2013 Final class, 100% of Spring 2014 Feedback class and 89% of Spring 2015 Final class agreed or strongly agreed that the peer game they played reflected accurate course concepts. However, 78% of the Spring 2015 Final class agreed or strongly agreed that the peer game helped them increase and/or practice applying their knowledge of course concepts compared to 100% of Fall 2013 Final class and 98% of Spring 2014 Feedback class, both classes that participated in Feedback Game Day (Fall 2013 Feedback class was not surveyed on this question). This indicates that devoting time midway through the semester experience, herein called Feedback Game Day, may play an influential role in the quality of games produced; students that participated in a Feedback Game Day regardless of participating in a Final Game Day or not reported greater game benefits than students that only participated in a Final Game Day.

Student Reporting of Accuracy and Application of Course Concepts in Games

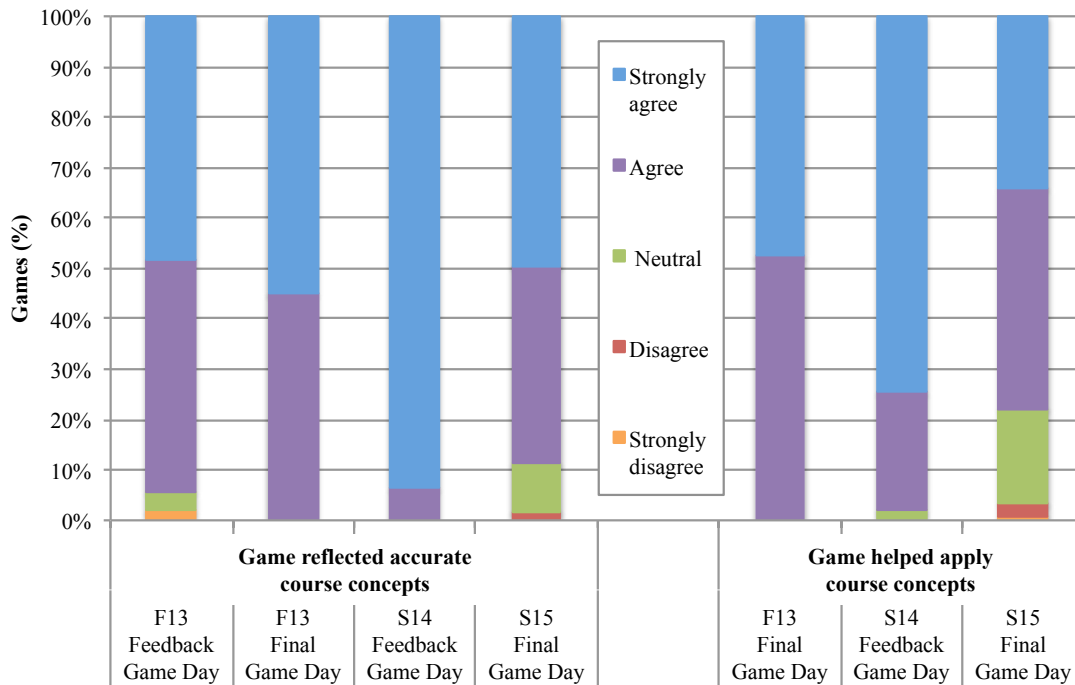


Figure 12. Student Reporting on Peer’s Games for Concept Accuracy and Course Relevancy. The Game Design Module was divided into three distinct days: Intro Game Day, Feedback Game Day, and Final Game Day. Fall 2013 (F13, n = 58) students participated in all three days where as Spring 2014 (S14, n = 42) students participated in Intro and Feedback Game Days and Spring 2015 (S15, n = 80) in Intro and Final Game Days. Students responded via anonymous survey to the statements “this game applied course concepts accurately” and “this game help me increase and/or practice applying my knowledge of course concepts” with “strongly agree,” “agree,” “neutral,” “disagree,” or “strongly disagree” as response options.

Student reporting of their peer’s student-developed game weaknesses and strengths is presented in Figure 13. After students played each others games on Feedback and Final Game Days, they were asked “what are the weaknesses of this game” and “what are the strengths of this game” by selecting all (or none) of the possible answers, including “instructions,” “scoring of game,” “board/game piece design,” “application of course concepts,” and/or “other: please describe”. The authors note that students could have responded to these questions by selecting the same game components as both weaknesses and strengths or splitting the components between weaknesses and strengths

or some combination of both response strategies. The results show that the greatest game weakness for Fall 2013 Feedback games was “other: please describe” (49%) and students reported game timing, number of game pieces, difficulty of game questions as the game weaknesses. Fall 2013 Final Game Day students selected “board/game piece design” as the greatest game weakness (32%), compared to Spring 2014 Feedback and Spring 2015 Final Game Days, which students reported “instructions” as the greatest game weakness (30% and 37%, respectively). With the exception of Spring 2015 Final, students reported on Fall 2013 Feedback and Final and Spring 2014 Feedback that “application of course concepts” was the greatest game strength. In Spring 2015, students reported that “board/game piece design” was a greater strength than “application of course concepts” by a slight margin (33% to 28%). The results show that “instructions” and “other: please describe” are consistent weaknesses of the games, with the exception of Fall 2013 Final instructions, which were likely improved as a result of student participation in three game days in compared to the two game days held in Spring 2014 and 2015. Game components that were both consistent weaknesses and strengths included “scoring of game” and “board/game piece design”. The only consistent strength was “application of course concepts,” indicating that while there are inconsistencies between student teams in delivering games with clear instructions, appropriate scoring and professional board/game piece design, the core learning outcome of course concepts applied through games is consistently achieved every semester according to students.

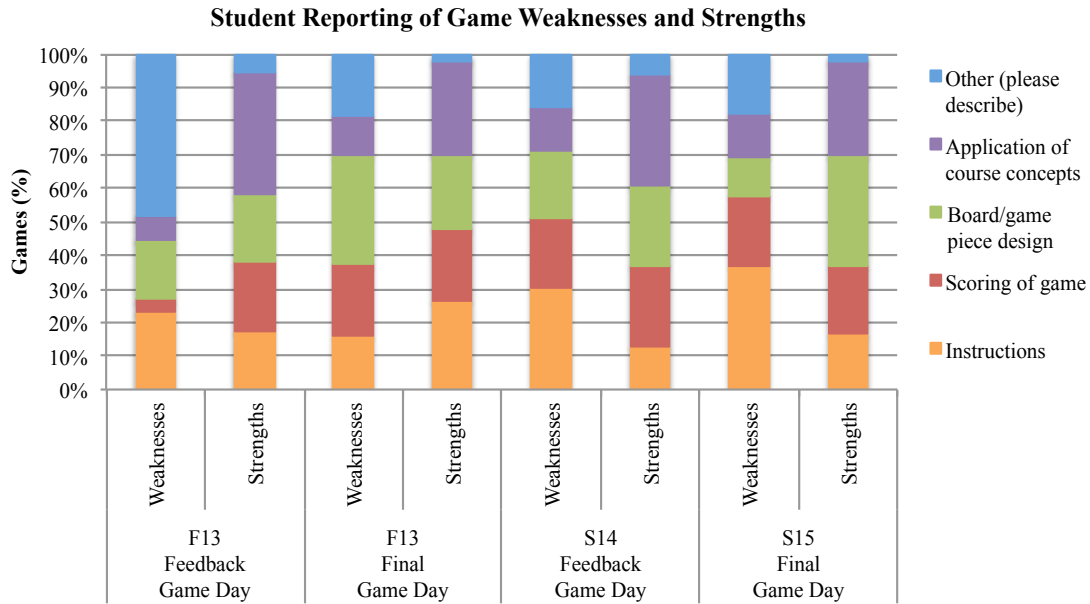


Figure 13. Student Reporting of Game Weaknesses and Strengths.

The Game Design Module was divided into Intro Game Day, Feedback Game Day, and Final Game Day. Fall 2013 (F13, n = 58) students participated in both all three days; Spring 2014 (S14, n = 42) students participated in Intro and Feedback Game Days only and Spring 2015 (n = 80) in Intro and Final Game Days only. Students were given an anonymous survey and asked “what are the weaknesses of this game” and “what are the strengths of this game” by selecting all (or none) of the possible answers, including “instructions,” “scoring of game,” “board/game piece design,” “application of course concepts,” and/or “other: please describe”. Students could have responded to these questions by selecting the same game components as both weaknesses and strengths, splitting the components between weaknesses and strengths or some combination of both response strategies.

Student reporting of their peer’s game instruction clarity is presented in Figure 14. Students were surveyed at the end of Feedback and Final Game Days and responded to “the instructions for this game were well written, clear, followed a logical progression and were professionally presented and formatted” by selecting either “strongly agree,” “agree,” “neutral,” “disagree,” or “strongly disagree”. Despite student reporting of instructions as a consistent game weakness 89% of Fall 2013 Feedback, 96% Fall 2013 Final, and 93% Spring 2014 Feedback classes agreed or strongly agreed that the game instructions were clear. In comparison, 64% of the Spring 2015 Final class agreed or strongly agreed that the game instructions were clear. This suggests that the inclusion of

Feedback Game Day, with or without Final Game Day, has higher impact on instruction clarity than holding just Final Game Day absent of the peer-review process that occurs on Feedback Game Day.

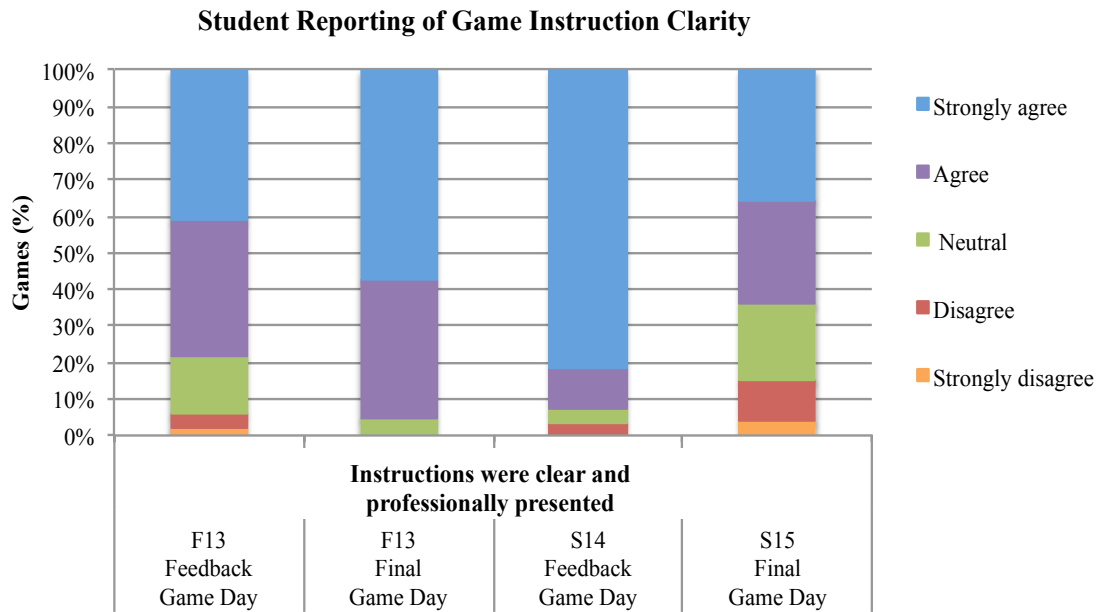


Figure 14. Student Reporting of Game Instruction Clarity.

The Game Design Module was conducted over three distinct days; Intro Game Day, Feedback Game Day, and Final Game Day. Fall 2013 (F13, n = 58) students participated in all three days where as Spring 2014 (S14, n = 42) students participated in Intro and Feedback Game Days only and Spring 2015 (S15, n = 80) in Intro and Final Game Days only. Students were given an anonymous survey and asked whether “the instructions for this game were well written, clear, followed a logical progression and were professionally presented and formatted” by selecting either “strongly agree,” “agree,” “neutral,” “disagree,” or “strongly disagree” as response options.

The survey also asked students if they would recommend the game assignment for future semesters of CON 252 (Figure 15). The results show that 98% of students from the Fall 2013 Final Game Day and 93% of students from the Spring 2014 Feedback Day agreed or strongly agreed that the game design assignment should be recommended to other students future sections of this course. In comparison, 71% of students from the Spring 2015 Final Game Day agreed or strongly agreed that the assignment should be

recommended in the future. Students in the Spring 2015 Final Game Day class more often reported “application of course concepts and clear instructions” as a weakness of their peers’ games (Figure 13), which may explain why these students were less enthusiastic about implementing game design in future semesters. All results from the student evaluations of their peers’ games indicate that having a Feedback Game Day not only impacts the quality of the games, which in turn may also impact students’ desire to recommend the assignment to future semesters of students.

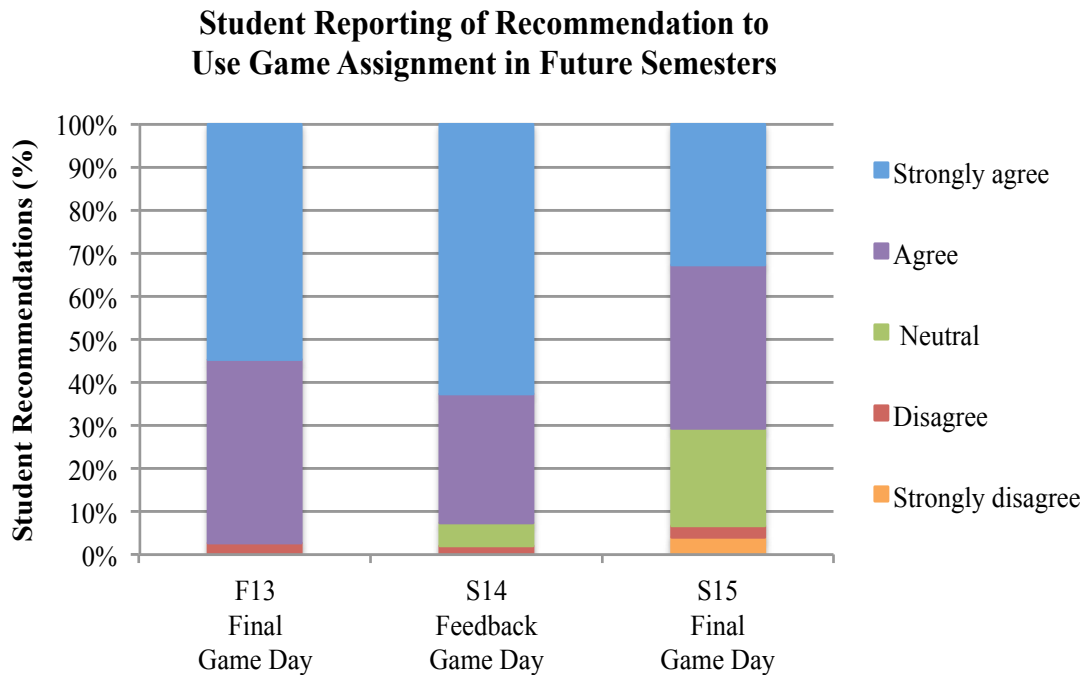


Figure 15. Student Reporting of Recommendation to Use Game Assignment in Future Semesters. The Game Design Module was divided among three distinct days, including Intro Game Day, Feedback Game Day, and Final Game Day. Fall 2013 (F13, n = 58) students participated in all three days; Spring 2014 (S14, n = 42) students participated in Intro and Feedback Game Days and Spring 2015 (S15, n = 80) students participated in Intro and Final Game Days. Students were asked to respond anonymously to the following question: “I would recommend this game development activity to other students in future sections of this course” with either “strongly agree,” “agree,” “neutral,” “disagree,” or “strongly disagree” as possible options.

Reflective Journals

Common themes present in students' reflective journals are presented in Figure 16. Students completed a reflective journal entry at the end of their game design experience (post-Feedback Game Day for Spring 2014 and post-Final Game Day for Fall 2013 and Spring 2015). The authors reviewed responses to the reflective journal entries via word search for nine words/phrases that indicate students experience in the games, summarized in the key in Figure 16. The results show the Fall 2013 specific questions that students responded to individually resulted in more themes than when student teams were given a general assignment of describing how their game meets the learning objectives in Spring 2014 and 2015. Fall 2013 themes included six additional themes of critical thinking, communication, creativity, teamwork, reinforce/apply course material, and provide context for course material beyond to use repetition to learn and have fun while learning which were also present in Spring 2015. This indicates that the multiple questions assignment may have prompted students to think more broadly than the single question assignment and students responding individually generated more themes than when students worked in teams. The only themes present in Spring 2014 journal entries were competition and reinforce/apply course material. In comparison, Spring 2015 themes included both competition and reinforce/apply course material and communication, use repetition to learn, have fun while learning, despite any changes in the journal assignment between semesters. The extra credit offered to the Spring 2015 students to create a game adaptable for a younger audience may have resulted in the differences between themes from each semester; 100% of students took advantage of the extra credit. Those who took advantage tended to journal about using repetition to learn,

citing that younger audiences could learn construction terminology through repetition regardless of their experience with the topic. Overall, students report that the use of this game module enhanced their learning, enabled them to utilize teamwork skills to collaborate on game development and was an enjoyable approach to demonstrating knowledge of course content.

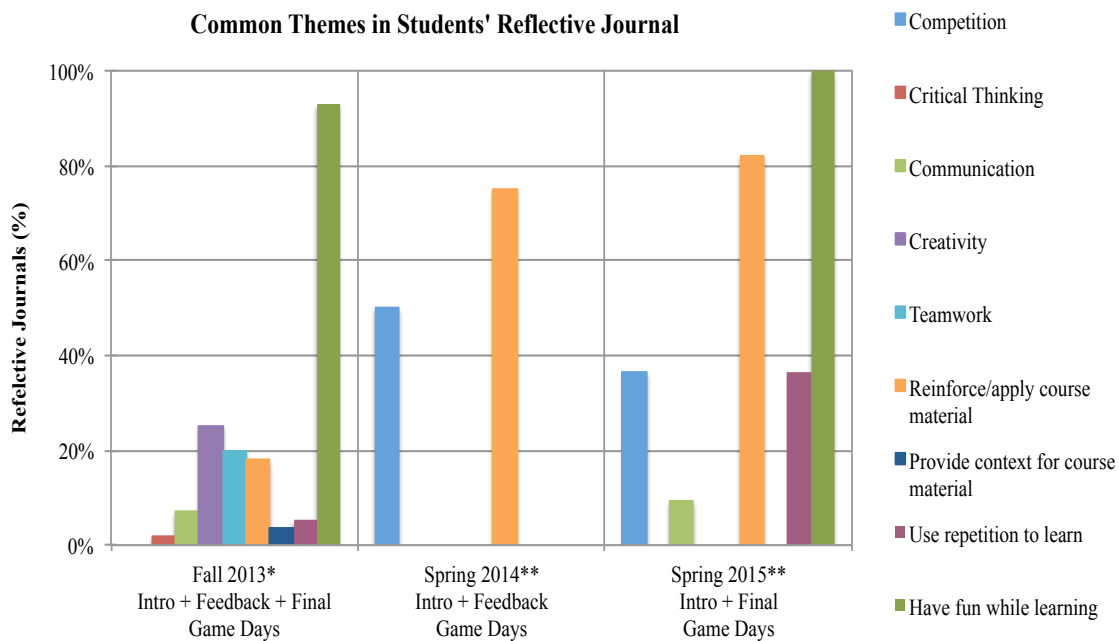


Figure 16. Common Themes in Students' Reflective Journal Post-Game Project.

Fall 2013 (n = 58) students participated in both Intro, Feedback, and Final Game Days. Spring 2014 (n = 42) students participated in Intro and Feedback Game Days. Spring 2015 (n = 80) students participated in Intro and Final Game Days. *After Final Game Day Fall 2013 students were asked to respond individually to three questions, including “how do you envision creating and playing games with the CON 252 course content impacting your future career,” “what did you learn from the experience of creating a game using the course learning objectives and applicable terms,” and “do you think the game development activity should be included in CON 252 next semester- why or why not.” **After Feedback Game Day Spring 2014 and Final Game Day Spring 2015, students were asked to prepare a 1-page reflective journal entry on how their team’s game met the given learning objectives; note this was a team assignment (one journal entry per team).

Student performance: Rubric evaluation of student designed games

Instructor evaluation of game learning objective accuracy is presented in Figure 17. The CON 252 instructor evaluated the games via rubric after games were turned in; evaluation was conducted after Final Game Day for Fall 2013 and Spring 2015 semesters and two weeks after Feedback Game Day for Spring 2014. The rubric assessed student games based on accuracy of learning objectives incorporated into the games. The results show that the instructor agreed or strongly agreed that 80% of the Fall 2013 final games accurately incorporated learning objectives into their games. This is likely a function of the game design assignment because Fall 2013 students were not given a learning objective and were required to select their learning objectives from the course list on the syllabus. In comparison, 100% of Spring 2014 draft games accurately incorporated learning objectives into their games. Students in Spring 2014 class turned their games in to the instructor after playing them with their peers and had several weeks to improve the games based on peer feedback. Conversely, 86% of Spring 2015 final games without peer feedback accurately incorporated learning objectives. Peer feedback not only plays an important role in student perceptions of their games but also in instructor game grades.

Instructor Evaluation of Accuracy of Learning Objectives Incorporated into Final Game

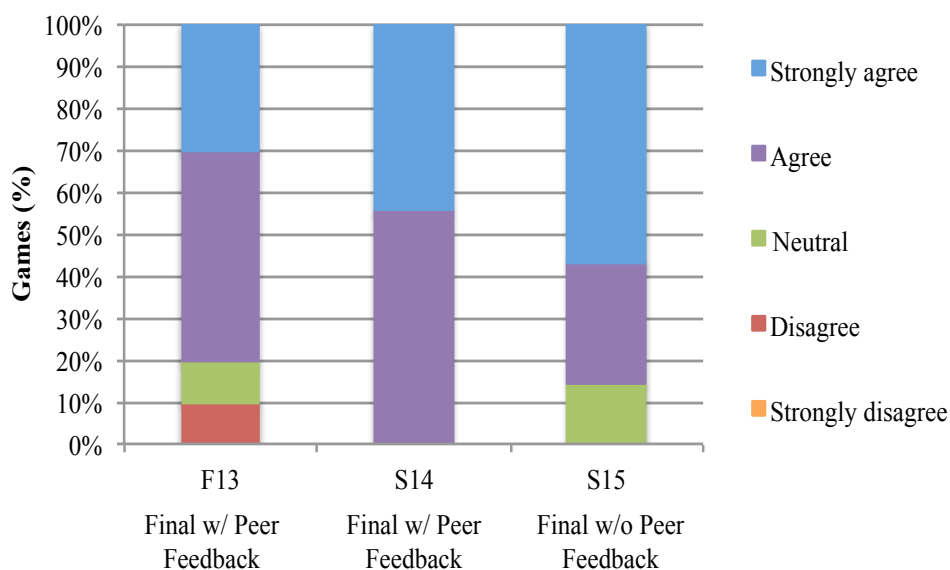


Figure 17. Instructor Evaluation of Accuracy of Learning Objectives.

The Game Design Module was implemented in three distinct days: Intro Game Day, Feedback Game Day, and Final Game Day. Fall 2013 (F13, n = 58) students participated in all three days where as Spring 2014 (S14, n = 42) students participated in Intro and Feedback Game Days only and Spring 2015 (S15, n = 80) in Intro and Final Game Days only. Students brought draft games into class on Feedback Game Day **and** final games into class on Final Game Day and traded their games with their peers for game play. The CON 252 instructor evaluated the final games from each semester using a rubric to determine whether the learning objectives were accurately incorporated into the final games by responding with either “strongly disagree,” “disagree,” “neutral,” “agree,” or “strongly agree.”

The instructor also evaluated professionalism and effectiveness of the student games (Figure 18). The CON 252 instructor evaluated the game via rubric post-Final Game Day Fall 2013 and Spring 2015 semesters and two weeks after Feedback Game Day Spring 2014. The rubric assessed student games based on professionalism and effectiveness of game instructions and game itself; from Fall 2013 rubric the instructor determined whether “this game’s design was professional (i.e. resembled a purchasable game) and effective (i.e. resembled a playable game) and from Spring 2014 and 2015 rubric the instructor determined whether “this game’s description/ instructions and game itself was professionally presented and formatted” with responses of either “strongly

agree,” “agree,” “neutral,” “disagree,” or “strongly disagree”. The results show that 50% Fall 2013 games and 56% of Spring 2014 games, compared to 79% of Spring 2015 games, were professional and effective. During the first semester, students played the Nano Game, which is an educational game that does not relate at all to the construction course concepts. Students from Spring 2015 class were the only class of student to play past games developed by Fall 2013 and Spring 2014 students. Spring 2015 students may have learned from past peer’s game designs and altered the professionalism and effectiveness of their designs, thus playing games previously designed by other students improves students’ understanding of the expectations for the use of games in lieu of a final exam.

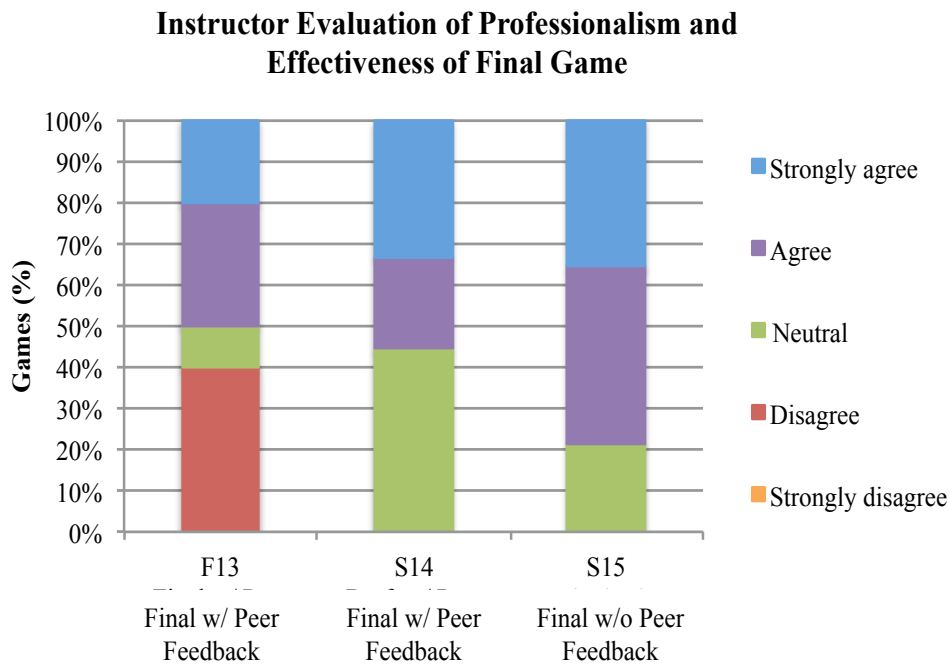


Figure 18. Instructor Evaluation of Professionalism and Effectiveness of Final Game. Fall 2013 (F13, n = 58) students participated in all three days where as Spring 2014 (S14, n = 42) students participated in Intro and Feedback Game Days only and Spring 2015 (S15, n = 80) in Intro and Final Game Days only. Students brought draft games into class on Feedback Game Day and final games into class on Final Game Day and traded their games with their peers for game play. The CON 252 instructor evaluated the final games from each semester using a rubric to determine whether the final games were professional and effective by responding with either “strongly disagree,” “disagree,” “neutral,” “agree,” or “strongly agree.”

Student performance: Comparison of grades across control and game module

Student grades for the Control Activity and the Game Design Module are presented in Figure 19. The Control Activity was implemented in two semesters of CON 252 in Fall 2012 and Fall 2013. The Game Design Module was also implemented in Fall 2013 in addition to the Spring 2014 and Spring 2015 semesters. The CON 252 instructor evaluated the Control Activity via straight grade comprised of number of terms included in the glossary (based on the assigned 100 words) and corresponding definitions, and pictures. The Game Design Module, also evaluated by the same CON 252 instructor, was assessed via rubric on the accuracy of learning objectives, instructions, professionalism, creativity and overall game design. Both the Control Activity and the Game Design Module were graded out of 100 possible points. While Fall 2013 and Spring 2014 games were assessed for incorporating beyond the minimum 70 bolded and 30 non-bolded words in their games, Spring 2015 students were able to earn up to an additional 20% for incorporating beyond the minimum words and they were also given the opportunity to earn up to 10% extra credit by designing a game that was adaptable for a younger audience. The results show that there is no significant difference in grades between the control and the games assignments for student grades; all grade averages are within 8%. Grades were statistically significant at $p\text{-value} = 0.05$ between Fall 2012 control, Fall 2013 control, Fall 2013 games and Spring 2014 games when compared to Spring 2015 game grades. The instructor assessments illustrate that students achieved better levels of mastery in the game-only implementation than was shown with the “traditional” control assignment (Fall 2012) or traditional and game assignment (Fall 2013).

The average games grades have increased from Fall 2013 (86%) to Spring 2014 (91%) to Spring 2015 (94%). While the average Fall 2013 control and game grades is similar at 87% and 86%, respectively, both of these grades were lower when compared to just control (average Fall 2012: 91%) and just games (average Spring 2014: 91% and Spring 2015: 94%). Requiring both assignments rather than one or the other likely overwhelmed the students; student journaling did reflect students being overwhelmed and revealed that students felt the module lend itself to greater learning opportunities than the control. Spring 2015 students were the only class to play construction games designed in previous CON 252 semesters. Spring 2015 students had notably higher grades than previous semesters, and students' experience playing constructions games as well as having the opportunity to receive and incorporate feedback is an important factor to improve both the student experience and student learning.

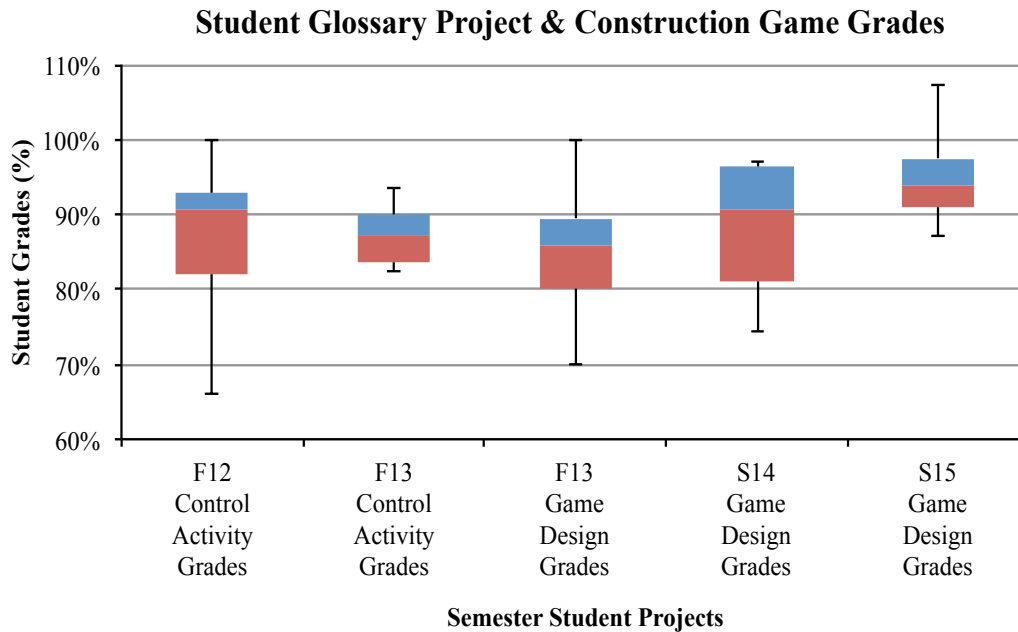


Figure 19. Grades for Student and Construction Game Projects.

The Control Activity was implemented Fall 2012 (F12, n= 37) and Fall 2013 (F13, n = 58) and the Game Design Module was implemented in Fall 2013, Spring 2014 (S14, n = 42) and Spring 2015 (S15, n = 80). In Spring 2015 students were given the opportunity to earn up to 10% extra credit by designing a game that was adaptable for a younger audience; Spring 2015 grades shown do not include extra credit however it was possible to earn up to 120 points out of 100 if students covered more than the minimum word count. The ends of the whiskers are set at 1.5*interquartile range (IQR) above the third quartile and 1.5*IQR below the first quartile. The upper quartile is shown blue and lower quartile is show in red. Minimum or maximum values outside this range they are outliers. Two outliers exist within these data sets; in Fall 2012 one student received a grade of 0 on the control activity for failing to complete the assignment and in Spring 2015 one team received a grade of 120 for a game that incorporated beyond the minimum number of words.

Conclusion

This paper presents assessment of student construction and engineering concept mastery through student-designed board games via a Game Design Module. The module introduced students to the concepts of active and experiential learning through games and includes a discussion on key game components such as learning objectives, materials/board game design, instructions/ scoring. The module was divided into three distinct days, Intro Game Day, Feedback Game Day and Final Game Day and was implemented into three sections of CON 252: Building Methods, Materials and

Equipment at Arizona State University. The module was assessed using a mixed-methods approach of module surveys, reflective journal entries, rubric evaluation of student games, and comparison of student grades. A Control Activity, called the Glossary Project, represented a traditional assessment of student concept mastery and was utilized as a comparison to the module results. The results indicate that students can demonstrate mastery of concepts through board game design. Students tended to struggle with articulating game learning objectives on their own and their performance increased when the instructor defined the learning objectives. Three game days in Fall 2013 were too many and two games days in Spring 2014 and 2015 were too few. Because Feedback Game Day is critical to students' professional game design, to optimize student performance and experience, the Game Design Module should be split into one full Intro Game Day and two half Feedback and Final Game Days, which would require pairing it with another assignment for the second half of class. Results show that students' experience playing constructions games designed by previous classes as well as having the opportunity to receive and incorporate feedback is an important factor to improve both the student experience and student learning. Overall students report enjoying the Game Design Module more than the Control Activity because of the creativity and teamwork involved. Games can be used as an effective tool for instructors to evaluate student learning in lieu of traditional reports or exams.

In future work the evaluators will utilize Inter-Rater Reliability (IRR) best practices to understand the impact of the evaluators on rating-scale/rubric results. IRR is defined as the process through which two or more raters classify subjects or objects independent of one another [34]. High IRR verifies that the raters can be used

interchangeably, thereby establishing the rater as an abstract entity to the main focus of study, the subjects [34, 35].

Acknowledgments

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Chapter 4

UTILIZING CIVIL ENGINEERING SENIOR DESIGN CAPSTONE TO EVALUATE SUSTAINABILITY EDUCATION OVER ENGINEERING CURRICULUM

This chapter evaluates students' cumulative sustainability knowledge at two institutions using the stand-alone course method to integrate sustainability into engineering curriculum via a novel sustainability rubric developed in this thesis. This chapter was a collaboration with three students also working on the TUES 2 project, Kevin J. Ketchman, Rebekah D. Burke, and Troy A. Hottle.

Abstract

While many institutions express interest in integrating sustainability into their engineering curriculum, the engineering community lacks consensus on established methods for infusing sustainability into curriculum and verified approaches to assess engineers' sustainability knowledge. Two main strategies have emerged for integrating sustainability and National Academy of Engineering (NAE) Grand Challenges of Engineering into engineering curriculum. In the stand-alone course method, engineering programs establish one or two distinct, stand-alone courses. In the module method, engineering programs integrate grand challenges throughout a host of existing courses. This paper presents a descriptive study utilizing civil engineering senior design capstone projects to evaluate students' sustainability knowledge at two institutions using the stand-alone course method to integrate sustainability into engineering curriculum. The sustainability content within Spring 2014, Fall 2014, and Spring 2015 senior design capstone projects from Arizona State University (ASU, $n = 181$ students, $n_p = 28$ projects) and University of Pittsburgh (UPitt, $n = 106$ students, $n_p = 15$ projects) was evaluated using a mixed-methods approach, where students at each university took at least one stand-alone class dedicated to sustainability. A mixed-methods approach

included observation of student senior design project presentations, evaluation of student reports via a novel rubric created for evaluating sustainability content, and an anonymous post-course student survey to understand student perceptions of sustainability in engineering. The developed rubric utilized existing assessment approaches and built upon them to evaluate student reports for nine different factors including dimensions of sustainability, Bloom's taxonomy, sustainability links, drivers for including sustainability, location of sustainability within report, qualitative/quantitative incorporation, sustainability source/reference, sustainability topics, and NAE Grand Challenges of Engineering topics. Students surveyed reported that sustainability and creating solutions for NAE Grand Challenges of Engineering will likely play a role in their future career. 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 concepts that they learned from prior classes. Thus, senior design project requirements should be updated to explicitly require holistic sustainability applications to the engineering designs. 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 as demonstrated in one senior design project. Not only would this approach support students throughout their senior design project but it would better prepare them for the role of a 21st century engineer.

Introduction

Engineers of the future must be prepared to address the complex, multidisciplinary problems that necessitate engineering solutions in sustainable and global contexts. Engineering education can provide students with the tools to approach these grand challenges of the 21st century while considering aspects that are key for designing sustainable systems [1, 2]. Furthermore, according to the National Academy of Science report, *Changing the Conversation*, youth are seeking careers that make a difference [3, 4]. Sustainable engineering offers a solution to pressing challenges, in conjunction with appealing to our youth. Furthermore, as of 2015 the Accreditation Board for Engineering and Technology (ABET) has recognized the importance of sustainability for student outcomes and in engineering curriculum; criterion three and five have been updated to include engineering designs that meet desired needs within realistic constraints, such as sustainability, and curriculum that includes principles of sustainability [5].

The National Academy of Engineering (NAE) developed and issued the Grand Challenges of Engineering, with five of the fourteen directly related to sustainability (solar energy, carbon sequestration, nitrogen cycle, clean water, and infrastructure) [6]. The Grand Challenges offer a framework for exposing engineering students to role of an engineer in modern society. Adoption of these challenges within engineering curricula engages a diverse array of interested students by establishing contextualized linkages between course content and the contributions an engineer makes to solve global issues through systems-thinking innovation [7].

Strategies for assessing student sustainability knowledge and application are limited to a few studies [8-14]. The strategies include what and how students should be assessed, including defining learning objectives related to assessing understanding of sustainable development via critical, holistic thinking and assessing the number of times a student mentions sustainably concepts, whether or not a student links three pillars of sustainability (environmental, economic, social), utilizing instructor-created rubrics on course content or available assessments such as Sustainability in Higher Education Assessment Rubric (SHEAR) or Sustainability Assessment Survey [8-12, 15]. Despite the usability of instruments like SHEAR or SAS, sustainability in higher education assessments often lack details indicative of interdisciplinary knowledge transfer necessary for learning sustainability, thus researchers have recently adopted a concept mapping approach of assessing students. This approach compliments the nature of current global issues, which are complex and interconnected, and gauges whether students can rationally infer interactions between and within human and natural systems [16]. Conversely, the strategy for assessing student engineering knowledge and application is widely recognized in a culminating undergraduate engineering experience: senior design capstone projects [17].

Two main strategies have emerged from universities attempting to integrate grand challenges such as sustainability into the curriculum; termed herein as the *stand-alone course method*, and the *module method*. In the *stand-alone course method*, engineering programs establish one or two distinct, stand-alone courses that address sustainability grand challenges in depth. Semester courses can enable an in-depth exploration of sustainability and sustainable engineering, enhancing students' knowledge of both

fundamentals and engineering applications for sustainability. In the *module method*, engineering programs integrate sustainability grand challenges throughout a host of existing courses by threading individual sets of course skills together in an effort to reach higher levels of intellectual behavior via interdisciplinary concept connection [18]. Modules can be designed to fit into one lecture or over a series of lectures. Modules typically include everything an instructor needs for implementation: a summary of learning objectives and module activities, lecture slides and notes, recommended readings, and an assignment for students.

The current state-of-the-practice for senior design focuses on the design elements from the primary CEE compartments: Construction, Steel & Concrete Structures, Water Management and Infrastructure. The American Society for Civil Engineers (ASCE) Body of Knowledge 2 (BOK2) summarizes the required engineering content knowledge of 24 outcomes, organized into three compartments: foundational, technical, and professional [17]. Outcome ten is sustainability [17]. The foundational outcomes create the base for continued learning in the technical and professional categories. Bloom's taxonomy was adopted by BOK2 to define achievement goals of cognitive behavior, including "knowledge," "comprehension," "application," "analysis," "synthesis," or "evaluation," within the 24 outcomes [19, 20]. ASCE assigns each outcome a specific Bloom's level; during the bachelor's degree the expected level of achievement for the sustainability outcome is Bloom's level knowledge, comprehension, and application. BOK2 expects that analysis be reached through work experience, i.e. after the bachelor's degree. The sustainability outcome meets or exceeds Bloom's taxonomy levels for 16 of 24 outcomes. BOK specifies the synthesis level for 7 outcomes, including experiments, design,

technical specialization, communication, lifelong learning, professional and ethical responsibility, and evaluation level for 3 outcomes, including design, technical specialization, professional and ethical responsibility [17].

This paper develops a rubric for evaluating students' sustainability knowledge that should have been learned as they took at least one stand-alone course during their curriculum; the rubric is applied to senior design capstone projects. This paper presents a descriptive study through the evaluation of two institutions' senior design projects for students' use of sustainability and reflects on the use of an engineering-focused design project as the place for assessing sustainability [21].

Methods

This methods section first provides an overview of the engineering curriculum at two U.S. institutions from their introduction to sustainability to their capstone experiences, Arizona State University (ASU) and University of Pittsburgh (UPitt). Next, the methods describe the development of a novel rubric for assessing how and to what cognitive extent students integrate sustainability concepts into senior design projects. And finally, the mixed-methods assessment is described, which includes observation of student senior design project presentations, the rubric evaluation, and an anonymous post-course student survey to understand student perceptions of sustainability in engineering. This survey research was approved exempt under IRB protocol #1206007924 at Arizona State University and #PRO10010207 at the University of Pittsburgh.

Engineering Curriculum and Senior Design Course Descriptions

Arizona State University

At Arizona State University (ASU), sustainability is emphasized in teaching, learning, research and operations. ASU has made a significant investment in sustainability; the Global Institute of Sustainability (GIOS) is entirely made up of sustainability scientists, and is the first of its kind in the world to offer degrees in sustainability, including a sustainability minor for engineers, which requires the completion of six sustainability courses. The School of Sustainable Engineering and the Built Environment (SSEBE) offers degrees in Civil and Construction Engineering and currently requires one stand-alone sustainable engineering undergraduate course, CEE 400 Earth Systems Engineering and Management (ESEM) that students take in their junior or senior year. SSEBE also offers eight sustainable engineering elective courses that students may select to fulfill 18 elective credits required, shown in Table 9. ASU represents the stand-alone course method; ASU has established one distinct, required, stand-alone course, CEE 400 ESEM, which addresses sustainability grand challenges in depth, and generally follows the content summarized in Allenby's The Theory and Practice of Sustainable Engineering [22].

Table 9. Arizona State University Sustainability in Civil and Environmental Engineering Curriculum.

	Term	Course Number	Course Name	#
CEE Required Courses	Term 1	ENG 101	First-Year Composition/Advanced Composition	3
		CEE 100	Introduction to Civil and Environmental Engineering	3
	Term 2	ENG 102	First-Year Composition/Advanced Composition	3
	Term 3	CEE 210	Engineering Mechanics I: Statics	3
	Term 4	CEE 212	Engineering Mechanics II: Dynamics	3
		CEE 213	Introduction to Deformable Solids	3
		EEE 202 OR MAE 240	Circuits I (Civil opt 1 & Construction) or Thermofluids (Civil opt 2 or Environmental)	4
	Term 5	IEE 380	Probability and Statistics for Engineering Problem Solving	3
		CEE 321	Structural Analysis and Design	4
		CEE 351	Geotechnical Engineering	4
		CEE 353	Civil Engineering Materials	3
		CEE 384	Numerical Methods for Engineers	3
	Term 6	CEE 361	Introduction to Environmental Engineering	4
		CEE 300	Engineering Business Practice	3
		CEE 341	Fluid Mechanics for Civil Engineers	4
		CEE 372	Transportation Engineering	4
	Term 7	CEE 400	Earth Systems Engineering and Management	3
		student selects	Upper Division Design Elective	3
		student selects	Upper Division Technical Elective	3
		student selects	Upper Division Technical Elective	3
student selects		Upper Division Technical Elective	3	
Term 8	CEE 486	Integrated Civil Engineering Design	4	
	student selects	Upper Division Design Elective	3	
	student selects	Upper Division Technical Elective	3	
CEE Elective	Term 7 or 8	CEE 194	Topic: Technology, Society & Sustainability	3
		CEE 485	Sustainable CEE System Engineering	3
		CEE 486	Sustainability Ethics for Science and Engineering	3
		CEE 494	Sustainable Energy Technologies	3
		CEE 494	Urban Infrastructure Anatomy and Sustainable Development	3
		CEE 494	Sustainable Environmental Biotechnologies	3
		CEE 498	Clean Technology Entrepreneurship for Sustainable	1
		CEE 498	Sustainable Energy and Material Use	3
SOS Minor	Any Term	SOS 100	Introduction to Sustainability	3
		SOS 300	Advanced Concepts and Integrated Approaches in Sustainability	3
		Theme Courses	Earth Sys, Human Trans of the Earth, Coupled Human-Environ Sys, OR Soc, Pol, Econ Trmt of Nat Res and Environ	6
		Addl Electives	School of Sustainability elective courses	6

Arizona State University's Civil and Environmental Engineering (CEE) curriculum includes one stand-alone sustainable engineering undergraduate course, Earth Systems Engineering and Management (ESEM), and eight additional sustainable engineering elective courses that students may select to fulfill 18 elective credits required during terms 7 and 8 of their senior year. Civil and environmental engineering students can also work towards a sustainability minor through the School of Sustainability, which requires completion of six sustainability courses. Non-engineering required/elective courses are not listed in this table. Sustainable engineering and sustainability courses are highlighted in green. Senior design course is highlighted in blue.

The School of Sustainable Engineering and the Built Environment at ASU requires all students to participate in the senior design course (CEE 486). The senior design project at ASU encompasses a comprehensive land development plan involving engineering roles of due diligence, drainage, traffic circulation, water, wastewater, structural, and geotechnical analysis. Students work in teams of five to seven people per project and within each team students select a civil engineering sub-discipline role based on their interest. The teams are partnered with a local engineering firm whose role is to support students throughout their projects through mentorship. The senior design project requires students to produce engineering design plans for their development, compile a comprehensive written report featuring all engineering sub-discipline roles, and present their engineering designs in a culminating presentation at the end of the semester. Sustainability is a required component of their engineering design; within each engineering subdiscipline, students are required to include innovative sustainability technologies as a stand-alone section. A total of 181 students participated in ASU senior design during Spring 2014 (73), Fall 2014 (41), and Spring 2015 (67) semesters.

University of Pittsburgh

University of Pittsburgh's (UPitt) Swanson School of Engineering through the Mascaro Center for Sustainable Innovation (MCSI) and the Department of Civil and Environmental Engineering (CEE) has made a significant investment in sustainable engineering. While UPitt does not offer a minor in Sustainability, UPitt does have an Engineering for Humanity Certificate and (at the time of this writing) a nearly approved University-wide Sustainability Certificate. Similar to ASU, UPitt represents the *stand-*

alone course method. Sustainable engineering faculty housed in CEE have developed and taught four stand-alone sustainable engineering undergraduate courses since 2008, including CEE 1209 Life Cycle Assessment Methods and Tools (LCA), CEE 1210 Engineering and Sustainable Development (ESD), CEE 1217 Green Building Design and Construction (GB), and CEE 1218 Design for the Environment (DFE) shown in Table 10. Students in CEE are required to take one of these four stand-alone courses that address sustainability grand challenges in depth. CEE 1209 introduces students to LCA, including the methodology and tools used to conduct an LCA and follows Matthews, Hendrickson, and Matthews' Life Cycle Assessment: Quantitative Approaches for Decisions that Matter [23]. CEE 1210 covers concepts of industrial ecology and sustainable development and follows Graedel and Allenby's Industrial Ecology and Sustainable Engineering [24]. CEE 1217 introduces students to green buildings, life cycle of buildings, and utilizes the United States Green Building Council's Leadership in Energy and Environmental Design (LEED) green building rating system to demonstrate one possible green rating system [25]. CEE 1218 is a topical course that introduces students to concepts of design for environment tools and also includes in-depth investigations such as residential energy assessments. The Engineering and Sustainable Development (ESD) class and ASU's ESEM class are very similar in course content; the instructors are authors on this paper and collaborated in developing the classes. More recently, UPitt's Provost selects a theme to integrate throughout all curricula and activities; UPitt dedicated the 2014-2015 academic year to sustainability.

Table 10 Students in CEE are required to take one of these four stand-alone courses that address sustainability grand challenges in depth. CEE 1209 introduces students to LCA, including the methodology and tools used to conduct an LCA and follows Matthews, Hendrickson, and Matthews' Life Cycle Assessment: Quantitative Approaches for Decisions that Matter [23]. CEE 1210 covers concepts of industrial ecology and sustainable development and follows Graedel and Allenby's Industrial Ecology and Sustainable Engineering [24]. CEE 1217 introduces students to green buildings, life cycle of buildings, and utilizes the United States Green Building Council's Leadership in Energy and Environmental Design (LEED) green building rating system to demonstrate one possible green rating system [25]. CEE 1218 is a topical course that introduces students to concepts of design for environment tools and also includes in-depth investigations such as residential energy assessments. The Engineering and Sustainable Development (ESD) class and ASU's ESEM class are very similar in course content; the instructors are authors on this paper and collaborated in developing the classes. More recently, UPitt's Provost selects a theme to integrate throughout all curricula and activities; UPitt dedicated the 2014-2015 academic year to sustainability.

Table 10. University of Pittsburgh Sustainability in Civil and Environmental Engineering Curriculum.

	Term	Course Number	Course Name	#
CEE Required Courses	Term 1	ENGR 0011	Introduction to Engineering Analysis	3
	Term 2	ENGR 0012	Introduction to Engineering Computing	3
	Term 3	ENGR 0020	Probability and Statistics for Engineers	4
		ENGR 0131	Statics for Civil and Environmental Engineers	4
		IE 1040	Engineering Economic Analysis	3
		CEE 1503	Introduction to Environmental Engineering	3
	Term 4	CEE 1105	Materials of Construction	3
		ENGR 0141	Mechanics of Materials in CEE	3
		CEE 0109	Computer Methods in CE 1	3
	Term 5	CEE 1330	Introduction to Structural Analysis	3
		CEE 1402	Fluid Mechanics	3
		CEE 1811	Principles of Soil Mechanics	3
		ENGR 0151	Dynamics for CEE	3
	Term 6	CEE 1200	Construction Management	3
		CEE 1412	Hydrology & Water Resources	3
		CEE 1209, 1210, 1217, 1218	Sustainability Course: Life Cycle Assessment Methods and Tools, Engineering and Sustainable Development, Green Building Design and Construction, Design for Environment	3
		CEE 1703	Transportation Engineering	3
		Design Elective	Structural, Water Resources, Enviro., Geotech., OR Pavement	3
	Term 7	Design Elective	Structural, Water Resources, Enviro., Geotech., OR Pavement	3
		Design Elective	Structural, Water Resources, Enviro., Geotech., OR Pavement	3
		Design Elective	Structural, Water Resources, Enviro., Geotech., OR Pavement	3
		Engr Elective	Any engineering elective course	3
	Term 8	CEE Elective	Any non-required CEE or ENGR course	3
		CEE 1233/ 1333/ 1433/ 1533/ 1733/ 1833	Senior Design	3
CEE Elective		Any non-required CEE or ENGR course	3	
CEE Elective		Any non-required CEE or ENGR course	3	
CEE Elective	Term 8	CEE 1209	Life Cycle Assessment Methods and Tools	3
		CEE 1210	Engineering and Sustainable Development	3
		CEE 1217	Green Building Design and Construction	3
		CEE 1218	Design for Environment	3

University of Pittsburgh’s Civil and Environmental Engineering (CEE) curriculum includes one required stand-alone sustainable engineering undergraduate course; students select from one of the following courses: Life Cycle Assessment (LCA), Engineering and Sustainable Development (ESD), Green Buildings Design and Construction (GB), Design for the Environment (DFE), or Engineering for a Better Environment-Brazil (EBE). Students may also choose to fulfill CEE/ENGR elective credits required during terms 7 and 8 of their senior year with sustainability courses while still maintaining graduation requirements. Non-engineering required (e.g., Math, Physics) and elective courses are not listed. Sustainable engineering courses are highlighted in green. Senior design course is highlighted in blue.

The Civil and Environmental Engineering Department at UPitt requires all students to participate in the senior design course (CEE 1233/1333/1433/1533/

1733/1833). Students work in teams of five to seven people per project. Each student takes on a civil engineering sub-discipline role within his or her larger senior design team. The teams are partnered with a local engineering firm or associate; the firm supports students throughout their projects through mentorship and exposure to ‘real-world engineering’. The senior design project at UPitt encompasses a comprehensive engineering design simulated from real-world engineering projects. Students write a comprehensive report and present their project at the end of the semester. Sustainability is embedded in one section of the UPitt senior design project rubric; UPitt students are requested to consider constraints, one of which includes sustainability. A total of 106 students participated in UPitt senior design during Spring 2014 (43), Fall 2014 (27), and Spring 2015 (36) semesters.

Collection of Student Reports

Students turned in their final senior design projects to their instructor on presentation day during the last week the Spring 2014, Fall 2014 and Spring 2015 semesters. The authors collected the student reports after the completion of each course from the instructors. The same instructors taught senior design during the three semesters of this study; similarly the rubric and expectations given to the students remained the same during each semester at both universities. The projects and firms were different for every project team.

Mixed-Methods Assessment

Observation of Student Presentations

Students in senior design courses at both ASU and UPitt present their final projects to an audience of engineering professionals, their instructor and other engineering faculty on a single day at the end of the Spring 2014, Fall 2014, and Spring 2015 semesters. The authors viewed all student presentations each semester and recorded their observations for sustainability content using a developed observation sheet. The observations of student presentations were in part used to develop and refine the rubric, which was then used to evaluate the sustainability aspects of the student projects. The observation sheet contained the following five columns, which were used to guide notes taken during the presentation:

1. Presentation title
2. Sustainability Concepts Incorporated (Yes: please describe, or No)
3. Was sustainability in the project client-driven, student-driven or other? (Client, Student, Rubric, or Other: please describe)
4. Calculation or superficial incorporation of sustainability? (Calculation: please describe or Superficial: please describe)
5. Source/reference cited for sustainability concept (Yes or No)

Due to the number of students in each semester of senior design at ASU, student presentations were split into two concurrent sessions, with one final presentation that everyone observed. The authors divided themselves between the rooms during the concurrent sessions and, to address consistency between author notes, all authors observed the final presentation together and compared notes afterwards. UPitt students presented their final projects in one session each semester; the authors were able to compare notes for each presentation.

Development of Sustainability Rubric

The rubric was developed to assess the sustainability content within students' senior design projects. The rubric was developed in two phases; phase one derived best practices from a literature review of methods to assess sustainability content in student projects, and phase two developed new sustainability assessment measures and integrated them with best practices to create a holistic assessment tool.

Phase one of rubric development mined best practices from literature approaches used to assess the sustainability content of student projects, which are summarized in the top half of the rubric described in Table 11. Bielefeldt 2013 utilized *Dimensions of Sustainability* to assess the pillars of sustainability (environmental, economic, social) and the number of times (“no evidence” = no mention, “weak” = mentioned but no specific example, “fair” = mentioned one example, “good” = mentioned multiple examples) these concepts were incorporated into students' projects [9]. In addition, *Bloom's Taxonomy* was utilized to assess levels of intellectual behavior within the student homework assignments (“knowledge,” “comprehension,” “application,” “analysis,” “synthesis,” or “evaluation”) [19, 20]. McCormick et al 2014 utilized *Sustainability Links* to evaluate the linkages between the three pillars of sustainability, including “concepts” (societal, economic, environmental), “crosslinks” (societal-economic, environmental-economic, societal-environmental) and “interdependency” (societal-economic-environmental) [8]. McCormick et al 2014 did not include a “no evidence” response option; the authors added this option. Table 11 reflects these three approaches to assess *Dimensions of Sustainability*, *Bloom's Taxonomy*, and *Sustainability Links* in student projects as criteria 1-3, respectively.

Phase two of rubric development created additional sustainability assessment items based on the authors' expertise and experience in sustainability. During observation of student presentations, the authors took notes on who seemed to drive the inclusion of sustainability, which was used to develop the rubric category, *Drivers for Including Sustainability*, which aims to gain insight into the motivating actors for incorporating sustainability into student report. In the rubric, drivers can include "student," "client," "other" and the combination of "rubric/instructor." The rubric also documented where and to some extent how sustainability was integrated into student reports in the category, *Location of Sustainability Within Report*. Location assesses whether sustainability was "integrated throughout the report" or present in a "stand-alone section" only. The depth to which students apply sustainability was added to the rubric in the category *Quantitative/Qualitative Incorporation*. This category evaluates whether sustainability was incorporated into the project via calculations and quantitative methods or superficial, qualitative methods for each of the three pillars of sustainability. Another rubric category for evaluating the depth to which students address sustainability reviews reports for references: the *Sustainability Source/Reference* category looks for sustainability citations. A list of sustainability topics, shown in Table 11, based on topics taught in students' sustainable engineering courses were used to create the rubric category *Sustainability Topics*. These topics were tracked as "implicitly presented" where students did not call out the topic directly but were discussing the topic, or "explicitly presented" where students directly described the topic in their report. Six "other" topics not covered in the stand-alone classes were added during the review of student projects based on common topics present in the student presentations, including "other - recycling, - water reuse, -

energy reduction, - urban heat island effect, - alternative transportation, - consider needs of people/stakeholder engagement. The final criteria on the rubric tracked *NAE Grand Challenges of Engineering Topics* present in student reports through implicit mention without calling out Grand Challenge and explicit description of Grand Challenge.

Bloom's Taxonomy

Bloom's taxonomy provided a measurement scheme through which students' levels of intellectual behavior were assessed. Bloom's taxonomy is divided into six compartments, including "knowledge," "comprehension," "application," "analysis," "synthesis," and "evaluation" [19]. These levels were used within the rubric developed herein to create six Bloom's cognitive levels. Projects were coded based on which of the six levels of Blooms students achieved; "knowledge" was coded if a student recalled a vocabulary term, "comprehension" was coded by discussion of vocabulary terms, "application" was coded by applying knowledge of vocabulary to design or problem-solve, "analysis" was coded by identification of patterns and trends, "synthesis" was coded by using old concepts to create new ideas, and "evaluation" was coded by comparing ideas or assessing theories.

Dimensions of Sustainability

Bielefeldt's Dimensions of Sustainability were used to quantify the number of times a pillar of sustainability (economic, environmental, and social) was discussed in student reports. Students' examples of dimensions of sustainability were judged on four criteria, including "no evidence" = no mention of sustainability dimension, "weak" =

mentioned dimension but no specific example was given, “fair” = mentioned one example related to that dimension, and “good” = mentioned multiple examples [9].

Sustainability Links

McCormick’s Sustainability Links were used to assess the connections and interrelatedness between the three dimensions of sustainability. Students’ examples of sustainability links were judged on three criteria, including “concept” = discussion of a topic(s) in relation to a single sustainability pillar, “crosslink” = discussion of a topic(s) in relation to two sustainability pillars, and “interdependency” discussion of a topic(s) in relation to all three sustainability pillars [8]. “Concepts” were defined as comprehension of sustainability topic in relation to a pillar of sustainability. As such, a project must demonstrate comprehensions by scoring “fair” or “good” in Dimensions of Sustainability to score concept-level in Sustainability Links. “Crosslinks” were defined as explicit or implicit discussion of two or more pillars of sustainability and their interaction. Students could achieve crosslinks through several avenues; students may explicitly describe the interconnectivity of two dimensions of sustainability in a single sentence or through several paragraphs implicitly link the two pillars of sustainability. “Interdependency” was defined as demonstrating knowledge of interconnectivity between the three dimensions of sustainability in the context of each project. As such, demonstration of interdependency necessitated demonstrating crosslinks, but demonstrating crosslinks did not always result in interdependency demonstration in all three pillars of sustainability.

Table 11. Sustainability Rubric Developed to Assess Student Application of Concepts.

Criteria		Possible Score
1. Dimensions of Sustainability (Bielefeldt 2013)	Environmental	No Evidence, Weak, Fair, Good
	Economic	
	Social	
2. Cognitive levels of sustainability topics incorporated (Anderson et al 2001)		1. Knowledge (recall of information)
		2. Comprehension (demonstrating, discussing)
		3. Application (applying knowledge, designing, experimenting)
		4. Analysis (recognizing trends and patterns)
		5. Synthesis (using old concepts to create new ideas)
		6. Evaluation (assessing theories and outcomes)
3. Sustainability Links (McCormick et al 2014)	No Evidence	
	Concepts	Societal
		Economic
		Environmental
	Crosslinks	Societal-Economic
		Economic-Environmental
		Environmental-Societal
Interdependent	Societal-Economic-Environmental	
4. Was sustainability in the project client-driven, student-driven or other?		Student
		Client
		Other
		Rubric / Instructor
5. Was sustainability integrated throughout report or stand-alone section of the report?		Sustainability was integrated throughout sections
		Sustainability was stand-alone section in report
6. Quantitative or qualitative incorporation of sustainability?	Environmental	Quantitative Qualitative
	Economic	
	Social	
7. Source/ reference cited for sustainability concept		Yes
		No
8. Sustainability Topics (explicit/ implicit)	Sustainable Agriculture, Sustainable Land Use, Industrial Ecology, Corporate Sustainability, Climate Change, Renewable Energy, Green Buildings, Sustainability Infrastructure, Green Construction, LCA (Life Cycle Assessment), Material Flow Analysis, Natural Resource Depletion (or Scarcity), Pollution Prevention, Design for the Environment, Green Chemistry, Environmental Justice, Embedded/Virtual Water Use, Anthropogenic Environmental Impacts, Sustainability Rating Schemes (e.g. LEED), Resilience, Urbanization/urban sprawl, Sustainability economics, Governance for sustainability, Sustainable Innovation, Sustainability Ethics, Other 1- recycling, Other 2- water reuse, Other 3- energy reduction, Other 4- Urban heat island effect, Other 5- alternative transportation, Other 6- consider needs of people/ stakeholder engagement, None of the above	
9. NAE Grand Challenge (called out or not)	Make solar energy economical, Provide energy from fusion, Develop carbon sequestration methods, Manage the nitrogen cycle, Provide access to clean water, Restore and improve urban infrastructure, Advance health informatics, Engineer better medicines, Reverse-engineer the brain, Prevent nuclear terror, Secure cyberspace, Enhance virtual reality, Advance personalized learning, Engineer the tools of scientific discovery, None	

Students' senior design projects were evaluated via rubric to assess the sustainability content in the reports. The rubric included dimensions of sustainability (Bielefeldt 2013), Bloom's taxonomy (Anderson et al 2001), links (McCormick et al 2014), motivations, quantitative/qualitative incorporation of sustainability, references, and topics and NAE Grand Challenges of Engineering. Students had to score fair or good in dimensions of sustainability to be considered concept-level or greater in sustainability links.

Evaluation of Student Reports via Rubric

Four graduate students evaluators utilized an approach similar to Inter-Rater Reliability (IRR) ensure that the evaluation and scoring of all 43 projects was consistent. IRR is defined as the process through which two or more raters classify subjects or objects independent of one another [26]. High IRR verifies that the raters can be used interchangeably, thereby establishing the rater as an abstract entity to the main focus of study, the subjects [26, 27]. Utilizing an IRR-like approach, the rubric was applied to senior design projects in five steps; in step one three out of four evaluators scored one senior design project together, in step two the same three evaluators scored the same senior design project separately and met to discuss results, in step the same three evaluators scored a different project and met to discuss results, and in step four the evaluators scored the rest of the projects and met to review all results. In step five, a fourth graduate student evaluator was utilized to score random senior design projects to ensure consistency amongst the previous three evaluators.

ASU and UPitt senior design reports from Spring 2014 and Fall 2014 were divided evenly between three evaluators such that every person reviewed several projects from both of these semesters. During Spring 2015 projects were gathered in paper format; evaluations were completed at each institution and not split among evaluators.

Evaluation of Student Perceptions of Sustainability via Survey

The survey questions, shown in Table 12, included multi-response, open-response and Likert-scale questions [25]. Students in the Fall 2014 and Spring 2015 classes at

ASU and UPitt took the anonymous, digital survey via Survey Monkey during the last week of the senior design course (students in Spring 2014 were not surveyed). The survey questions assessed student perceptions of their engineering curriculum, including course content that covered sustainability topics related to engineering and NAE Grand Challenges of Engineering, interests in addressing sustainability and Engineering Grand Challenges in their career along with ideal future career. The average survey response rate for Fall 2014 at ASU was 20% and UPitt was 26%. The average survey response rate for Spring 2015 at ASU was 30% and UPitt was 11%.

Table 12. Post-Course Survey Questions.

Question	Possible Response
1. Based on credit hours, I am currently a:	Undergraduate- Junior, -Senior
2. What is your current major, if you have declared one? Please (select all that apply)	Computer science, Construction management, Engineering - Aerospace, - Biomedical, - Civil, - Civil and environmental, - Chemical, - Computer systems, - Construction, - Environmental, - Electrical, - Geotechnical, - Industrial, - Material science, - Mechanical, - Structural, - Transportation, Geography, Planning, Sustainability, Other (please specify)
3. What is your current minor, if you have declared one? Please describe with as much detail as possible.	Open-Ended Response
4. If you have an undeclared minor or focus, what is it? Please describe with as much detail as possible.	Open-Ended Response
5. Since starting your current degree plan (e.g. BA/BS or MS/PhD), what percentage of your course content covered sustainability topics related to engineering?	0-20%, 21-40%, 41-60%, 61-80%, 81-100%
6. Since starting your current degree plan (e.g. BA/BS or MS/PhD), how was sustainability covered in your courses? (select all that apply)	My instructor did not cover it, Lecture, Syllabus, Case Studies, Open-ended questions, Discussions, Projects, Homeworks, Readings, Other
7. Since starting your current degree plan (e.g. BA/BS or MS/PhD), what NAE Grand Challenges for Engineering have you covered using one or more of the following methods: lecture, syllabus, case studies, open-ended questions, discussions, projects, homeworks, reading? (select all that apply)	Make solar energy economical, Provide energy from fusion, Develop carbon sequestration methods, Manage the nitrogen cycle, Provide access to clean water, Restore and improve urban infrastructure, Advance health informatics, Engineer better medicines, Reverse-engineer the brain, Prevent nuclear terror, Secure cyberspace, Enhance virtual reality, Advance personalized learning, Engineer the tools of scientific discovery, None
8. Since starting your current degree plan (e.g. BA/BS or MS/PhD), what NAE Grand Challenges for Engineering are you most interested in learning about OR wish you had learned more about in your courses? (select all)	
9. I can envision myself finding a career that creates solutions for one (or more) of the NAE Grand Challenges for Engineering. (select one)	Very Likely, Likely, Neutral, Unlikely, Very Unlikely
10. When you graduate from your current degree plan, what is your IDEAL future career? (be specific)	Open-Ended Response
11. I can envision using sustainability concepts within my future career. (select one)	Very Likely, Neutral, Not At All Likely
12. I feel excited to bring sustainability concepts from my college courses to other aspects of my life (e.g. implement energy-saving practices at my apartment). (select one)	Yes, Somewhat, No

Students took the anonymous survey during the last week of the senior design course. The survey was administered digitally via email and Survey Monkey. Survey questions covered student perceptions of their engineering curriculum, including exposure to and interest in sustainability and NAE Grand Challenges of Engineering in their future careers and a description of students' ideal future career.

Results and Discussion

The rubric developed herein provides a method for evaluating student projects for knowledge of sustainability topics, level of cognitive use of sustainability, and students' ability to apply sustainability at different depths such as showing linkages across sustainability pillars or their use of quantitative versus qualitative methods. Results are discussed by each category of the rubric, presented in Figures 20-27.

Dimensions of Sustainability

Students' senior design projects were scored on the *Dimensions of Sustainability* to understand students' incorporation of environmental, economic, and social pillars of sustainability. Projects were assigned one of the following scores: "no evidence" = no mention, "weak" = mentioned but no specific example, "fair" = mentioned one example, or "good" = mentioned multiple examples based on the definitions provided [9]. The results (Figure 20) show that the majority of ASU senior design projects scored "good" in environmental pillar (79%), "fair" in economic pillar (54%), and "weak" in social pillar (32%). In comparison, the majority of UPitt senior design projects scored "fair" in social pillar (53%), "weak" in economic pillar (53%), and "weak" in environmental pillar (40%). ASU and UPitt senior design projects most often discussed examples for one to two pillars; rarely did a single project discuss all three pillars of sustainability (environmental, social, and economic), despite exposure to all three pillars of sustainability within their stand-alone sustainable engineering course.

ASU and UPitt senior design projects most often discussed examples from one or two pillars; rarely from all three pillars of sustainability (environmental, social, and

economic), despite exposure through stand-alone and course modules dedicated to sustainability. Senior-level students are expected to discuss multiple dimensions of sustainability reaching “fair” or “good” levels.

Students from ASU performed strongest in environmental, followed by economic and social, while UPitt projects were strongest in economic, followed by environmental, and social. Students’ association of sustainability with environmental impacts more than other dimensions, compounded by the ease of quantifying or connecting environmental issues, led to 100% of senior design projects discussing environmental aspects.

Discussing economic issues in the context of sustainability was primarily done through cost comparison of different project scopes, which is a general rubric requirement for projects to provide cost analysis. UPitt projects performing stronger in economic than environmental is correlated to the rigidity of project descriptions, such as designing bridges or installing water systems, in addition to minimal incorporation of sustainability in the rubric. Lastly, social aspects of sustainability are weakest at both universities.

While UPitt projects do a better job of incorporating social sustainability, it is difficult to measure students’ true understanding of social sustainability, because these projects inherently address social aspects (e.g. access to clean water, engaging stakeholders, or sustainability ethics) through sustainability driven clients. While students discussed some social elements it is possible they do not make the necessary connection between their project goals and societal implications. However, these outcomes are in line with hypothesized outcomes, where students show strong discussion in the environmental pillar followed by economic, and weak correlation in the social pillar.

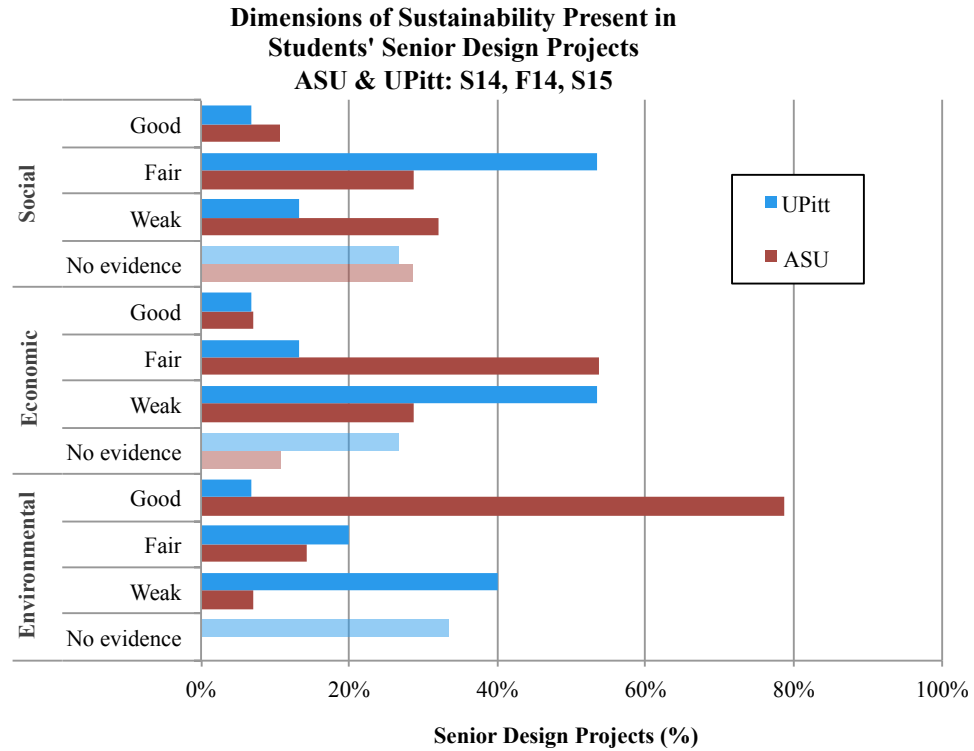


Figure 20. Dimensions of Sustainability Present in Senior Design Projects.

Arizona State University (ASU, $n = 181$ students, $n_p = 28$ projects) and University of Pittsburgh (UPitt, $n = 106$ students, $n_p = 15$ projects) senior design projects were collected from the course instructors at the end of the Spring 2014, Fall 2014, and Spring 2015 semesters. Projects were evaluated via rubric by three evaluators with expertise in sustainable engineering. The rubric evaluated the projects for *Dimensions of Sustainability* to understand students' incorporation of environmental, economic, and social pillars of sustainability. Projects were assigned one of the following scores: "no evidence" = no mention, "weak" = mentioned but no specific example, "fair" = mentioned one example, or "good" = mentioned multiple examples based on the definitions provided [9].

Bloom's Taxonomy

Students' senior design projects were scored based on *Bloom's Taxonomy* to document students' overall level of application of sustainability concepts. Projects were assigned one of the following scores: "knowledge," "comprehension," "application," "analysis," "synthesis," or "evaluation" [19, 20]. The results (Figure 21) show that 57% of ASU projects apply sustainability concepts at the "comprehension" level; these concepts were demonstrated through understanding of knowledge. In addition, 73% of UPitt projects apply sustainability concepts at the "knowledge" level; these concepts

were demonstrated through recall of knowledge. The American Society for Civil Engineering (ASCE) Body of Knowledge 2nd edition (BOK2) suggests that civil engineering students will reach up to Bloom's level "application" for sustainability concepts by their senior undergraduate year [17]. While 14% of ASU and 13% of UPitt senior design projects reach "application" of sustainability and apply knowledge in new ways, the overwhelming majority of projects for both institutions do not reach this level. This issue may be addressed by providing more examples of higher Bloom's levels of sustainability applied to engineering design and/or requiring that students reach higher levels of sustainability application within their senior design projects through a combination of instructor request and course syllabus/project rubric requirements.

While 14% of ASU and 13% of UPitt senior design projects reach "application" of sustainability and apply knowledge in new ways, the overwhelming majority of projects for both institutions do not reach this level. Senior design projects are a culmination of students' academic career, where they are asked to incorporate civil and environmental engineering learning into a multi-faceted project. Limited incorporation of sustainability by instructors into the semester-long classroom furthered by minimal rubric weighting, leads project focus towards those rubric categories that benefit their final grade. Additionally, stand-alone sustainability courses may not provide students with understanding of the relationship between sustainability and their core civil engineering curriculum, thereby hindering students' abilities to design, experiment, and analyze results (i.e. reaching "application"). This issue may be addressed by providing more examples of higher Bloom's levels of sustainability applied to engineering design and/or requiring that students reach higher levels of sustainability application within their

senior design projects through a combination of instructor request and course syllabus/project rubric requirements.

According to BOK2, students are expected to reach “analysis” during their post-undergraduate work experience [17]. “Analysis” builds on modeling and experimentation through further identification, understanding, and interpretation of results. “Synthesis” and “evaluation” represent the highest levels of intellectual behavior and are typically associated with graduate-level study. These levels of cognition are not expected in senior design projects; “synthesis” would be demonstrated through the proposal of research, while “evaluation” would be demonstrated through comparing ideas and assessing theories-

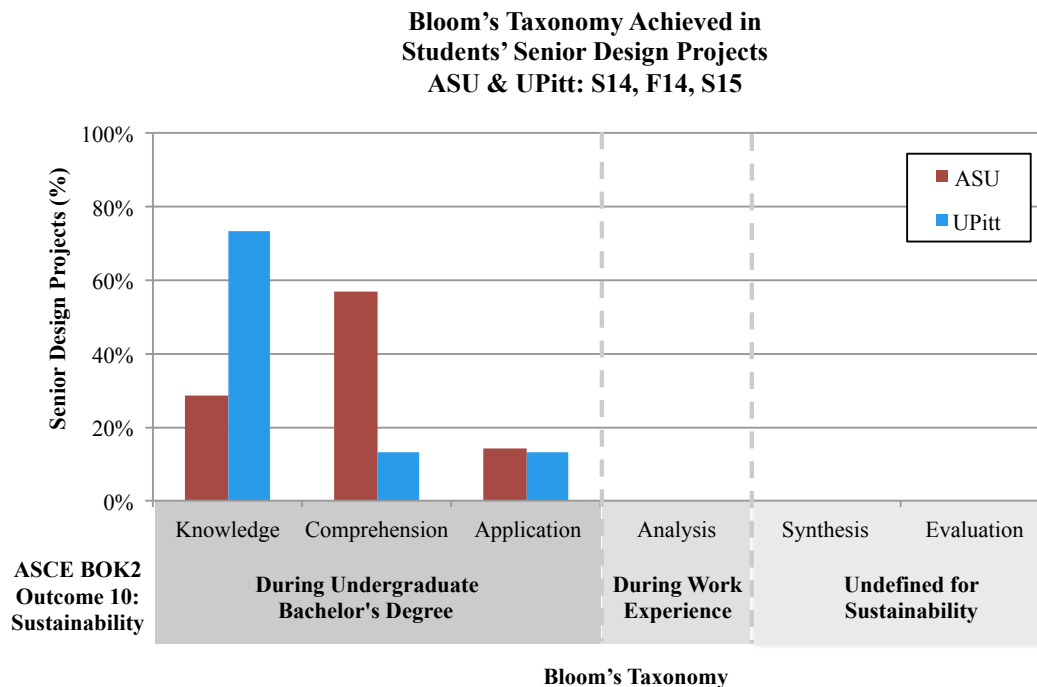


Figure 21. Bloom’s Taxonomy Achieved in Senior Design Projects. Arizona State University (ASU, n = 181 students, n_p = 28 projects) and University of Pittsburgh (UPitt, n = 106 students, n_p = 15 projects) senior design projects were collected from the course instructors at the end of the Spring 2014, Fall 2014, and Spring 2015 semesters. Projects were evaluated via rubric by three evaluators with expertise in sustainable engineering. The rubric evaluated the projects for *Bloom’s Taxonomy* to understand students’ overall level of application of sustainability concepts. Projects were assigned one of the following scores: “knowledge,” “comprehension,” “application,” “analysis,” “synthesis,” or “evaluation” [19, 20].

Sustainability Links

Students' senior design projects were evaluated on the linkages between the three pillars of sustainability, including "concepts" (societal, economic, environmental), "crosslinks" (societal-economic, environmental-economic, societal-environmental) and "interdependency" (societal-economic-environmental) [8]. Because the definition for "concepts" was "recognition of the need to..." projects were required to first score "fair" or "good" in *Dimensions of Sustainability*, shown in Figure 20, to be considered "concept"-level or greater in *Sustainability Links*. As a consequence, projects with "no evidence" or "weak" evidence received "no evidence" scores for sustainability links, shown in Figure 22. ASU results show 93% of projects displayed environmental concepts (100% projects showed environmental *Dimensions of Sustainability* however 7% of projects did not demonstrate recognition of environmental concepts), 61% of projects displayed economic concepts, and 39% of projects displayed social concepts related to sustainability. None of the ASU senior design projects displayed interdependency between all three pillars of sustainability, however the most common (21%) cross-link was between environmental-social. UPitt results show 60% of projects displayed social concepts, 27% of projects displayed environmental concepts, and 20% of projects displayed economic concepts related to sustainability. None of the UPitt senior design projects displayed interdependency between all three pillars of sustainability, and both environmental-social and economic-social pillars had the most linkages (13% each). No sustainability links were present in 7% of ASU projects and 33% of UPitt projects. ASU and UPitt students are exposed to the linkages between sustainability pillars in their stand-alone sustainable engineering courses. At ASU the required sustainability course

(ESEM) that all students take covers all three pillars of sustainability; while the UPitt equivalent course (ESD) covers all three pillars, not all UPitt students take ESD.

ASU and UPitt students are exposed to the linkages between pillars in their sustainable engineering courses. Students' deficiency in demonstrating these crosslinks perpetuates the notion that instructors and rubric drive students' incorporation of sustainability into their project designs. Discussed in a later section, many projects incorporated sustainability into a separate section near the end of the project reports, containing minimal information, suggesting that sustainability was an afterthought, done only to meet rubric requirements. These findings suggest a need for deeper penetration of sustainability into instructor-student interaction time typically through class time, and succinct incorporation of sustainability requirements (i.e. quantitative and qualitative analysis) to the project rubric.

Sustainability Links Present in Students' Senior Design Projects
ASU & UPitt: S14, F14, S15

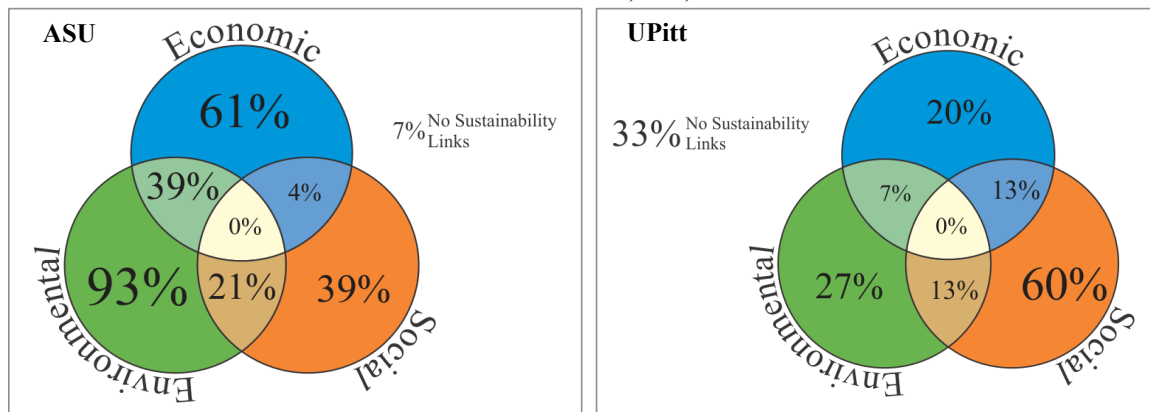


Figure 22. Sustainability Links Present in Senior Design Projects. Arizona State University (ASU, $n = 181$ students, $n_p = 28$ projects) and University of Pittsburgh (UPitt, $n = 106$ students, $n_p = 15$ projects) were collected from the course instructors at the end of the Spring 2014, Fall 2014, and Spring 2015 semesters. Projects were evaluated via rubric by three evaluators with expertise in sustainable engineering. The rubric evaluated the projects for *Sustainability Links* between the three pillars of sustainability. Projects were assigned one of the following scores: “concepts” (societal, economic, environmental), “crosslinks” (societal-economic, environmental-economic, societal-environmental) and “interdependency” (societal-economic-environmental) [8] and “no evidence”. Projects needed to score fair or good in *Dimensions of Sustainability* to be considered concept-level or greater in *Sustainability Links*.

Drivers for Including Sustainability

The reason that students decided to include sustainability in their report was determined by reviewing the class rubric and students’ reports. The rubric category, *Drivers for Including Sustainability*, evaluates whether sustainability was integrated based on student interest (i.e. students demonstrated personal motivation towards sustainability), client request (i.e. client mission statement addressed sustainability), rubric/instructor driven (i.e. rubric requires students to demonstrate underlying rationale behind incorporating sustainability and/or requires specific sustainability sections), or other (could also include projects that do not address sustainability). Projects could have multiple drivers. The findings show that all ASU projects incorporated sustainability in the sections required by the senior design rubric, which results in 100% of projects being

rubric/instructor driven, while 21% of projects were student driven and 21% client driven. Conversely, only 40% of senior design projects from UPitt were determined to have rubric/instructor as the driver for sustainability. At Pitt, 33% of all projects were student driven, 33% were client driven, and 7% “other,” which documented non-sustainability drivers for the senior design project. The results show that the instructor and the rubric used in senior design has significant influence on drivers for incorporating sustainability within the senior design projects. ASU’s rubric requires an explicit stand-alone section on sustainability; all student reports delivered on this requirement, though to different extents. Thus, reports showed higher instance of sustainability linkages. In comparison, UPitt’s rubric requires that students address sustainability, but it is embedded within the rubric under ‘addressing constraints’ for the overall project, not within each subdiscipline.

Location of Sustainability Within Report

Students’ senior design projects were evaluated for the *Location of Sustainability Within Report* as an indicator of the depth to which students apply sustainability beyond their standalone class. Senior design reports were scored based on how sustainability was integrated into the report, where the report either “integrated” sustainability throughout the report or “stand-alone” where sustainability was only in a single section of report. Reports could score either or both, depending on the location of sustainability. Sustainability was discussed in a stand-alone section for 100% of ASU reports; 25% of ASU reports discussed sustainability throughout the entire report in addition to discussions within the stand-alone sections. Conversely, 27% of UPitt reports discussed

sustainability in a stand-alone section while 67% of reports discussed sustainability throughout the report. Seven percent of UPitt reports did not present any sustainability concepts in the report. Similar to *Drivers for Including Sustainability*, the project rubric has significant influence location of sustainability within the senior design projects. All ASU senior design project reports discussed sustainability in stand-alone sections as required by their rubric. In comparison, while required by the rubric to discuss constraints including, but not limited to, sustainability, 27% UPitt senior design projects discussed sustainability in stand-alone sections. As a result, sustainability was better woven throughout the project.

Qualitative/Quantitative Incorporation

Quantitative and qualitative incorporation of environmental, economic and social pillars of sustainability within students' senior design projects are presented in Figure 23. Students' senior design projects were scored for quantitative and qualitative incorporation of sustainability on a binary scale (0 = no evidence, 1 = evidence). The results show that all pillars of sustainability were incorporated qualitatively at both universities and that ASU projects incorporated environmental and economic concepts quantitatively while UPitt projects incorporated only economic quantitatively. This finding suggests that students default to qualitative descriptions of sustainability rather than quantified metrics. The standalone classes that students are required to take include quantitative approaches to economic and environmental sustainability, so students should have these tools available to them. However, students may need additional examples of how to address sustainability through quantities in addition to qualities, thus greater emphasis should be

placed on providing qualitative and quantitative applications of sustainability to senior design reports.

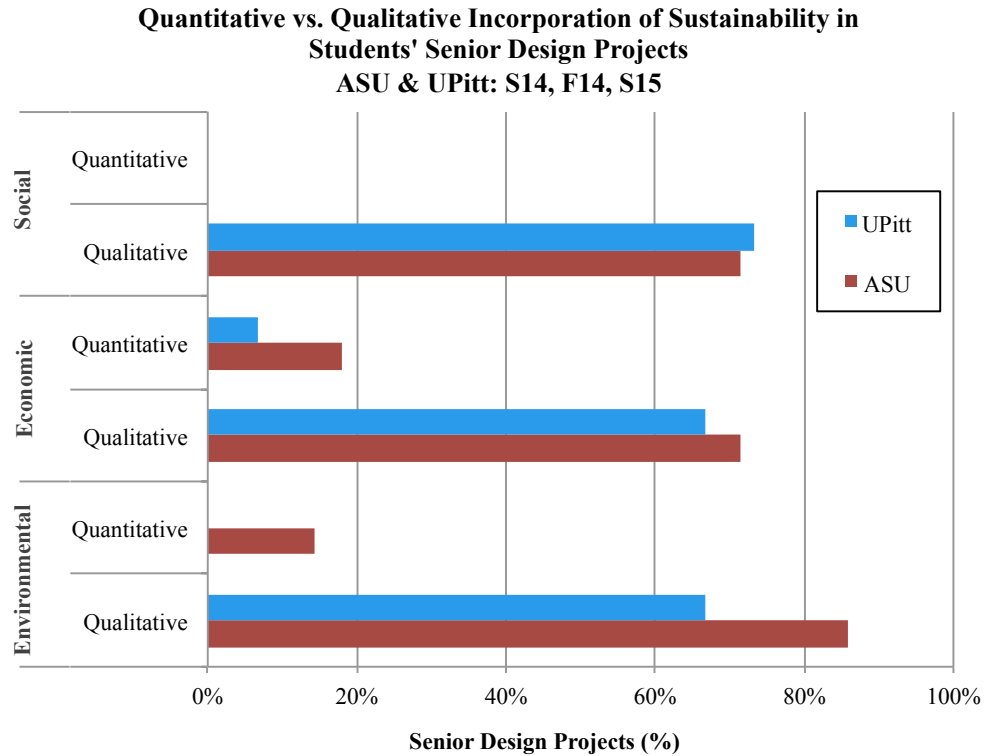


Figure 23. Quantitative/Qualitative Incorporation of Sustainability in Senior Design Projects. Arizona State University (ASU, n = 181 students, n_p = 28 projects) and University of Pittsburgh (UPitt, n = 106 students, n_p = 15 projects) senior design projects were collected from the course instructors at the end of the Spring 2014, Fall 2014, and Spring 2015 semesters. Projects were evaluated via rubric by three evaluators with expertise in sustainable engineering. The rubric evaluated the projects for type of incorporation for each sustainability pillar by tracking “quantitative” and “qualitative” within environmental, economic, and social.

Sustainability Source/Reference

Students’ senior design projects were evaluated for their use of a citation, source, or reference as another method to evaluate the depth to which students apply sustainability. The *Sustainability Source/Reference* rubric category was scored with a binary “yes” or “no” for the presence of at least one reference supporting a sustainability statement or claim. Forty-three percent of ASU students cited a reference for the

sustainability concepts within their senior design projects; common sources include direct references for technologies, manufacturers and metrics for analyzing the sustainability of a product or process. No UPitt students cited a reference for the sustainability concepts within their senior design reports. In the standalone classes at both universities, students are taught how to find and use references within reports. However, the expectations for senior design differ from the standalone courses. A culture of citing sustainability sources should be fostered such that senior-level students understand the science behind sustainability. Rubrics should require sustainability citations in order for students to receive credit for discussing and connecting sustainability to their engineering designs.

Sustainability Topics

Finally, the rubric assessed the number and type of sustainability topics covered within the reports in an effort to understand what concepts students utilize from their standalone classes. These topics were evaluated for the manner in which students included them; either explicitly or implicitly (**Figure 24**). Students' senior design projects were scored for sustainability topics based on topics taught in the students' Civil and Environmental Engineering (CEE) curriculum. The topics were tracked as "implicitly presented" where students did not mention topic directly but were discussing the topic, or "explicitly presented" where students directly mentioned the topic in their report. ASU results show the greatest explicit incorporation of sustainable innovation (SUI), water reuse (WRE), and anthropogenic environmental impacts (AEI) while ASU's implicit incorporation of sustainability focused sustainability infrastructure (SIF), pollution prevention (PPR), and renewable energy (REN). Conversely, UPitt's greatest explicit

incorporation of sustainability focused on stakeholder engagement (SEN), alternative transportation (ALT), and pollution prevention (PPR) while UPitt's implicit incorporation of sustainability focused on sustainability infrastructure (SIF), pollution prevention (PPR), and sustainability economics (SEC). In CEE 400 Earth Systems Engineering and Management, a required sustainable engineering course, ASU civil engineering students are exposed to fifteen sustainability topics and despite this exposure none of the ASU senior design projects incorporated climate change, pollution prevention, corporate sustainability, sustainability economics, sustainable agriculture, green buildings, and industrial ecology. Similarly, UPitt students are required to take one of the following three courses (additional may count toward elective credit): CEE 1209 Life Cycle Assessment Methods and Tools, CEE 1210 Engineering and Sustainable Development, CEE 1217 Green Building Design and Construction, or CEE 1218 Design for Environment. Despite this, UPitt senior design projects incorporated topics of stakeholder engagement, alternative transportation, pollution prevention, sustainability economics, sustainability infrastructure, recycling, sustainable innovation, and green buildings. This finding suggests that despite extensive exposure to sustainability topics within their curriculum in a stand-alone class, students do not apply these topics to their senior design projects. Students demonstrate the level at which their senior design rubric describes, and no more. Greater emphasis on higher cognitive application of sustainability and requirements to demonstrate knowledge of all three pillars may increase the number and level to which students integrate these sustainability topics within their senior design projects.

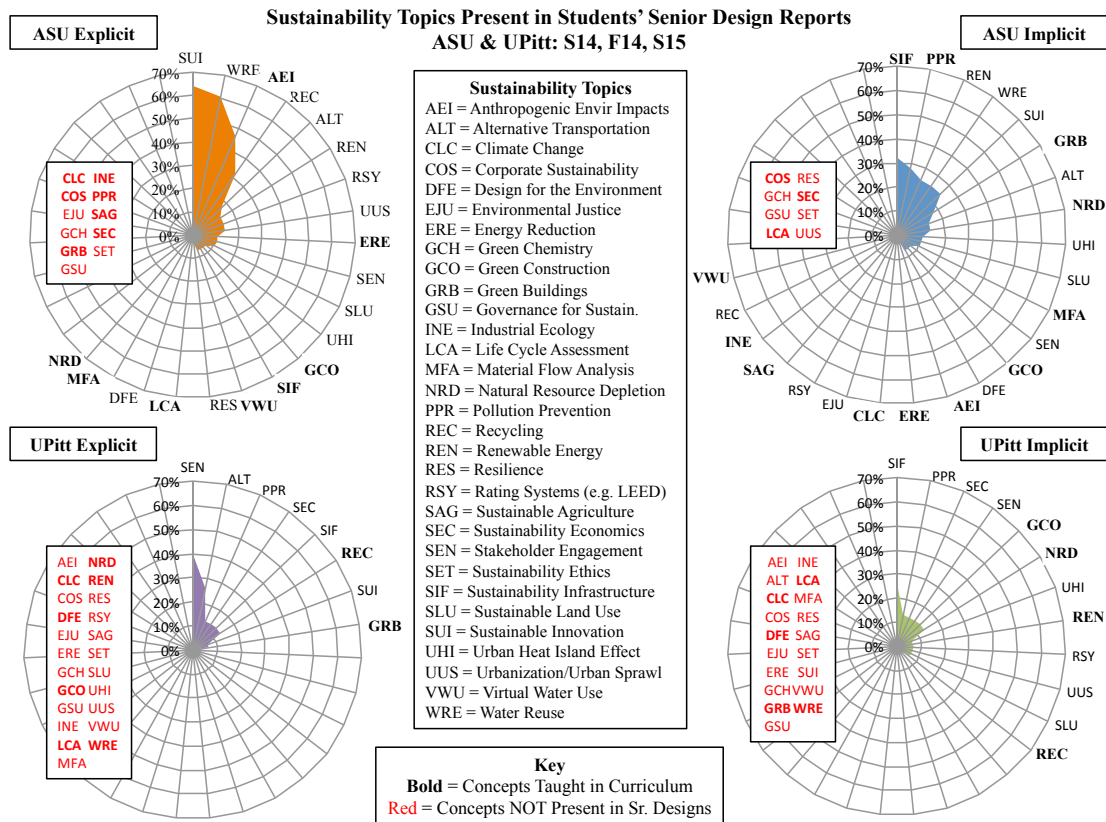


Figure 24. Sustainability Topics Present in Senior Design Projects.

Arizona State University (ASU, $n = 181$ students, $n_p = 28$ projects) and University of Pittsburgh (UPitt, $n = 106$ students, $n_p = 15$ projects) senior design projects were collected from the course instructors at the end of the Spring 2014, Fall 2014, and Spring 2015 semesters. Projects were evaluated via rubric by three evaluators with expertise in sustainable engineering. The rubric evaluated the projects for *Sustainability Topics* incorporated into the students' projects based on topics taught in the students' Civil and Environmental Engineering (CEE) curriculum. The topics were tracked as "implicitly presented" where students did not mention topic directly but were discussing the topic, or "explicitly presented" where students directly mentioned the topic in their report. The topics were given a three letter code and grouped into four categories, "environmental," "governance," "infrastructure," and "materials".

NAE Grand Challenges of Engineering Topics

A total of 28 ASU projects and 13 UPitt projects from Spring 2014, Fall 2014, and Spring 2015 were assessed for explicit (concept included and called out as Grand Challenge) and implicit (concept included but not called out as Grand Challenge) incorporation of NAE Grand Challenges of Engineering. Of the total projects, none of the Grand Challenges were explicitly addressed and only three were implicitly addressed in

the senior design projects; 4% of ASU projects implicitly addressed “manage the nitrogen cycle” and 21% implicitly addressed “restore and improve urban infrastructure” while 33% of UPitt projects implicitly addressed “provide access to clean water” and 47% implicitly addressed “restore and improve urban infrastructure.” This finding suggests that while students’ senior design projects may be addressing some or many components of an NAE Grand Challenge, students are either unaware of the Grand Challenges, unaware of the connection between their project and the Grand Challenge or are not motivated to called out the Grand Challenge, despite reporting the likelihood of a future career creating solutions for one of these challenges. In their required standalone sustainability classes, ASU students are exposed to the Grand Challenges in at least one lecture in ESEM.

Overall results show that students are not demonstrating the ability to apply sustainability or grand challenges learned from their standalone sustainability classes in their senior capstone culminating projects. However, when a sustainability expert served as the project mentor, students incorporated qualitative and quantitative sustainability topics at high cognitive levels (Bloom’s “application” level, as expected by ASCE BOK2), demonstrating that students can apply sustainability successfully to their senior design projects [17]. At ASU, one project in Spring 2014 had a sustainable engineering faculty member as the team mentor. The resulting senior design project showed increased cognitive levels, crosslinks, quantification of environmental and economic pillars, and addressed 40% more sustainability topics than the next highest report (11 explicit and 4 implicit sustainability topics in this single report).

Comparing across the different assessment methods, employing only Bloom's Taxonomy to assess senior design projects results only 14% of projects achieving "application" levels of intellectual behavior. Application is defined in ASCE's BOK2 as the target level for senior undergraduates. In addition, utilizing Bloom's Taxonomy alone masks students' demonstration of understanding the relationship between the three pillars of sustainability. Conversely, utilizing only Dimensions of Sustainability, the senior design projects score favorably; 69% of projects displayed "fair" or "good" evidence for environmental, 47% of projects "fair" or "good" in economic evidence, and 46% of projects "fair" or "good" social evidence. However, by definition this approach only provides a numbered count of topics included in a report and does not provide insight into the cognitive levels of student performance nor the demonstration of interconnectedness between sustainability pillars. Due to the coupled assessment with Dimensions of Sustainability, applying only Sustainability Links results in few crosslinks (28% environmental-economic, 19% environmental-social, and 7% societal-economic) in student projects. The rubric presented herein covers a variety of aspects, including cognitive level, student understanding of topics and the linkages between topics, students' ability to apply and calculate, and students' use of sources to support their ideas.

Post-Course Student Survey

ASU and UPitt senior design students were surveyed at the end of the Fall 2014 and Spring 2015 semesters about their perceptions of sustainability in engineering (Figure 25). The average survey response rate for Fall 2014 at ASU was 20% and UPitt

was 26%. The average survey response rate for Spring 2015 at ASU was 30% and UPitt was 11%. Most ASU and UPitt senior design students surveyed, 92% and 82% respectively, reported that their civil engineering curriculum incorporated 60% or less sustainability. While ASU offers eight elective courses on sustainability in engineering compared to four at UPitt, 18% of UPitt students reported that their curriculum covered 81-100% sustainability. While students recognize that their engineering curriculum incorporates some sustainability, most acknowledge that sustainability is not the major focus for their degree. This raises questions of the level to which engineering students should focus on sustainability while working towards a civil engineering degree.

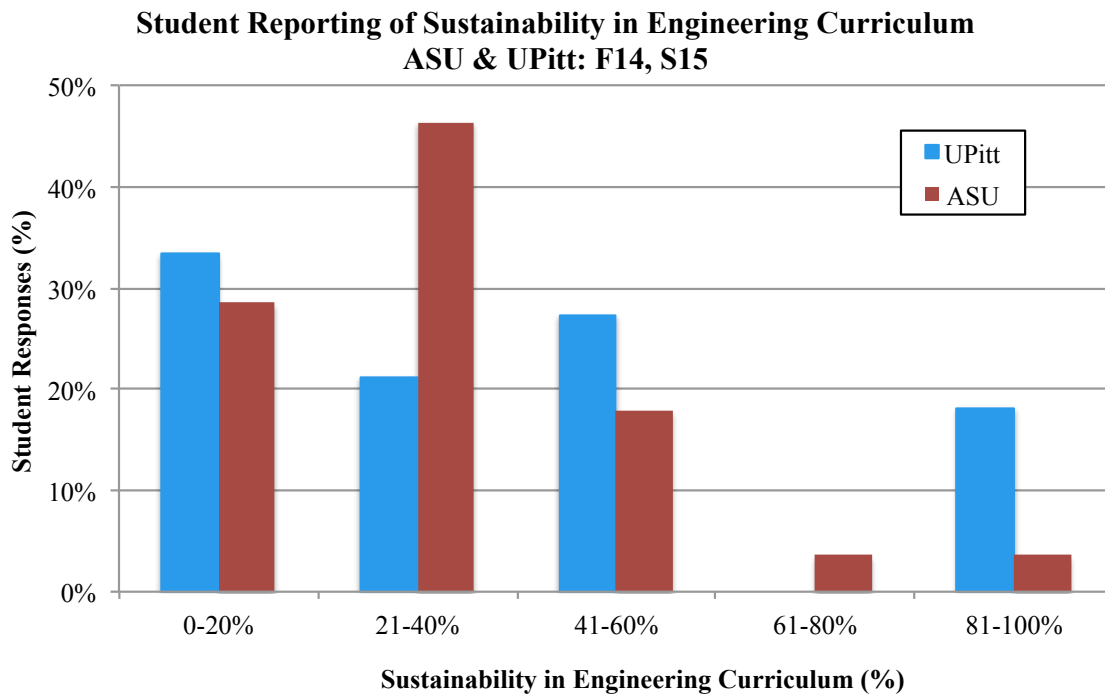


Figure 25. Student Reporting of Sustainability in Engineering Curriculum. Arizona State University (ASU, n = 181 students, n_r = 28 survey respondents) and University of Pittsburgh (UPitt, n = 106 students, n_r = 11 survey respondents) senior design students were surveyed at the end of the Fall 2014 and Spring 2015 semesters on their perceptions of sustainability and NAE Grand Challenges of Engineering in their engineering curriculum and in their future careers. Surveys were delivered digitally via Survey Monkey. Students were asked to select the “percent of sustainability in their engineering curriculum” with one of the following responses: “0-20%,” “21-40%,” “41-60%,” “61-80%,” or “81-100%”.

Results from student reported use of sustainability concepts in their future career are presented in Figure 26. The results show that, of the survey respondents, 87% of ASU and 100% of UPitt students reported either “likely” or “very likely” to use sustainability concepts in their future career. This finding suggests that most senior civil engineering students recognize that sustainability will likely play a role in their future career therefore engineering curriculum should incorporate sustainability in order to produce relevant, 21st century engineers.

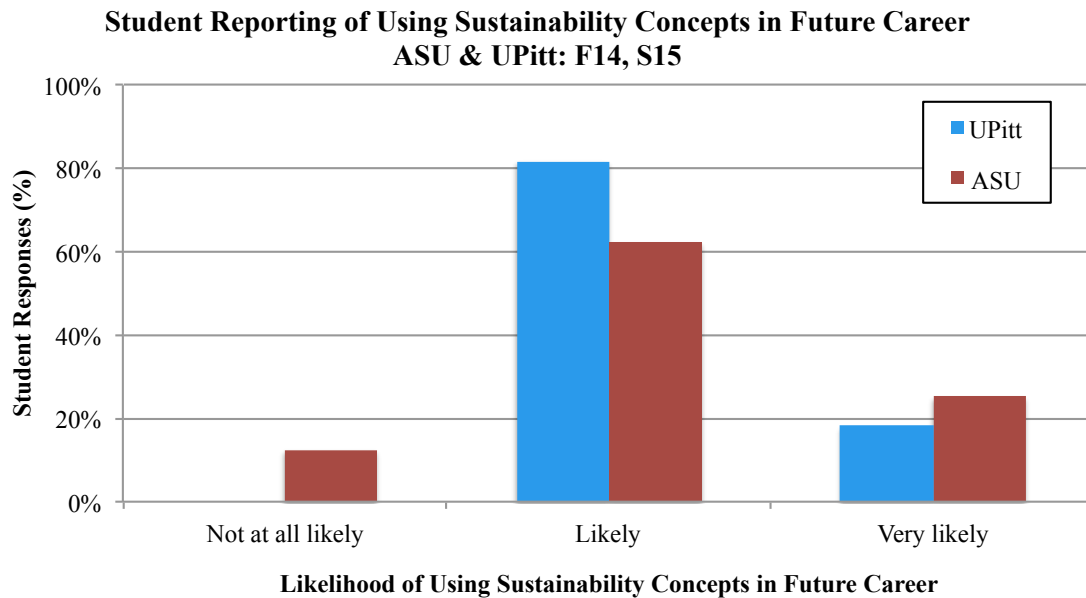


Figure 26. Student Reporting of Using Sustainability Concepts in Future Career. Arizona State University (ASU, n = 181 students, n_r = 28 survey respondents) and University of Pittsburgh (UPitt, n = 106 students, n_r = 11 survey respondents) senior design students were surveyed at the end of the Fall 2014 and Spring 2015 semesters on their perceptions of sustainability and NAE Grand Challenges of Engineering in their engineering curriculum and in their future careers. Surveys were delivered digitally via Survey Monkey. Students were asked to select the “likelihood of using sustainability concepts in future career” with one of the following responses: “not at all likely,” “likely,” or “very likely”.

Results from student reporting of finding a career creating solutions for NAE Grand Challenges of Engineering are presented in Figure 27. Students were asked to report the “likelihood of finding a career creating solutions for NAE Grand Challenges of

Engineering”. The results show that, of the survey respondents, no student reported “very unlikely” to finding a career creating solutions for Grand Challenges; 17% of ASU and 9% of UPitt survey respondents reported “unlikely”. In addition, 46% of ASU and 63% of UPitt students reported “likely” or “very likely” while 37% of ASU and 27% of UPitt students were “neutral,” indicating that they may be unsure of their future career or unsure whether their future career addresses a Grand Challenge. The NAE Grand Challenges of Engineering are not explicitly incorporated into the civil engineering curriculum for either ASU or UPitt, although ASU does offer a Grand Challenge Scholars programs, which serves less than 1% of engineering students. While all of the Grand Challenges can and should involve engineers to some degree, the authors have identified five challenges that fit well within CEE curriculum; “restore and improve urban infrastructure,” “provide access to clean water,” “make solar energy economical,” “develop carbon sequestration methods,” and “manage the nitrogen cycle.”

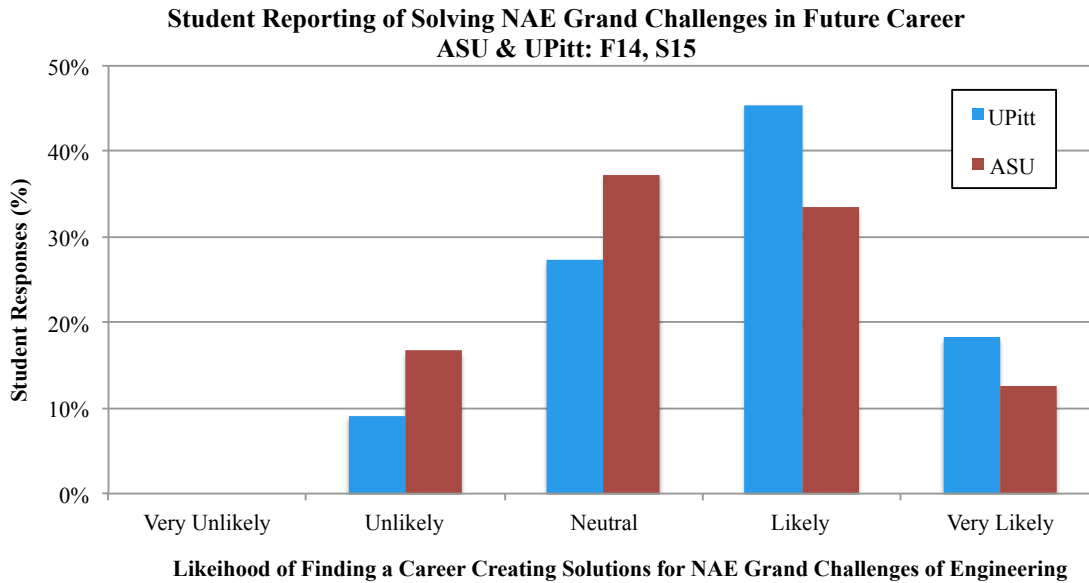


Figure 27. Student Reporting of Solving NAE Grand Challenges in Future Career.

Arizona State University (ASU, $n = 181$ students, $n_r = 28$ survey respondents) and University of Pittsburgh (UPitt, $n = 106$ students, $n_r = 11$ survey respondents) senior design students were surveyed at the end of the Fall 2014 and Spring 2015 semesters on their perceptions of sustainability and NAE Grand Challenges of Engineering in their engineering curriculum and in their future careers. Surveys were delivered digitally via Survey Monkey. Students were asked to select the “likelihood of finding a career creating solutions for NAE Grand Challenges of Engineering” with one of the following responses: “very unlikely,” “unlikely,” “neutral,” “likely,” or “very likely”.

Conclusion

This paper presents the development of a novel rubric for evaluating students’ sustainability knowledge learned as they took at least one stand-alone sustainable engineering course during their curriculum. The rubric was applied to senior design capstone projects in Spring 2014, Fall 2014, and Spring 2015 at Arizona State University (ASU, $n = 181$, $n_p = 28$ projects) and University of Pittsburgh (UPitt, $n = 106$, $n_p = 15$ projects). Rubric evaluation of student reports revealed that students work toward the instructor’s expectations and rubrics set forth in the class, and a limited number of students demonstrated applying knowledge or skills that they had learned elsewhere. In one example at ASU, however, a sustainability expert served as the project mentor. The resulting senior design project incorporated qualitative and quantitative sustainability

topics at high cognitive levels (Bloom's "application" level, as expected by ASCE BOK2), demonstrating that students can apply sustainability successfully to their senior design projects.

The rubric presented herein is extremely detailed and may be cumbersome to apply at other institutions. Streamlining this rubric to ease application should include at minimum cognitive levels achieved, quantitative/qualitative, sustainability links and sustainability topics. Only applying these four categories to senior design projects in this study results in all students achieving appropriate undergraduate levels of cognition, identifies which sustainability pillars are students more likely to quantify, demonstrates that some students are capable of linking the pillars and summarizes the sustainability topics students most often discuss in reference to the ones they were exposed to in their curriculum. Streamlining also enables the use of this rubric for other learning objectives through the substitution of sustainability with another topic such as ethics.

Furthermore, students surveyed reported that sustainability and creating solutions for NAE Grand Challenges of Engineering would likely play a role in their future career. Thus, senior design expectations should be amended to require sustainability concepts. In order to challenge students to draw upon the information learned throughout their previous classes, for example from a standalone sustainability class, instructors should engage a sustainability expert as an advisor to the course and/or as a project mentor to the teams such there is a clear expectation for all senior design projects to holistically address sustainability.

Acknowledgments

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Chapter 5

CONCLUSION

While many institutions express interest in integrating sustainability into their engineering curriculum, the engineering community lacks consensus on established methods for infusing sustainability into curriculum and verified approaches to assess engineers' sustainability knowledge. Two main strategies have emerged for integrating sustainability and National Academy of Engineering (NAE) Grand Challenges of Engineering into engineering curriculum. In the stand-alone course method, engineering programs establish one or two distinct, stand-alone courses. In the module method, engineering programs integrate grand challenges throughout a host of existing courses.

This thesis aimed to apply best practices from engineering education, including active and experiential learning pedagogies, survey assessments, and rubric and rating-scale evaluations, to develop content and assess methods for integrating sustainability and grand challenges into engineering curricula to inform best practices for faculty and universities. Through this research new sustainability modules (Chapter 2: Sustainable Metrics Module) and methods (Chapter 3: Game Design Module) for evaluating the modules' effectiveness on student cognitive and affective outcomes were developed. This research also evaluated the stand-alone course method for integrating sustainability into curriculum. A novel rubric for evaluating sustainability in student projects was developed and tested on senior design capstone projects to evaluate students' ability to apply sustainability learned throughout their academic career to a culminating project (Chapter 4: Senior Design).

Chapter 2 evaluated the module method of integrating sustainability into curriculum (Research Objective 1) via the development and mixed-methods assessment of the Sustainable Metrics (SusMet) Module. The SusMet Module introduced engineering students to explicit concepts of “design for end-of-life”, “design for disassembly,” and the implied concept of “sustainable metrics” through the disassembly of office chairs. The SusMet Module was implemented in six freshman-level Introduction to Engineering courses (Intro A-F) and one junior-level Engineering Projects in Community Service Gold II course (EPICS II). The SusMet Module was also implemented in one intro-level course (Intro + Ret) where students participated in the entire module and one control course (Control) where the activity portion of the module was removed. Both the Intro + Ret and Control courses completed a design retention assignment two weeks after the module to understand the impact of the activity on retention of learning objectives. The module was assessed using a mixed-methods approach of anonymous digital pre-and post-module survey to test cognitive and affective outcomes and a rubric assessment to test the activity portion on student retention of module learning objectives.

The results indicated that no single instructor’s students performed consistently better or worse post-module. All Freshmen and Junior students performed best when definitions were explicit (“design for end-of-life” and “design for disassembly” concepts) rather than implied (“sustainable metrics” concept). Junior-level students were more capable of providing correct definitions for implied module learning outcomes than freshman students. Freshman students reported higher confidence in their abilities post-module when compared to Junior students whose accuracy was consistently higher than

Freshman students for both explicit and implicit concepts. Retention of learning objectives was most impacted by the activity portion of the module; students that participated in activity and completed an additional design assignment post-module (Intro+Ret class) retained module-learning objectives to a greater degree than students that did not participate in the activity but also completed the design assignment (Control class). In addition, concepts students tended to struggle with, i.e., design for end-of-life (explicit) and sustainable metric (implicit), were retained to a greater degree when delivered through experiential learning. This result signifies that one of the important components of the SusMet module is the hands-on, active learning approach.

The SustMet module relies on the use of several large office chairs, which are not portable. Their size and high cost make transferability and portability of this module difficult. Redesign of the module revealed that replacing the office chair with any product that can be disassembled and still achieve the multiple layers of learning outcomes associated with the chairs is quite difficult to replicate. Five elements present in the office chairs that make them ideal objects for this module include: object access, design evolution, sustainable metrics, design for disassembly and design for end-of-life. Analysis of new products based on these five elements revealed that substituting an alternative object is not a simple task. A decision matrix was utilized to assess alternatives objects of fan, cell phone, monitor, printer, coffeemaker and clock radio against the five elements. Through this process the highly weighted elements of this module were recognized as object access, sustainable metrics, and design for disassembly; objects needed to be affordable, have a “green claim” to test, and be capable of being disassembled by multiple students at once. Cell phones, monitors, printers,

coffee makers and clock radios are all too small despite their affordability and “green claims”. Fans, however, appeal to all elements present in the chair, including size, and could be utilized as an alternative object to replace the chair.

Chapter 3 evaluated the module method and explicitly looked at active learning using games to reinforce course concepts and enhance the instructor’s ability to evaluate student performance (Research Objective 2) via the development and mixed-methods assessment of the Game Design Module. The Game Design Module introduced students to the concepts of active and experiential learning through games and includes a discussion on key game components such as learning objectives, materials/board game design, instructions/ scoring. The module was divided into three distinct days, Intro Game Day, Feedback Game Day and Final Game Day and was implemented into three sections of CON 252: Building Methods, Materials and Equipment at Arizona State University. The module was assessed using a mixed-methods approach of module surveys, reflective journal entries, rubric evaluation of student games, and comparison of student grades. A Control Activity, called the Glossary Project, represented a traditional assessment of student concept mastery and was utilized as a comparison to the module results. The results indicate that students can demonstrate mastery of concepts through board game design. Students tended to struggle with articulating game learning objectives on their own and their performance increased when the instructor defined the learning objectives. Three game days in Fall 2013 were too many and two games days in Spring 2014 and 2015 were too few. Because Feedback Game Day is critical to students’ professional game design, to optimize student performance and experience, the Game Design Module should be split into one full Intro Game Day and two half Feedback and

Final Game Days, which would require pairing it with another assignment for the second half of class. Results show that students' experience playing constructions games designed by previous classes as well as having the opportunity to receive and incorporate feedback is an important factor to improve both the student experience and student learning. Overall students report enjoying the Game Design Module more than the Control Activity because of the creativity and teamwork involved. Games can be used as an effective tool for instructors to evaluate student learning in lieu of traditional reports or exams.

Chapter 4 evaluated students' cumulative sustainability knowledge at two institutions, Arizona State University (ASU) and University of Pittsburgh (UPitt), using the stand-alone course method to integrate sustainability into engineering curriculum via a novel sustainability rubric (Research Objective 3). The sustainability content within Spring 2014, Fall 2014, and Spring 2015 senior design capstone projects from ASU ($n = 181$, $n_p = 28$ projects) and UPitt ($n = 106$, $n_p = 15$ projects) was evaluated using a mixed-methods approach, where students at each university took at least one stand-alone class dedicated to sustainability. A mixed-methods approach included observation of student senior design project presentations, evaluation of student reports via a novel rubric created for evaluating sustainability content, and an anonymous post-course student survey to understand student perceptions of sustainability in engineering. The developed rubric utilized existing assessment approaches and built upon them to evaluate student reports for nine different factors including dimensions of sustainability, Bloom's taxonomy, sustainability links, drivers for including sustainability, location of sustainability within report, qualitative/quantitative incorporation, sustainability

source/reference, sustainability topics, and NAE Grand Challenges of Engineering topics. Students surveyed reported that sustainability and creating solutions for NAE Grand Challenges of Engineering will likely play a role in their future career, however 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 concepts that they learned from prior classes. Thus, senior design project requirements should be updated to explicitly require holistic sustainability applications to the engineering designs. 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 as demonstrated in one senior design project. Not only would this approach support students throughout their senior design project but it would better prepare them for the role of a 21st century engineer.

Engineering educators should pursue modules, such as the Sustainable Metrics Module described in this thesis, that connect sustainability grand challenges to engineering concepts, because student performance improves and students report higher satisfaction. Instructors should utilize pedagogies that engage diverse sets of students and impact retention of learning concepts, such as active and experiential learning utilized in the Game Design Module to reinforce course concepts and assess student learning. When evaluating the impact of sustainability in the curriculum, innovative assessment methods, like the rubric developed in this thesis, should be employed to understand student mastery and application of course concepts and the impacts that topics and experiences have on student satisfaction.

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