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Utilizing Civil Engineering Senior Design Capstone Projects to Evaluate Students' Sustainability Education across Engineering Curriculum

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ABSTRACT

While many institutions express interest in integrating sustainability into their civil engineering curriculum, the engineering community lacks consensus on established methods for infusing sustainability into curriculum and verified approaches to assess engineers' sustainability knowledge. This paper presents the development of a sustainability rubric and application of the rubric to civil engineering senior design capstone projects to evaluate students' sustainability knowledge at two institutions. The rubric built upon previous assessment approaches 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, and sustainability topics. The sustainability content within Spring 2014, Fall 2014, and Spring 2015 senior design capstone projects from university A (UA, n = 181 students, n_p = 28 projects) and university B (UB, n = 106 students, n_p = 15 projects) was evaluated using a mixed-methods approach. The mixed-methods assessment included observation of student project presentations and evaluation of student reports via rubric. Rubric evaluation of student reports revealed that students' performance in senior design projects is primarily driven by their instructor's expectations; if sustainability is not a major deliverable, then students are less likely to integrate sustainability concepts that they learned from prior classes in their reports. To make sustainability a priority, senior design project requirements should be updated to explicitly require holistic sustainability applications. 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 the success of one senior design project at each institution during this study.

Key words: Sustainability, capstone design, mixed methods

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 21^{st} century while considering aspects that are key for designing sustainable systems (David Allen et al. 2006, Davidson et al. 2010). Furthermore, according to the National Academy of Science report, *Changing the Conversation*, youth are seeking careers that make a difference (Sullivan 2011, National Academy of Sciences 2008). Sustainable engineering offers a solution to vital challenges, in conjunction with appealing to our youth (Oswald Beiler and Evans 2014). 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; ABET 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 (Accreditation Board for Engineering and Technology 2015).

LITERATURE REVIEW

Strategies for assessing students' sustainability knowledge and application are limited to a few studies (McCormick et al. 2014b, Bielefeldt 2013, Svanström, Lozano-García, and Rowe 2008, Warburton 2003, Mckeown 2011, Riley, Grommes, and Thatcher 2007, Watson et al. 2013, McCormick et al. 2014a). The strategies include what topics need to be assessed and how to best measure student performance, 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), and utilizing instructor-created rubrics on course content or available assessments such as Sustainability in Higher Education Assessment Rubric (SHEAR) or Sustainability Assessment Survey (SAS) (Svanström, Lozano-García, and Rowe 2008, Bielefeldt 2013, McCormick et al. 2014b, Warburton 2003, Mckeown 2011, Vacca 2008). Despite the usability of instruments like SHEAR or SAS, assessments for sustainability in higher education often lack details indicative of interdisciplinary knowledge transfer necessary for learning about 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 (Borrego et al. 2009). Conversely, the strategy for assessing student engineering knowledge and application is widely recognized in a culminating undergraduate engineering experience: senior design capstone projects (ASCE 2008).

Incorporating sustainability into civil engineering curriculum presents considerable challenges to overcome the already constrained curriculum (Christ et al. 2014, Brown et al. 2014). Two main strategies have emerged from universities attempting to sustainability; 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 and grand challenges in depth. Semester-long 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 and 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 (Fogarty 1991). 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 sub-disciplines: 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 twenty-four outcomes, organized into three types of outcomes: foundational, technical, and professional (ASCE 2008). Outcome ten is sustainability (ASCE 2008). 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 twenty-four outcomes (Anderson, Krathwohl, and Bloom 2001, Bloom et al. 1956). 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 sixteen of the twenty-four outcomes. BOK specifies the synthesis level for seven outcomes, including experiments, design, technical specialization, communication, lifelong learning, professional and ethical responsibility, and evaluation level for three outcomes, including design, technical specialization, professional and ethical responsibility (ASCE 2008).

This paper develops a rubric for evaluating students' sustainability knowledge based on integrating previous assessment approaches with additional metrics. The rubric presented herein is applied to senior design capstone projects at two institutions employing *stand-alone course method* to evaluate students' use of sustainability within their designs.

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, University A (UA) and University B (UB). Next, the methods describe the development of a 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 and rubric evaluation (Borrego, Douglas, and Amelink 2009).

Engineering Curriculum and Senior Design Course Descriptions

University A

At University A (UA), sustainability is emphasized in teaching, learning, research, and operations. UA has made a significant investment in sustainability, including a sustainability minor for engineers, which requires the completion of six sustainability courses. University A 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. University A also offers eight sustainable engineering elective courses that students may select to fulfill 18 elective credits required. University A represents the stand-alone course method; UA has established one distinct, required, stand-alone course, CEE 400 ESEM, which addresses sustainability and grand challenges in depth, and generally follows the content summarized in Allenby's The Theory and Practice of Sustainable Engineering (Allenby 2014).

University A requires all students to participate in the senior design course (CEE 486). The senior design project at UA 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 and, in many cases, serve as 'clients' for student projects. 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 that directly address design considerations within their project. A total of 181 students participated in UA senior design during Spring 2014 (73), Fall 2014 (41), and Spring 2015 (67) semesters.

University B

University B's (UB) Department of Civil and Environmental Engineering (CEE) has made a significant investment in sustainable engineering. While UB does not offer a minor in Sustainability, UB does have an Engineering for Humanity Certificate and (at the time of this writing) a nearly approved University-wide Sustainability Certificate. Similar to UA, UB 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 (LCA) Methods and Tools, CEE 1210 Engineering and Sustainable Development (ESD), CEE 1217 Green Building Design and Construction (GB), and CEE 1218 Design for the Environment (DFE).

Students in CEE are required to take one of these four stand-alone courses that address sustainability and 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 (Mathews, Chris T. Hendrickson, and Deanna H. Matthews 2015). CEE 1210 covers concepts of industrial ecology and sustainable development and follows Graedel and Allenby's Industrial Ecology and Sustainable Engineering (Graedel and Allenby 2010). 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 (US Green Building Council 2007). 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 UA's ESEM class are very similar in course content; the instructors are authors on this paper and collaborated in developing the classes. More recently, UB's Provost selects a theme to integrate throughout all curricula and activities; UB dedicated the 2014-2015 academic year to sustainability.

The Civil and Environmental Engineering Department at UB 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 UB 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 UB senior design project rubric; UB students are requested to consider constraints, one of which includes sustainability. A total of 106 students participated in UB 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 of 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

The senior design projects were assessed using a mixed-methods approach combining observation of student presentations and rubric evaluation of student reports.

Observation of Student Presentations

Students in senior design courses at both UA and UB 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, faculty and graduate students in Sustainable Engineering, viewed all senior design 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)

The observers utilized Brundtland Commission definition of sustainability in this research; "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (Commission 1987). Due to the number of students in each semester of senior design at UA, 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, two authors observed the final presentation together and compared notes afterwards. UB 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 (Mertler 2001).

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 1. Bielefeldt 2013 utilized *Dimensions of Sustainability* to assess the pillars

Table 1. Sustainability rubric developed to assess student application of concepts.

Criteria		Possible Score
1. Dimensions of Sustainability (Bielefeldt 2013)	Environmental Economic Social	No Evidence, Weak, Fair, Good
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 Economic Social	Quantitative Qualitative
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	

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 and references. Students had to score fair or good in dimensions of sustainability to be considered concept-level or greater in sustainability links.

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 (Bielefeldt 2013). 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") (Anderson, Krathwohl, and Bloom 2001, Bloom et al. 1956). 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) (McCormick et al. 2014b). McCormick et al. 2014 did not include a "no evidence" response option; the authors added this option. Table 1 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 1, 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 recycling, water reuse, energy reduction, urban heat island effect, alternative transportation, consider needs of people/stakeholder engagement.

Bloom's Taxonomy

Bloom's taxonomy provides syntax and a measurement scheme through which students' levels of intellectual behavior can be assessed. Bloom's taxonomy is divided into six compartments, including "knowledge," "comprehension," "application," "analysis," "synthesis," and "evaluation" (Anderson, Krathwohl, and Bloom 2001). 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, based on the Triple Bottom Line definition of sustainability (Elkington 2008). Students' examples of dimensions of sustainability were judged on four criteria, including "no evidence" = no mention, "weak" = mentioned but no specific example, "fair" = mentioned one example, and "good" = mentioned multiple examples (Bielefeldt 2013).

Sustainability Links

McCormick's et al. 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 (McCormick et al. 2014b).

"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.

Evaluation of Student Reports via Rubric

Three graduate student evaluators utilized an Inter-Rater Reliability (IRR) approach to 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 (Gwet 2014). 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 (Gwet 2014, Armstrong et al. 1997). Utilizing an IRR approach, the rubric was applied to senior design projects in five steps; in step one the evaluators, scored one senior design project together, in step two the evaluators scored the same senior design project separately and met to discuss results, in step three the 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.

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

RESULTS AND DISCUSSION

Faculty and graduate students in Sustainable Engineering viewed all senior design student presentations each semester for binary (yes/no) presence of sustainability content based on the Brundtland Commission definition (Commission 1987). The observations revealed that all students at both UA and UB mentioned the incorporation of sustainability into their projects. However, binary approach to scoring student projects did not provide granularity needed to evaluate the spectrum of students' incorporation of sustainability, indicating that further review of student projects via rubric analysis was necessary to differentiate between Triple Bottom Line sustainability (Elkington 2008).

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, and students' ability to use of quantitative and qualitative methods for sustainability. Results are discussed by each category of the rubric, presented in Figures 1–5.

Dimensions of Sustainability

Students' senior design projects were marked on the *Dimensions of Sustainability* to understand students' incorporation of environmental, economic, and social pillars of sustainability. Projects were

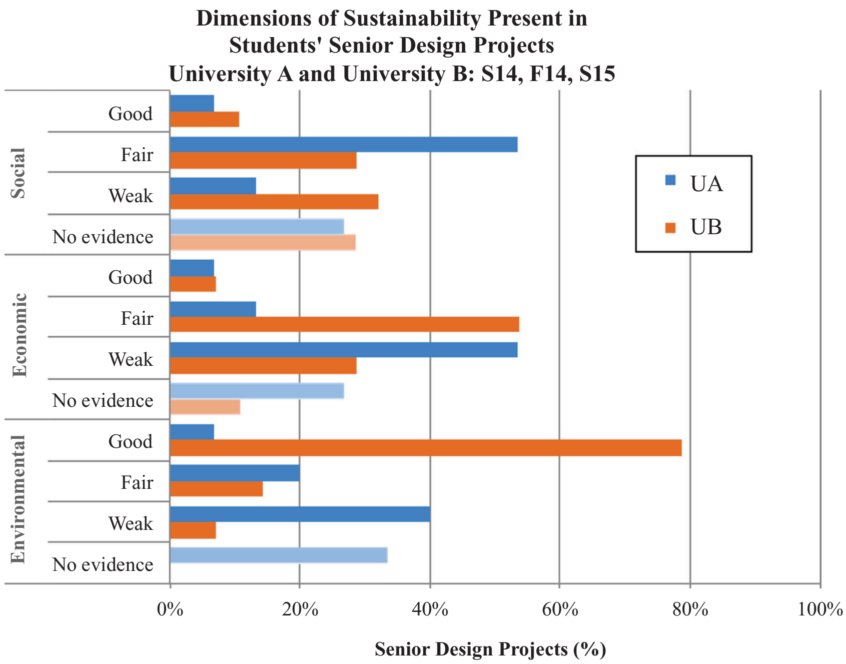

Figure 1. Dimensions of Sustainability Present in Senior Design Projects.

University A (UA, n = 181 students, n_p = 28 projects) and University B (UB, n = 106 students, n_p = 15 projects) senior design 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 (Bielefeldt 2013).

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 (Bielefeldt 2013). Prior to the senior design course, all students at UA and UB had taken courses that covered all three pillars of sustainability. The results (Figure 1) show that the prevailing score of UA senior design projects achieved "good" in environmental pillar (79%), "fair" in economic pillar (54%), and "weak" in social pillar (32%). In comparison, the majority of UB senior design projects scored "fair" in social pillar (53%), "weak" in economic pillar (53%), and "weak" in environmental pillar (40%). UA and UB 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 the required stand-alone sustainable engineering course taken earlier in their educational careers. Senior-level students are expected to discuss multiple dimensions of sustainability reaching "fair" or "good" levels, according to ASCE BOK2.

Students from UA performed strongest in environmental, followed by economic and social, while UB projects were strongest in economic, followed by environmental, and social. Students' association of sustainability with environmental impacts more than other dimensions, combined by the ease of quantifying or connecting environmental issues, led to 100% of UA 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. UB projects performing stronger in economic than environmental may be due to the rigidity of project descriptions in addition to minimal incorporation of sustainability in the rubric. Lastly, social aspects of sustainability are weakest at both universities. While UB 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. It is unknown why the two universities differ in strengths/weaknesses of incorporating the three pillars, but may be related to instructor emphasis within the senior design course and ease of addressing each pillar, where students tend to struggle most with social sustainability.

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" (Anderson, Krathwohl, and Bloom 2001, Bloom et al. 1956). The results (Figure 2) show that 57% of UA projects apply sustainability concepts at the "comprehension" level; these concepts were demonstrated through understanding of knowledge. In addition, 73% of UB 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 (ASCE 2008). While 14% of UA and 13% of UB 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.

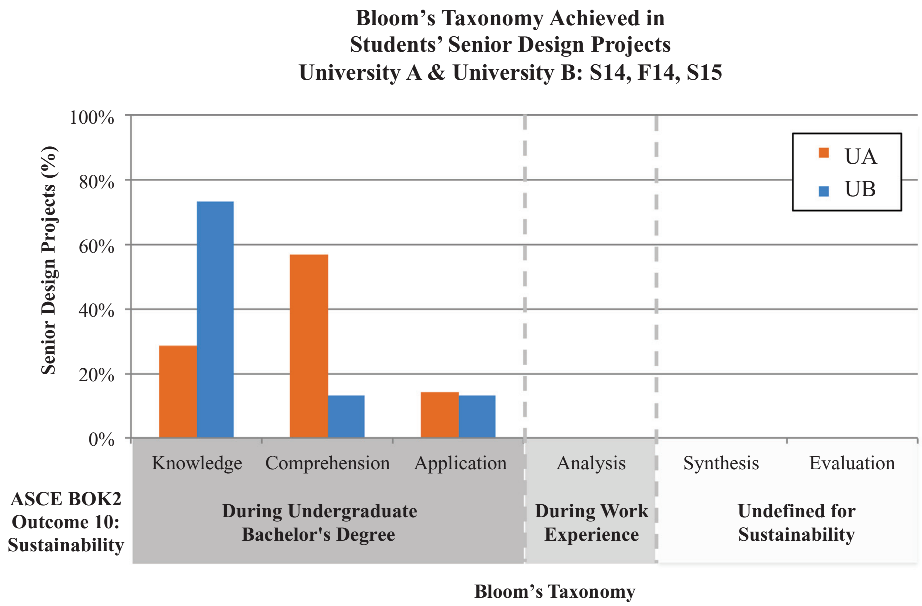

Figure 2. Bloom's Taxonomy Achieved in Senior Design Projects.

University A (UA, n = 181 students, n_p = 28 projects) and University B (UB, n = 106 students, n_p = 15 projects) senior design 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" (Anderson, Krathwohl, and Bloom 2001, Bloom et al. 1956).

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. Both stand-alone sustainability courses and sustainability modules should provide students with understanding of the relationship between sustainability and their core civil engineering curriculum, thereby enhancing 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. "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.

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) (McCormick et al. 2014b). 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 1**,** 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 3. UA 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 UA senior design projects displayed interdependency between all three pillars of sustainability, however the most common (39%) cross-link was between environmental-economic. UB 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 UB 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 UA projects and 33% of UB projects. UA and UB students are exposed to the linkages between sustainability pillars in their stand-alone sustainable engineering courses. At UA the required sustainability course (ESEM) that all students take covers all three pillars of sustainability; while the UB equivalent course (ESD) covers all three pillars, not all UB students take ESD.

UA and UB students are exposed to the linkages between pillars in their sustainable engineering courses. Students' deficiency in demonstrating these crosslinks further supports the idea 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

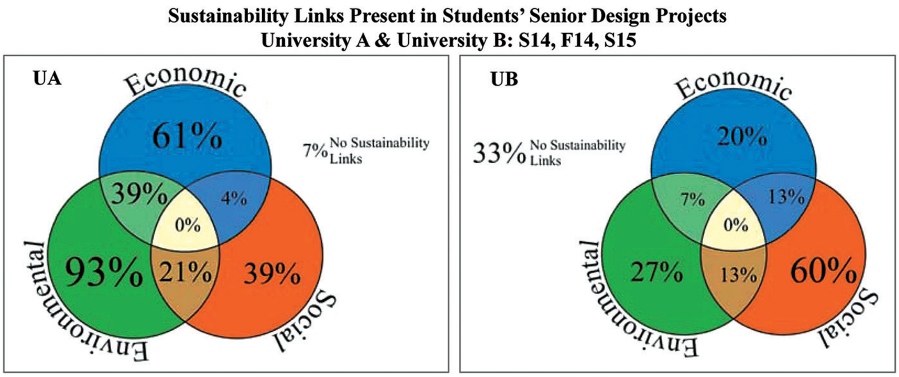

Figure 3. Sustainability Links Present in Senior Design Projects.

University A (UA, n = 181 students, n_p = 28 projects) and University B (UB, n = 106 students, n_p = 15 projects) 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) (McCormick et al. 2014b) and "no evidence". Projects needed to score fair or good in *Dimensions of Sustainability* to be considered concept-level or greater in *Sustainability Links*.

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.

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 of students' partnered firm 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, including student, client, or instructor. The findings show that all UA 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 UB were determined to have rubric/instructor as the driver for sustainability. At UB, 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. UA'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, UB'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 UA reports; 25% of UA reports discussed sustainability throughout the entire report in addition to discussions within the stand-alone sections. Conversely, 27% of UB reports discussed sustainability in a stand-alone section while 67% of reports discussed sustainability throughout the report. Seven percent of UB reports did not present any sustainability concepts in the report. Similar to *Drivers for Including Sustainability*, the project rubric has significant influence on location of sustainability within the senior design projects. All UA 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% UB senior design projects discussed sustainability in stand-alone sections. As a result, sustainably was better woven throughout the project.

Qualitative/Quantitative Incorporation

Quantitative and qualitative incorporation of environmental, economic and social pillars of sustainably within students' senior design projects are presented in Figure 4**.** 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 UA projects incorporated environmental and economic

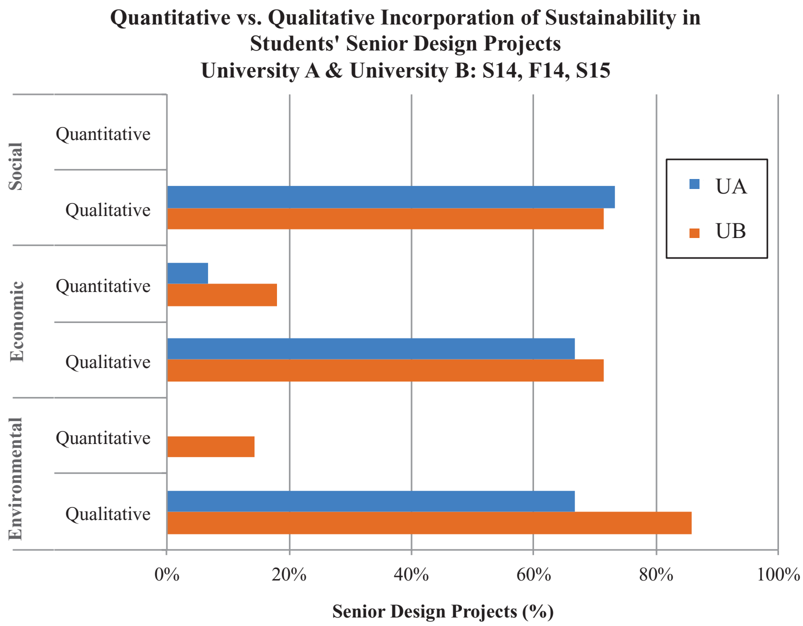

Figure 4. Quantitative/Qualitative Incorporation of Sustainability in Senior Design Projects.

University A (UA, n = 181 students, n_p = 28 projects) and University B (UB, n = 106 students, n_p = 15 projects) senior design 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.

concepts quantitatively while UB projects incorporated only economic quantitatively. At both UA and UB the instructors do not require quantitative incorporation of sustainability but it is a strong recommendation. This finding suggests that students default to qualitative descriptions of sustainability rather than quantified metrics. The standalone sustainability 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.

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 UA students citied 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 UB students cited a reference for the sustainability concepts within their senior design reports. In the standalone sustainability classes at both universities, students are taught how to find and use references within reports. However, the expectations for senior design differ from the stand-alone 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 in an effort to understand concepts students applied within students' chosen senior design projects. These topics were evaluated for the manner in which students included them; either explicitly or implicitly (Figure 5). 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 the topic directly but discussed the topic, or "explicitly presented" where students directly mentioned the topic in their report. UA results show the greatest explicit incorporation of sustainable innovation (SUI), water reuse (WRE), and anthropogenic environmental impacts (AEI) while UA's implicit incorporation of sustainability focused on sustainability infrastructure (SIF), pollution prevention (PPR), and renewable energy (REN). Conversely, UB's greatest explicit incorporation of sustainability focused on stakeholder engagement (SEN), alternative transportation (ALT), and pollution prevention (PPR) while UB'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, UA civil engineering students are exposed to fifteen sustainability topics and despite this exposure none of the UA senior design projects incorporated climate change, pollution prevention, corporate sustainability, sustainability economics, sustainable agriculture, green buildings, and industrial ecology. Similarly, UB 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, UB senior design projects incorporated topics

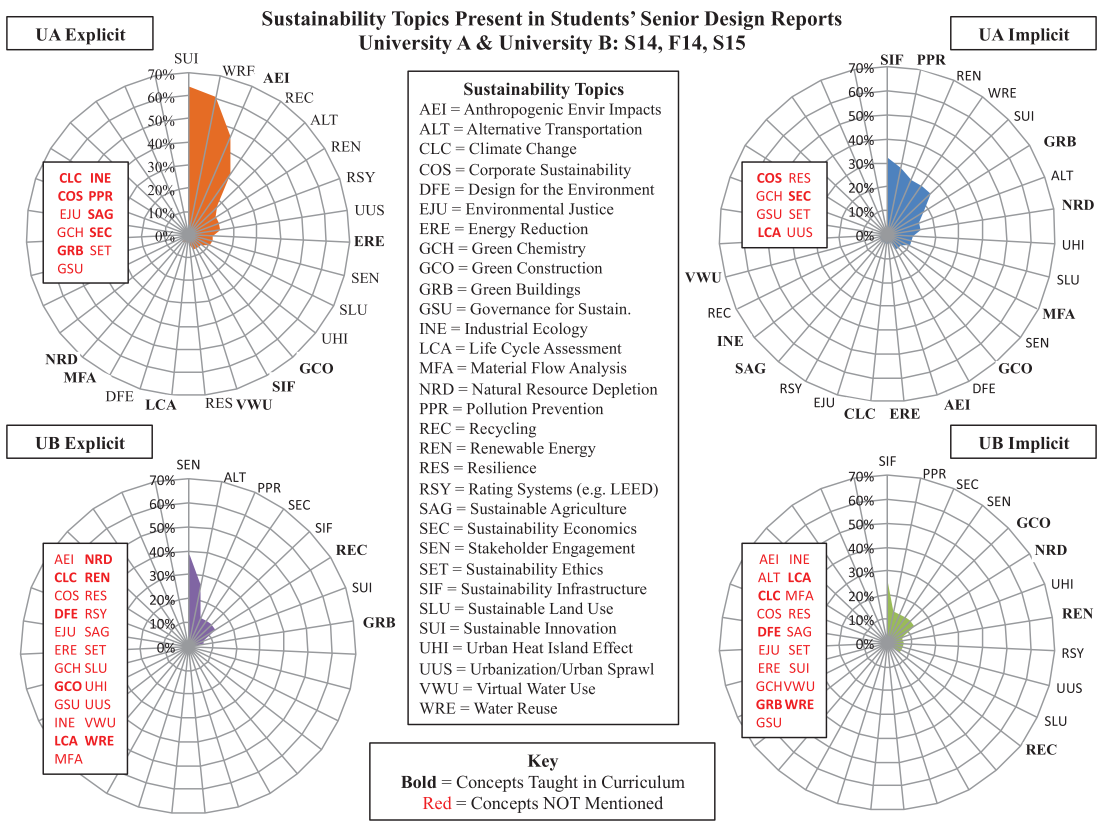

Figure 5. Sustainability Topics Present in Senior Design Projects.

University A (UA, n = 181 students, n_p = 28 projects) and University B (UB, n = 106 students, n_p = 15 projects) senior design 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. **Bolded** topic codes represent concepts taught in students' curriculum. Red topic codes represent concepts not mentioned in students' senior designs. **Red bolded** topics represent concepts taught to students but not mentioned in senior designs.

of stakeholder engagement (SEN), alternative transportation (ALT), pollution prevention (PPR), sustainability economics (SEC), sustainability infrastructure (SIF), recycling (REC), sustainable innovation (SUI), and green buildings (GRB). This finding suggests that despite extensive exposure to sustainability topics within their curriculum in a stand-alone sustainability 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.

For one project group at UA a sustainability expert served as the project mentor and client. The resulting senior design project achieved sustainability crosslinks, quantification for environmental and economic sustainability, addressed 40% more sustainability topics than the next highest report (11 explicit and 4 implicit sustainability topics in this single report), and showed increased cognitive levels by achieving Bloom's "application" level, per ASCE BOK2 requirement to professional practice (ASCE 2008). This was a similar case for one project at UB, which also achieved "application" level Bloom's, demonstrating that students can apply sustainability successfully to their senior design projects and suggesting that a sustainability expert may improve incorporation of sustainability.

During the evaluation of senior design projects for sustainability inclusion and cognition, the development of a holistic assessment tool synchronizing peer-reviewed evaluative methods was necessary. Independent application of the three peer-reviewed methods, Bloom's Taxonomy, Dimensions of Sustainability and Sustainability Links, presents misleading results. Employing only Boom's Taxonomy to assess senior design projects, in the context of sustainability, indicates an overwhelming majority of reports (86%) falling short of ASCE's BOK2 cognitive achievement level, defined for senior undergraduates as the requirement for entry into the practice of civil engineering at the professional level. In addition, utilizing Bloom's taxonomy independent of other peer-reviewed evaluative methods is insufficient to assess 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 count of references from each pillar 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 holistic 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.

FUTURE RUBRIC IMPLEMENTATION

The authors found that future rubric implementation should include, at minimum, cognitive levels achieved, quantitative/qualitative, sustainability links, and sustainability topics. These four categories generated the greatest insight into students' levels of cognition, quantification of sustainability pillars, demonstration of pillar linkages, and sustainability topics. Dimensions of sustainability provided redundant information; students' ability to show more than one sustainability example was covered by aforementioned rubric sections.

CONCLUSION

Rubric evaluation of student reports revealed that students' performance in senior design projects is primarily driven by their instructor's expectations; if sustainability is not a major deliverable, then students are less likely to integrate sustainability concepts learned from prior classes in their reports. Despite this, when guided by project mentor and/or client with a sustainability mission, students demonstrated that they were capable of applying sustainability successfully to their senior design projects. The authors question whether students will translate their experiences in senior design to the civil engineering profession; if future clients do not request a high degree of sustainability, while there may be little-to-no incentive to incorporate it, these future civil engineers may not initiate it in on their own, as shown in the senior design results.

In order to challenge students to draw upon the information learned throughout their previous classes, senior design project requirements should be updated to explicitly require holistic sustainability applications to the engineering designs. In addition, instructors could approach raising sustainability expectations by engaging a sustainability expert as an advisor to the senior design course and/or utilizing a sustainability expert as project mentor 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.

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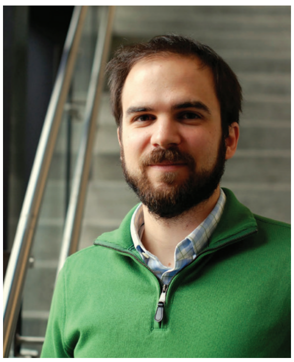

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