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# Pedagogies to Achieve Sustainability Learning Outcomes in Civil and Environmental Engineering Students

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**Abstract:** The civil and environmental engineering disciplines have identified the levels of knowledge about sustainability that are desirable for students to achieve as they graduate with a bachelor's degree, as well as sustainability-related competencies to be obtained during a master's degree, and on-the-job, prior to professional licensure. Different pedagogies are better suited to help students attain these levels of cognitive ability, while also developing affective outcomes. This paper provides examples of different methods that have been used at one institution to educate engineering students about sustainability, supported with data that indicates whether the method successfully achieved the targeted learning outcomes. Lectures, in-class active learning, readings, and appropriately targeted homework assignments can achieve basic sustainability knowledge and comprehension by requiring students to define, identify, and explain aspects of sustainability. Case studies and the application of software tools are good methods to achieve application and analysis competencies. Project-based learning (PBL) and project-based service-learning (PBSL) design projects can reach the synthesis level and may also develop affective outcomes related to sustainability. The results provide examples that may apply to a wider range of disciplines and suggest sustainability outcomes that are particularly difficult to teach and/or assess.

**Keywords:** Bloom's taxonomy; case studies; civil engineering; project-based learning; service-learning

## 1. Introduction

Although Education for Sustainability (EfS) should be a universal learning goal, there is a wide disparity in the knowledge outcomes related to sustainability that are required in the higher education institutions in different countries and disciplines. For example, across the 267 institutions which have participated in the American Association of Sustainability in Higher Education (AASHE) Sustainability Tracking, Assessment & Rating System (STARS), only 21% of the sustainability educational objective points were earned [1]. This score was based on the percentage of the students who graduated from programs with at least one required sustainability learning outcome. At any single university, 3% to 100% of the students graduated from programs with required sustainability learning objectives. Particular disciplines commonly had sustainability educational goals, such as environmental studies. More generally, an increasing number of degree programs, minors, and certificate programs worldwide are focused on sustainability [2].

The broad principles of EfS span a range of knowledge goals, attitudes, and teaching methods [3–6]. Many of these general knowledge domains are also common expectations for engineering education [7,8], such as lifelong learning, problem solving, and collaboration/teamwork. Within engineering, the degree accreditation criteria within the United Kingdom (UK) [9], New Zealand (NZ) [10], and the United States (US) [7] all include statements regarding sustainability. In NZ, for example, all four year engineering programs and three year engineering technology programs accredited by the Institution of Professional Engineers New Zealand (IPENZ) must have curriculum that include sustainability among five or four required elements, respectively [10]. Sustainability must be integrated through the curriculum including coverage of sustainable technologies/sustainable development and consideration of the social and environmental effects of engineering [10]. In addition, common among European Union (EU) [11], UK, and US standards is the requirement that engineers consider the social and environmental implications of engineering, but this falls short of a fully integrated consideration of sustainability.

The specific learning goals for students around the issue of sustainability must be articulated in order to determine the targeted outcomes for students' knowledge of sustainability. One framework that can be used to conceptualize the goals for EfS is the cognitive domain of Bloom's taxonomy [12,13]. As summarized in column 1 of Table 1, the cognitive domain represents intellectual skills and describes increasingly complex levels of knowledge. The American Society of Civil Engineers (ASCE) established sustainability as one of twenty-four desired learning outcomes in its Civil Engineering Body of Knowledge for the 21st Century (BOK2) [8]. The BOK2 articulates sustainability learning outcomes at different levels of cognitive achievement (Table 1). Students graduating with a bachelor's degree are expected to be at the application level of sustainability knowledge. The American Academy of Environmental Engineers (AAEE) adopted Daggett's rigor and relevance framework to describe the desirable sustainability learning outcomes for environmental engineers (Table 1) [14]. This framework encompasses Bloom's cognitive taxonomy and adds additional criteria that define the context of the knowledge.

**Table 1.** Sustainability outcomes recommended for civil and environmental engineers prior to professional licensure and potential teaching methods to meet these goals. (B = should be acquired at the bachelor's degree level).

| **Cognitive Levels [12,13]** | **Civil Engineering ASCE BOK2 [8]** | **Environmental Engineering AAEE BOK [14]** | **Teaching method and evaluation** |
|---|---|---|---|
| 1. Knowledge/Remembering | Define key aspects of sustainability relative to engineering phenomena, society at large, and its dependence on natural resources; and relative to the ethical obligation of the professional engineer. (B) | Recognize life-cycle principles in the context of environmental engineering design.<br>Identify components in an engineered system that are not sustainable. (B) | Lecture, in-class activity learning with clickers; homework to define sustainability |
| 2. Comprehension/Understanding | Explain key properties of sustainability and their scientific bases, as they pertain to engineered works and services. (B) | Explain the scientific basis of natural system processes and the impacts of engineered systems on these processes.<br>Explain the need for and ethics of integrating sustainability throughout all engineering disciplines and the role environmental engineers have in this. (B) | Readings; Homework |
| 3. Application/Applying | Apply the principles of sustainability to the design of traditional and emergent engineering systems. (B) | Quantify environmental releases or resources consumed for a given engineered process. (B) | Case studies; software tools |
| 4. Analysis/Analyzing | Analyze systems of engineered works, whether traditional or emergent, for sustainable performance. | Analyze the sustainability of an engineered system using traditional or emerging tools (e.g., industrial ecology, life cycle assessment, *etc.*).<br>Ascertain where new knowledge or forms of analysis are necessary for sustainable design. | Case studies;<br>Project-based learning (design); homework and project reports |
| 5. Synthesis/6. Creating | Design a system to perform sustainably, develop new more sustainable technology… | Design traditional or emerging engineered systems using principles of sustainability.<br>Design a complex system, process, or project to perform sustainably. | Capstone design<br>Project-based Service-learning |
| 6. Evaluation/5. Evaluating | Evaluate the sustainability of complex systems, whether proposed or existing. | Evaluate the sustainability of complex systems, whether proposed or existing. | |

The UK Joint Board of Moderators (JBM), which accredits civil engineering programs, requires that sustainable development is "pervasive" and a thread that runs through the engineering education program [15]. There are 19 different statements of the knowledge, abilities, and skills related to sustainability that students should possess. The majority of these relate to "awareness" or the lowest level of Bloom's cognitive taxonomy, including climate change and carbon emissions, ethics, environmental impact assessment, energy, and resource scarcity. There are also goals for students to understand the interdisciplinary and holistic nature of sustainability. The achievement of these learning goals must be demonstrable via student designs, projects, and examinations. More broadly, the Engineering Council in the UK (ECUK) requires a thread on "economic, social, and environmental context" for all engineering disciplines [11].

A Bloom's taxonomy approach to sustainability education has been taken within an entire engineering curriculum at James Madison University, where sophomore-level design courses focus on the knowledge and comprehension levels, junior-courses on the application and analysis levels, and senior year on synthesis and evaluation skills [16]. The students' knowledge at these levels was assessed using a homework assignment where the students analyzed a case study, with increasing complexity in each year of the curriculum. The student responses were scored for the social, environmental, economic, and technical aspects of sustainability, and whether each element was linked to the other aspects of sustainability. This approach allowed students' growth in sustainability knowledge to be evaluated.

EfS includes more than knowledge; it has been characterized as "more of a moral precept… concerned with the values people cherish" [17]. This notion is encompassed within the affective domain of Bloom's taxonomy, which includes attitudes, emotions, and feelings [12,13]. The five affective domain levels can be summarized as: (1) receiving, willing to participate; (2) responding by showing an interest; (3) valuing as an internal appreciation; (4) organization into a set of values; and (5) characterization by the value which is adopted into the long-term and pervasive value system of the individual [13]. The BOK2 discusses that the affective domain was considered to articulate the desired competencies for civil engineering professionals, but ultimately it was decided that the cognitive domain was more appropriate [8]. The BOK2 includes affective outcomes holistically within a single outcome termed "attitudes". The desired attitudes that are associated with professionalism among civil engineers include "commitment, confidence, consideration of others, curiosity, entrepreneurship, fairness, high expectations, honesty, integrity, intuition, judgment, optimism, persistence, positiveness, respect, self-esteem, sensitivity, thoughtfulness, thoroughness, and tolerance" [8]. Many of these attitudes are also appropriate considerations for sustainability, which includes "peace, human rights and fairness" [17]. The requirement that civil engineers should value sustainability is implicit because it is stated to be an ethical requirement.

Students' affective perceptions of sustainability are important, in order to ensure that they apply sustainability knowledge both personally and professionally. Indications of students' perceptions about the importance of sustainability have been gathered using a variety of methods, including a fairly extensive attitude survey rooted in expectancy value theory [18] and very simple survey questions for graduating seniors [19]. For example, to assess the extent to which students valued sustainability, senior students at the University of Colorado Boulder (CU) were asked to rank the importance of sustainability relative to the twenty-four learning outcomes in the ASCE BOK2. In 2011, these CU environmental, architectural, and civil engineering students on average ranked sustainability third, sixth, and sixteenth, respectively [19]. This indicates variability in the relative importance of sustainability to seniors in different engineering majors, and likely reflects both students' intrinsic interests and the extent to which sustainability was emphasized within their curriculum.

EfS has promoted student-centered learning and interdisciplinary teaching approaches [17]. The teaching methods used for sustainability education should be congruent with the level of achievement being targeted. Although multidisciplinary and interdisciplinary approaches are believed to be optimal for teaching sustainability due to its complexity [20], the restricted nature of many engineering curricula in the US make it particularly difficult to incorporate these experiences. As such, other methods are generally used to educate engineering students about sustainability. Further, Fink [21] believed that the various domains of learning could not be separated into cognitive and affective domains, but rather were holistically integrated. Sustainability is a topic where due consideration should be given to these integrated aspects of learning.

This paper provides examples of teaching methods targeting different levels of Bloom's cognitive taxonomy that have been used in engineering courses at one institution. Supporting data on the efficacy of each method in reaching the desired cognitive outcome is provided, along with indications of affective outcomes.

## 2. Experimental Section

The sustainability teaching methods that are described in this paper were used by the author in engineering courses taught at the University of Colorado Boulder (CU). Table 2 provides a summary of these seven courses and the sustainability-related activities. Each course was one semester long (15 weeks) with 50-minutes per week of in-class contact time per credit hour. The courses were targeted to either first-year undergraduate students working toward a bachelor's degree in an engineering discipline, terminal year bachelor's degree students (fourth year or fifth year senior undergraduates), and/or post-graduate students working toward a master's or doctoral degree in civil engineering. Sustainability was the focus of particular lectures and activities within each course. The method used to facilitate student learning about sustainability was often also used to assess sustainability knowledge. More details on the methods used to evaluate students' sustainability-related knowledge and attitudes are provided below.

In the first-year courses (ICE, IEE, IAE), student response systems, also known as "clickers", were used to provide in-class assessment of students' knowledge and/or attitudes about sustainability. The questions were multiple-choice with up to five possible responses. Some questions had a single correct answer among the choices; such as: *What are the three pillars of sustainability?* These questions typically only assessed the most basic cognitive knowledge (Bloom's level 1). Other questions were intended to spark discussion and did not have a correct answer; for example: *Rate how severe you think problems related to global climate change will be* (possible answers: minimal; some; moderate; severe). Other questions were used to assess attitudes toward sustainability; for example: *Rate your level of agreement with the statement 'Sustainability is a key component of civil engineering'*. The clicker questions were used to award participation points and did not contribute to students' grades based on correct answers. In-class participation in the clicker questions on the sustainability topics contributed about one percent to the students' overall course grades.

**Table 2.** Example University of Colorado Boulder (CU) engineering courses with Education for Sustainability (EfS) infusion teaching methods.

| Course Title [Abbreviation], credits | Level of Students | Year EfS 1st Added | EfS Teaching Methods | Evaluation |
|---|---|---|---|---|
| Introduction to Engineering [IE], 2 | First year | 2012 | Lecture, in-class active learning | In-class team worksheet, homework |
| Introduction to Civil Engineering [ICE], 1 | First year | 2009 | Lecture, in-class active learning, case studies, team design project | In-class clickers, homework, project report, reflective essay |
| Introduction to Environmental Engineering [IEE], 1 | First year | 2009 | Lecture, in-class active learning | In-class clickers, homework, project report, reflective essay |
| Introduction Architectural Engineering [IAE], 2 | First year | 2012 | Lecture, case studies, team design project | Homework, project report, reflective essay |
| Environmental Engineering Design [EED], 4 | Seniors (terminal year Bachelor's) | 2009 | Lecture, team design project, service-learning design project | Team design report and oral presentation, reflective essays |
| Hazardous & Industrial Waste Management [HWM], 3 | Seniors & post graduates | 2011 | Software tool, team design project | Homework, team design report and oral presentation |
| Bioremediation [BR], 3 | Post graduates | 2012 | Software Tool | Homework |

Homework assignments were intended to facilitate students' learning about sustainability and also assess their level of knowledge. Students were generally expected to learn some of the information needed to answer the questions on their own, via assigned reading material. The sustainability-focused homework assignment was one of seven assignments in the ICE, IEE, and IAE courses; it was worth 10% of the overall course grade. The learning goals of the assignment were: (1) define sustainability; (2) describe the importance of sustainability to engineering; and (3) identify aspects of sustainability in engineering projects. The specific questions asked on the assignment varied in the three courses and each year. For example, based on a case study students were instructed to discuss what was done to improve the sustainability of the project and provide specific examples of how the project achieved sustainability goals that mapped to each of the three pillars of sustainability.

Some believe that reflection is a critical part of the learning cycle [22,23]. Therefore, requiring students to reflect can enhance learning as well as provide an opportunity for assessment. Reflections are particularly useful to provide insight into affective learning outcomes. Reflective essays were required assignments in the ICE, IEE, IAE, and EED courses. The assignments were graded on the thoroughness of the discussion, rather than the answers themselves. These reflective essay assignments did not require the students to discuss sustainability. The reflective essays in the ICE, IEE, and IAE courses were due at the end of the semester and required to be two single-spaced pages long. The students were instructed to write their definition of civil/environmental/architectural engineering, discuss if they were interested in continuing to major in that discipline and why. The students were prompted to discuss personal experiences prior to college, content in the course, and other college courses that impacted this decision. The students were also instructed to "cite specific aspects of engineering and being an engineer that appeal to you and do not appeal to you."

The EED course included a number of shorter reflective writings throughout the semester on team processes, professional development, and civic responsibility [24,25]. For example, a mid-semester reflection of 300 to 400 words instructed students to describe the client, community partner, and/or stakeholders for their design project, the goals of these entities, if the project provided a service to anyone, and discuss any relation of the project to larger social, cultural, or economic issues. At the end of the semester, the students wrote a longer reflection on these same topics, in addition to describing personal benefits that they derived from the course.

Rubrics can support educators in examining the extent to which specific concepts have been learned, and may also provide feedback concerning students' attitudes and emotions within the field [26,27]. Analytic scoring rubrics allow for the evaluation of separate factors and are directed primarily towards content, whereas holistic rubrics support broader judgments concerning the overall quality of the process. In this research, rubrics to assess sustainability attributes were applied to the homework or design report assignments after the end of the semester in order to evaluate whether or not sustainability teaching goals were met; the rubrics were not used to grade the assignments. For example, in the ICE, IAE, and IE courses one of the case studies asked the students to: "provide a brief summary, and discuss how this project appears to address each of the three pillars of sustainability". The analytic rubric used to evaluate this case study question is presented in Table 3. Note that the points awarded to the student during grading used a "partial credit" model and not the rubric levels. So when grading to award up to ten points for this question, students were awarded four points for their summary and six points for the sustainability discussion, with two points for each sustainability pillar. The awarding of the two points was somewhat subjective, but was about 1 point for an answer at level 1 of the rubric, 1.5 points for level 2 of the rubric, and then varying levels at 1.6 to 2 points that correlated to level 3 of the rubric.

**Table 3.** Example of analytic rubric used to evaluate the case study within the ICE homework.

| **Dimension** | **No evidence 0** | **Weak 1** | **Fair 2** | **Good 3** |
|---|---|---|---|---|
| **Environmental** | Lacked any mention of environmental impacts | Mentioned environmental elements in discussion but did not give specific examples of how the case study considered environmental impacts | Gave one example of minimizing negative environmental impacts | Multiple examples of efforts to minimize negative environmental impacts, such as decreased air pollution, material recycling, waste minimization, minimized energy consumption, *etc.* |
| **Economic** | Lacked any mention of cost, local economic benefits, *etc.* | Mentioned cost or economics but did not show how the case study was a sustainable example | Gave one example of how the case study met an economic sustainability goal | Discussed multiple innovations that saved taxpayer money, provided jobs, *etc.* |
| **Social** | Lacked any mention of social benefits | Mentioned social benefit but did not give a concrete example that pertained to the case study | Gave one example of how the project provided positive social benefits or tried to minimize negative social impacts | Gave multiple examples that community input considered, contributed in a positive way to the community, considered social equity, *etc.* |

Content analysis was applied to design reports and reflective essays. Content analysis is a research method that analyzes the content of text [28], and has been previously used in a large number of studies exploring student learning and sustainability (examples include [29,30]). Content analysis was conducted by counting the total number of sustainability-related keywords in the EED final design reports from the student teams. These key words for each of the three sustainability pillars were defined by Paterson and Fuchs [31]. The search terms were separated into the economic, social, and environmental pillars of sustainability and counts of the use of these terms provided a rough indication of the level of consideration of these factors. For example, the social pillar included terms such as community, culture, educate, ethic, health, poverty, and social (among others). The presence of the search terms in the document was counted using computer software (MS Word or Advanced Search in Adobe for pdf files); for example *sustainab** (* = wildcard) for sustainable and sustainability. Then the usage of the term was examined to ensure that it was appropriate to the desired context. For example, *safety* used in the context of human safety was counted as social keyword but *safety factor* to discuss the technical design process was not counted. This analysis was conducted on a selection of the reports from 2010 to 2013. All four of the reports based on service learning (SL) projects for international communities were analyzed. These projects focused on drinking water, sanitation, or energy in developing communities. Four domestic SL projects were analyzed; these projects designed micro hydropower for local farmers, indoor air quality assessment and remediation in low income apartment complexes, and wastewater treatment systems serving a trailer park and a Native American community. Finally, seven non-SL projects were analyzed; these included drinking water, wastewater treatment, and energy projects that were part of design competitions.

A similar content analysis approach was used as the first step of sustainability content analysis of students' reflective essays. In this case, keyword searches enabled quickly locating ideas of interest within the essays. Then the surrounding context of the discussion was analyzed in more detail. Quotes from some of these assignments are provided as evidence of cognitive or affective outcomes in the sections below.

## 3. Results and Discussion

This section describes various teaching methods that have been used to instruct students about sustainability. Examples of the learning exercises completed by the students will be given, along with a description of the assessment method used to determine the success of the pedagogy. The teaching methods that will be described are: traditional lecture, in-class active learning, case studies, application of software tools, team-based design projects, and service-learning design projects.

### *3.1. Lecture*

A lecture can be used to provide basic information to assist students in reaching the knowledge and understanding levels in Bloom's taxonomy. This is an important foundation but only a start, and is therefore most appropriate in an introductory context such as courses targeting first year students. A good lecture can be constructed considering motivation-based learning theories [32,33]. This starts by explaining why someone should care about sustainability, including both intrinsic and extrinsic reasons. Intrinsic motivation is considered to be internal, due to interest or enjoyment. For example, informing students about climate change, carbon emissions, and declining natural resources may be interesting and provide motivation for sustainability via the global need to sustain human quality of life on the planet. Extrinsic motivation is due to external factors and the drive to attain an outcome. Extrinsic motivation can be tapped by explaining the demand to engineer sustainably as a job skill, including the move toward sustainability certifications for building and infrastructure.

The sustainability module embedded in the first year introductory courses for civil, environmental, and architectural engineering students at CU (ICE, IEE, IAE) included two to three lectures on sustainability. These were supplemented with required reading(s) [34–36]. The associated homework assignment required that the students define sustainable engineering, which readily enabled assessment of Bloom's level 1 for sustainability knowledge in the ASCE BOK2. For example, in 2009, 100% of the students discussed environmental aspects in their sustainability definition and over 97% included economic elements, but only 92%–96% of the students discussed social elements, and 51%–81% discussed the importance of future / long-term considerations [37]. This assessment led to an improved emphasis during lecture on elements that students tended to miss in their definitions.

### *3.2. In-Class Active Learning*

Active learning has been shown to increase knowledge acquisition among students, compared to traditional lectures [38]. Simple activities added into a lecture class can achieve active learning. In the first-year ICE and IEE courses the sustainability lecture included simple clicker questions. Clickers are active response systems that allow students to register an answer to multiple choice questions, and can be particularly effective in large courses [39,40]. Students were asked to identify the three pillars of sustainability, rate their level of personal familiarity with the terms sustainability and sustainable development, and opinion questions on the importance of sustainability to civil engineering and other disciplines. For example, in the 2011 class of first year civil engineering students, 62.5% were able to correctly identify the three pillars of sustainability prior to the lecture that presented that information.

In 2012, many of the clicker questions were revised to short think-pair-share activities where students first individually considered the question and registered their response, then turned to a neighbor and discussed the question, and then the whole class discussed the question. As an example, for the question "when do engineers think about sustainability", 56% answered before design, 44% answered during design; none answered during construction, operation, or maintenance. In reality the best answer would have been "all of the above" but this choice was not available to the students. This led to discussion around the issue, such as the importance to start thinking about sustainability before design and continue throughout the lifecycle of a project. On another discussion question many students indicated "Sustainability rating systems to compare designs must be specific to a type of project" (44%); this led to discussion contrasting the Leadership in Energy & Environmental Design (LEED) approach for sustainable buildings with different building categories [41] *versus* the ENVISION rating system intended to apply to all infrastructure [42]. In response to the same question, a large number of students (34%) agreed with the statement "Sustainability rating scores should be one attribute among many used to judge the best project". These questions are provided to supply examples of clicker questions designed to evoke discussion and students' active engagement, in contrast to questions with clear right or wrong answers that are used to evaluate students' knowledge of a specific topic.

More extensive active learning was used with the civil engineering module of the IE first-year course, when about 30 minutes of class time was devoted to a group-based activity. After a short lecture on sustainable engineering, the students were given the scorecard for the ENVISION Infrastructure Rating System [42]. They were asked to identify five point categories (of the 55 total categories) that could be mapped into each of the three pillars of sustainability. As a group, the students had the easiest time identifying environmentally-focused point categories, and the most difficult time with the economic elements. For example, the 'regional materials' category was often mischaracterized as an economic benefit. The groups also were asked to discuss the variable number of points available for each rating level in the different categories. While circulating around the class during this exercise, the instructor observed good discussions occurring and was able to answer questions. A written worksheet was turned in to document the group in-class activities. Students' performance on the in-class, group portion of the assignment averaged 86%, indicating that most students had reached the knowledge and comprehension cognitive levels of sustainability.

### *3.3. Case Studies*

A case study is a description of a real situation that provides rich learning opportunities by illustrating complexities [43,44]. The use of case studies allows students to develop higher levels of cognitive understanding of sustainability, including application and analysis. A case study that was constructed from a senior design project to remedy undersized wastewater evaporation lagoons for a Native American community [45] was used in the first year IEE course. This included a brief in-class presentation where students could ask questions. The students were also provided with the detailed case study write-up which included decision matrix tables, figures, and design information. The students then completed a homework assignment that included questions about the case study. In the final reflective essay one student wrote:

> "Learning about all the different types of water contamination and the methods for combating them reminded me that this is what I want to be doing with my life. One of the most interesting cases of water pollution we learned about was the one that took place on the Indian reservation. I thought the idea of using wetlands in place of the waste lagoon was such an interesting and novel idea. It's that kind of ingenuity that keeps makes me want to choose this career path."

In the first-year ICE course the Jubilee River project [34] was used as a case study as part of the homework assignment starting in 2010; in 2009, case studies were not included in the assignment. Starting in 2011, the US 97 Lava Butte case study [46] from the GreenRoads rating system [47] was added to the ICE homework assignment to replace other reading and writing questions. The case study approach seemed successful. Two example quotes that illustrate student understanding of sustainability are presented below:

> "MR-5 Regional Materials: four points were awarded in this category because 90% of the materials used were acquired from a 50-mile radius of the project site. This element contributes to sustainability by using local materials, which reduces the transportation of these materials to a

minimum. The reduction of transportation minimizes the use of fossil fuels when hauling the materials…"

"The project used only native, non-invasive plant species and didn't use any irrigation once the plant establishment period had passed. This contributes to the overall sustainability of the project because the native plants do not have a harmful effect on the ecosystem and help to avoid a future noxious weed issue. Having native plants also encourages wildlife and gives the structure a more natural and aesthetically pleasing look."

The IAE course used data from a LEED-platinum dormitory that was constructed on the University of Colorado Boulder campus as a case study. The students were provided with the LEED scorecard [41] and explanation of how the local dormitory met the criteria to earn these points. Two of the students in the course were living in the LEED-platinum dormitory, and other students were free to visit the dormitory on their own time. The case studies seemed to elicit some affective learning among the students, in addition to the cognitive outcomes. Nine of the 80 students discussed LEED in their final reflective essay on architectural or civil engineering, which reflected how the course content influenced their views and reflects progression through the affective domain to the "valuing" level [13]. Two example student quotes are provided below.

"Prior to CU structural was all I could think of and what I truly wanted to do. The thought of designing the means by which something can fight gravity, earthquakes and all nature … intrigued me far more than anything else. However, in this class… my view shifted away from just the design and science in architectural engineering and more towards the implementation and human element of the process. Thanks to lectures like that on Green Roads and LEED I found that design and science although great is not all there is. LEED in particular showed that the human/public element of large projects like buildings often outweigh the natural and physical forces that constrict design. Because of this I decided that to move more toward the human and public side of engineering (such as that in construction) would be just as good as structural just in a different realm."

"Before this class, I didn't understand how important "sustainability" is and how it is present in every aspect of every project. I thought that the LEED rating system was a little extensive at first, but soon realized that it was necessary and that we should value "green" engineering."

### *3.4. Software Tools*

The use of specialized software tools can be a valuable way to help students analyze sustainability aspects by assisting them in quantifying the various factors that relate to the sustainability of a project. Most software tools focus on quantifying the environmental impacts of an engineered product or process. Life cycle assessment (LCA) is a method to assess the environmental impacts associated with a product or process from cradle-to-grave including raw materials extraction and processing, manufacturing, transportation, use, upkeep, and disposal [48]. The most common environmental impacts that are assessed include energy use, natural resources consumption, and pollution effects (greenhouse gases, dioxin emissions, *etc.*). Software that conducts LCA is available such GaBi [49] and SimaPro [50]. However, the sophistication of these tools would require quite a bit of practice to master and as such may be most appropriate for courses dedicated to LCA. Alternatively, simpler software that targets specific project types is available. These can include the most basic sorts of environmental footprint analyzers online (e.g., [51]) to more complex, domain-specific software. In engineering, a variety of faculty have used various AutoDesk software tools to help students understand sustainable design [52–54].

The HWM and BR courses used the free, Excel-based Sustainable Remediation Tool (SRT) from the US Air Force Center for Environmental Excellence (AFCEE) [55]. The SRT can quantify various elements that impact the sustainability of different site remediation methods for contaminated soil and groundwater. This allows different remediation technologies to be compared on the basis of the sustainability indicators. These indicators are primarily environmental, including carbon dioxide, nitrogen oxides, sulfur oxide, and particulate matter emissions to the atmosphere; and total energy consumed. Economic impacts are represented by the lifecycle cost of the treatment process, and social impacts are represented by the amount of particulate matter emissions to air (which translates into negative human health) and safety/accident risk. However, it is unclear the extent to which students are able to thoughtfully interpret the results from this program. In 2013, the tool formed the basis for on an eight-question online quiz required as part of the HWM course. The overall scores on the quiz among the twenty students ranged from 26% to 86%. The students performed well on three questions that required them to identify the capabilities of the program in terms of the technologies and environmental impacts that it could evaluate by selecting multiple correct responses from among five choices; 80%–95% of the students answered these questions correctly. For example, 100% of the students recognized that carbon dioxide emissions to the atmosphere were an environmental impact computed by the program, but only 85% and 80% of the students correctly identified NOx emissions to the atmosphere and natural resource service in this manner. The wrong answers may have been due to not recognizing that these outputs were environmental impacts, or a lack of observing that these outputs were computed by the spreadsheet. The students disagreed on the most sustainable soil treatment method, with a three-way tie between the three options. In contrast, the instructor selected one technology as the most sustainable based on interpretation of the data, and felt that one other option was a distant second best, and the third clearly the worst. It is unclear if the students used different input values that led to different outputs from the software or interpreted the output data differently. This may alternatively indicate the limitations of multiple-choice questions to evaluate sustainability rather than a lack of analysis ability by the students. In the future, a better method is needed to assess students' sustainability analysis capabilities. The SRT software tool was also used in a BR course as part of two homework assignments and in the HWM course as part of one homework assignment; however, the scores for the sustainability analysis questions were not separately recorded.

### *3.5. Team Design Projects*

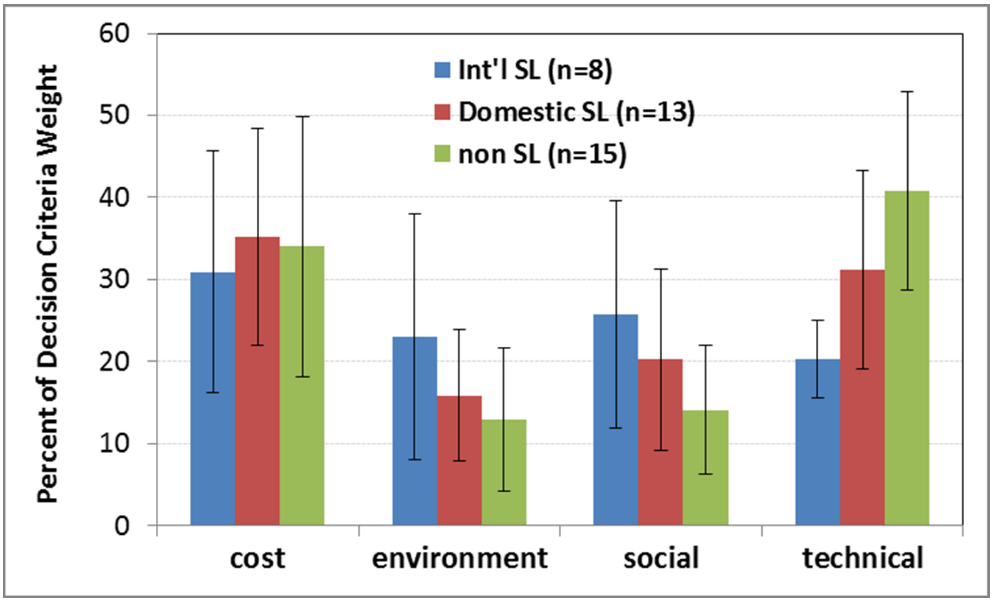
Design projects are a potential method to reach the synthesis level of Bloom's taxonomy for knowledge of sustainability. Working on these design projects in a team setting can help students to appreciate differences of opinion and work toward a consensus on the value of sustainability considerations within the design process. Design projects can vary significantly in terms of complexity and rigor.

In the ICE and IAE courses, students worked on teams using the West Point Bridge Designer software [56] to design a bridge that was judged on technical and sustainability factors. Each year the percentage of the assignment grade was varied between four factors: technical (the bridge must withstand the test-load with minimal deflection as shown within the computer program; 17%–25%); economic (capital cost as computed by the computer program; 33%–42%); environmental impacts (based on a discussion of design decisions related to excavation and materials use by the students; 22%–27%); and social factors (based on a combination of a "best" vote by all of the students in the course, which was largely driven by aesthetics, and a discussion by the students of safety and other factors; 13%–20%). Thus, what could be a purely cost and technical design exercise based on the software alone was modified in the assignment to embrace the pillars of sustainability. This simple three-week design project required students to consider and balance factors related to sustainability. In 2012, the eight teams of architectural engineering (AREN) students outperformed the eleven teams of civil engineering (CVEN) students on social factors (average 91% *versus* 79%, respectively; 2-tailed t-test $p$ value 0.07), were slightly better for environmental factors (average 91% *versus* 82%, respectively; $p = 0.40$); and both earned similar scores for cost (87%) and deflection (88%). Surveys among seniors at CU have found that there is a generally higher value placed on sustainability by AREN students compared to CVEN students, and the results from the design project support this finding. In the end-of-semester reflective essay assignment, one student wrote: "The bridge project opened my eyes to how much there is yet to learn. We used the West Point Bridge Designer, which does all the calculations of forces for us. Creating a bridge is more than just drawing something that looks good. There are many more factors that need to be added into it. The bridge project gave me a look at how much more there is to it."

Sustainability evaluation was added as an explicit requirement of the remediation feasibility studies in the HWM course in fall 2011. Teams of three to five students compared multiple options to remediate a site that was proposed to the US National Priorities List (to become so-called "Superfund" sites). The project instructions indicated that teams should "evaluate sustainability metrics for the treatment strategy" and recommended tools such as the SRT [55], SiteWise [57], and documents from the US Environmental Protection Agency [58]. For the previous ten years, the site project did not include this requirement. The outcomes among the projects provided evidence that sustainability was considered. Some groups quantified the carbon dioxide emissions associated with the process or energy consumption. Some groups used a sustainability framework for their weighted decision matrix that was used to compare remediation alternatives. For example, one team broke their decision criteria into four general categories: social, political, economic, and environmental, and all of the sub-criteria fell onto one of these categories. Another team explicitly included waste generated and carbon footprint (environmental impact, 12%), public perception and public health (social; 21%), and cost (economic, 40%) factors, among others such as time to meet remediation goals (which impacts both public health and the environment).

Within the EED course, sustainability was added as a specific lecture topic for the first time in 2009. Students were encouraged to consider sustainability early in the design process, starting in the early phases of identification of criteria and constraints and brain-storming possible solutions, and continuing into selecting an approach and the details of the design. However, the students were not explicitly required to include sustainability considerations within their projects. Some of the project descriptions from the clients or community partners discussed sustainability goals, while others did not. For example, in spring 2013 only three of ten projects included the word sustainability in the project description. The simplest reflection of the value that students' placed on sustainability was evident in the criteria that were used to select the best design option from multiple options. The criteria could be generally categorized as technical, economic, environmental, and social. In some cases, "sustainability" was also explicitly one of the criteria, but the description generally indicated that this was primarily environmental factors such as carbon footprint and waste minimization. Strong value on sustainable design might translate into selecting a technology based on a balance between factors rather than an over-emphasis on a single factor (such as cost). Figure 1 summarizes the average importance that the student design teams assigned to various factors that contribute to sustainability. Results varied widely between the different project teams, with some considering environmental or social factors to a very small degree (less than 10 percent weight among the design selection criteria).

**Figure 1.** Percentage of weighted decision matrix allocated to different categories of criteria from the alternatives assessment reports in the CU EED course. The team projects were separated into three types: international service-learning (SL), domestic SL, and non-SL projects. The average and standard deviation is shown.




A professional practices assessment was completed by the individual students in the design class per the Transferable Integrated Design Engineering Education (TIDEE) guidelines [24]. This required the students to rate the importance to the project and proficiency demonstrated in the project for seven areas of professional responsibility. The importance rating used a scale of 1 to 3 (1 = low, 2 = medium, 3 = high). The average ratings by the students were: communication honesty (2.8) > sustainability (2.5) > health/safety/well-being (2.4) > work competence = financial responsibility (2.3) > social responsibility (2.1) > property ownership (1.7). All of these areas relate to sustainability in some manner, thus, it was good that the importance of each was deemed of at least medium importance, on average. The achievement ratings used a scale of 0 to 3 (0 = not applied, 1 = low, 2 = medium, 3 = high), and were lower than the importance ratings. The largest differences were in property ownership (1.1), financial responsibility (0.9), social responsibility (0.6), and sustainability (0.5); these differences were statistically significant in paired t-tests. An example of a student's discussion of sustainability application in the project is given below:

> "Sustainability, or the ability to find an effective balance between the areas of economics, social, and technical aspects is very important… To make sure that we looked at all alternatives in a sustainable way, our team created a decision matrix with the aid of the [client]. With his help our team devised a way to rate all alternatives against the same scale and judge their sustainable impact. Through this process we were able to find the appropriate alternative for the airport that was sustainable."

The final reflective essays in the EED course also indicated that some students had considered sustainability in-depth:

> "The project conducted by my team was providing design options to reduce the greenhouse gas emissions of a wastewater treatment facility. While Pleasantville is not an actual location, the citizens would be concerned about the economic status of our project because their tax dollars would be funding our proposed designs. If Pleasantville was an environmentally progressive city, then environmental issues would also be a concern. The wastewater treatment facility's employees would be another important stakeholder and it would be our job to ensure a safe workplace for these employees. The citizens would also be concerned about the quality of their water but this aspect is addressed through state and federal regulations. Regardless of whether the job taken on by an engineer is serving a hundred people or a million people, there will always be stakeholders involved with social, cultural and economic agendas that an engineer must address. These aspects may not contribute to the technical success of a design, but they will play a vital role in the public acceptance and moral integrity of a design."

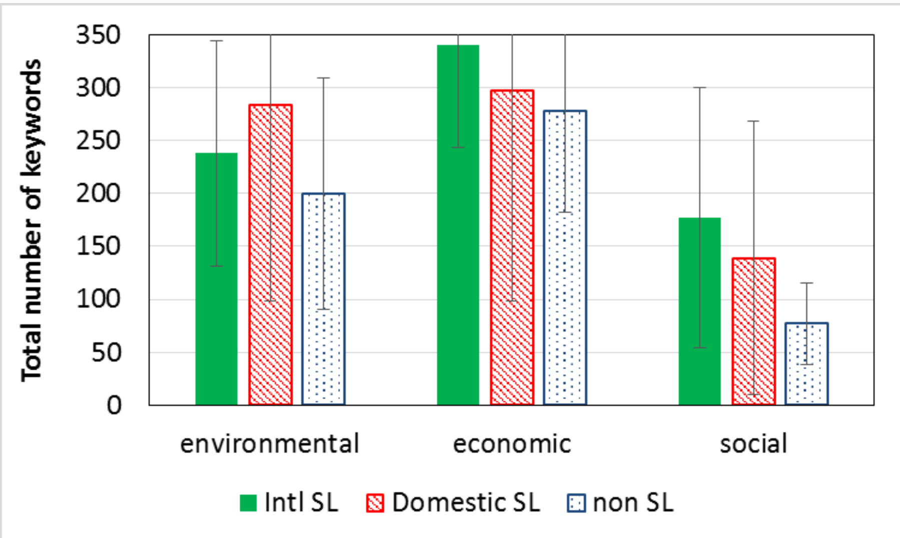
This student seemed to understand the importance of holistic considerations of the interplay between the technical, economic, environmental, and social aspects of engineering design.

### *3.6. Service-Learning Design Projects*

Service-learning (SL) may be an effective pedagogy to achieve sustainability learning outcomes [59–61]. The integration of sustainability learning goals with service-learning has been previously discussed by others [62–65]. In particular, community-based design projects may provide an opportunity to achieve higher level cognitive and affective sustainability learning outcomes among students. A number of learning theories offer a wide range of reasons why service-learning is a particularly effective teaching method [22,23,66]. A sub-set of the projects in the CU EED course were service-learning projects [25]. These were typically projects conducted for a non-profit facilitation group rather than directly with a community partner. Working with these groups alleviated the burden on the faculty instructor to locate appropriate community partners, and these groups also ensured that engagement with the community extended beyond the timeframe of the single-semester course. Two common partners were Engineers Without Borders (EWB-USA) and the International Center for Appropriate and Sustainable Technology (iCAST). Sustainability is a mission of both groups, keeping this goal at the forefront for the students who worked on these projects. Students who worked on these SL projects selected to do so from among a range of project options.

The complex and real situations associated with the SL projects required students to think holistically and more fully encounter the challenges associated with sustainability than the non-SL projects. Evidence of these differences between SL and non-SL projects can be found in the higher importance that SL students placed on social-related decision criteria compared to non-SL projects (Figure 1). This greater appreciation for the social dimensions of sustainability driven by community-specific concerns was also reflected in content analysis of the final design reports (Figure 2). Figure 2 shows the average number of sustainability-related keywords in the final team reports. The SL project design reports contained more social-related keywords than non-SL projects. The ten most commonly used social keywords, ranging from most to least common, were: community, regulations, health, safety, public, social, educate, policy, culture, and job. Overall, social-related terms were used less frequently than economic or environmental terms. Considerations of economic factors was the most predominant in the SL projects for international developing communities. The ten most predominant economic keywords in the reports were: cost, pay, economic, investment, financial, income, infrastructure, afford, money, and profit. The total number of environmental keywords was the highest among the domestic SL projects. The ten most prevalent environmental keywords were: energy, environment, contaminant, sanitation, climate, population, pollution, renewable, natural resources, and recycle. The word *sustainability* was counted in the international SL, domestic SL, and non-SL project reports an average of 21.8, 7.3, and 8.6 times, respectively.

**Figure 2.** Total counts of keywords in the final design reports from the EED course. A set of environmental, economic, and social keywords were counted. The team projects were separated into three types: international service-learning (SL), domestic SL, and non-SL projects. The average and standard deviation is shown.




Although all of the design projects considered sustainability-related ideas to some extent, it appears that SL projects may lend themselves more readily to EfS goals. If sustainable engineering is a key learning objective, then project partners and projects must be carefully selected to ensure that these goals will be met. Appropriately structured prompts for written reflection assignments to the students can also help to ensure that sustainability learning objectives are achieved. One of the students who worked on a local SL project wrote:

> "We designed a short and long term solution for improving and upgrading a very small wastewater treatment plant for a small community… It really drove home the reality of this project for me to hear [the operator] talking about how he had already implemented some of our suggestions. We realized just how important it was to provide a cost effective solution because the property manager really does not want to pay for any upgrades. That causes an imbalance between the best interest of the environment and quite possibly the health of the community. This is therefore an opportunity for us as engineers to help bridge that gap."

In contrast, some of the students who worked on projects for distant, international communities expressed frustrations with a lack of direct contact with the community. Excerpts from two of the student reflection essays illustrating this idea are provided below:

> "I chose this project and wanted to design a system to give the people of [the community] high quality drinking water. [But many of my questions] could only really be answered by a visit to the community. Since this was relatively impossible, it became very frustrating and confusing…. There was no contact with the community other than what we could learn from [our in-country liaison].... The whole point is that they are developing communities implying that communication, money, and other factors are going to be a problem. As soon as money is introduced compromises must be made and everything becomes more complicated. [Engineers] are [not only] expected to know the math behind design but also the economics, sustainability, social factors, any science involved, business management, laws, *etc.*"

> "[S]everal NGOs [requested] 'improved, low-cost household sanitation designs that can be sustainably applied to flood prone areas'. This idea of a "sustainable" solution implies that the ideal design will be cost effective, appropriate for the area, protective of the environment, and able to stand the test of time among other things. The real problems are related to funding, socio-economics, public perceptions, and various other cultural characteristics. Perhaps, as engineers, we should focus on acting as technical experts and leave the community development piece to other disciplines. If this is the case, however, it would be beneficial for our projects to incorporate multi-disciplinary teamwork. In hindsight, I believe more could be learned about engineering in development from projects with local actors who are readily available for discussion and feedback than those which involve far off developing countries."

Another student wrote about an interest in conducting a richer consideration of sustainability:

> "I feel that thus far the sustainability portion of the project has been pretty superficial. It has been an aspect that we have considered in terms of $CO_2$ emissions and other pollutants. …we should include a section about how renewable energy helps the sustainable future of [the country] by not only curbing emissions but stimulating the local economy through manufacturing, and teaching the technical trade of installation and maintenance of solar thermal technologies."

These quotes indicate that the students were trying to create sustainable designs for their community partners and appreciated the complex nature of striving for sustainable development. SL projects for both domestic and international communities helped students learn about sustainability. SL projects that partnered with local communities allowed more frequent and authentic interaction between the students and the community.

## 4. Summary and Conclusions

A thoughtfully designed curriculum for engineering students would embed sustainability-related learning activities into a broad range of required courses using a coordinated approach. This is the methodology required by the civil engineering degree accreditation process in the UK which requires a sustainability thread. A sustainability thread sends the message of "normalized sustainability" to students; that sustainability should always be considered in engineering and that good design is sustainable design [67]. Sustainability-related learning activities should be thoughtfully coordinated to build to higher cognitive and affective outcomes through the curriculum. A diversity of teaching approaches and student learning activities provided a good method to reach synthesis level cognitive skills. Students enter college differing in the amount to which they value and have knowledge of sustainability, sustainable development, and sustainable engineering. After initial courses present basic information enabling students to define and understand sustainability, increasingly complex tasks such as case study analysis, use of software to compute impacts, and design projects can develop higher order cognitive skills around sustainability. Assignments should be carefully designed to provide authentic learning experiences and evaluated to enable the assessment of targeted sustainability learning outcomes. In-class active learning may provide a good opportunity for formative assessment, while project reports can be used for summative assessment. While examples for civil and environmental engineering students have been provided in this manuscript, these types of activities could be readily adapted to a wide diversity of different disciplines.

While the approaches to teach and assess cognitive skills are reasonably straight forward, the path to successfully achieve affective outcomes is less clear. The goals of EfS are richer than reaching a laundry list of cognitive competencies among students. A curriculum truly designed with EfS in mind would likely require a paradigm shift in engineering. For example, reflective essays with appropriate prompts may encourage students to consider the value that they place on sustainability both personally and professionally, and this information could also be used to assess affective outcomes. However, engineering students are often uncomfortable engaging in these open-ended explorations of their values, feelings, and emotions. Research on the sustainability attitudes among engineering students have found that more positive attitudes about sustainability were correlated with student participation in experiential learning activities such as extracurricular clubs and study abroad [18]. However, it is unclear the extent to which students with sustainability values sought out these experiences *versus* the benefit of these activities in promoting sustainability values. More research is needed to understand which teaching methods are the most effective at promoting positive affective gains toward sustainability values among students. As there is variation in learning styles among individuals, a variation in teaching methods and learning experiences might be the best approach to instill sustainability knowledge and values in students.

## Conflicts of Interest

The author declares no conflict of interest.

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