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Development and Application of a Sustainable Design Rubric to Evaluate Student Abilities to Incorporate Sustainability into Capstone Design Projects

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Introduction

Sustainable Development

Sustainable development has emerged as a promising strategy for combating unsustainable patterns of population growth, resource consumption, poverty, and environmental degradation. The most widely accepted definition of sustainable development, published by the United Nations World Commission on Environment and Development (UNWCED) in 1987, states that sustainable development is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs[1]". The Johannesburg Declaration, released after the UN World Summit on Sustainable Development (UNWSSD), later proposed the three pillars of sustainable development to be economic development, social development, and environmental protection[2]. While endorsing sustainability requires valuing all three dimensions, it has been suggested that the environmental dimension is often over-emphasized[3,4,5,6], while the less developed social dimension is underemphasized[7]. Some authors have suggested that additional dimensions be added to the three-pillars conceptual framework, including temporal[8] and institutional dimensions[9]. Nevertheless, the dimensions of sustainability are complex and interrelated, and promoting sustainable development requires that tradeoffs between dimensions be simultaneously balanced.

Sustainability and Engineering Education

Although technological innovation has contributed to unsustainable practices, engineering is an important field for developing and implementing sustainable development strategies. Sustainable engineering has emerged as a new field aimed at integrating and balancing economic, environmental, and social systems during development[10]. While there may be a new breed of sustainable engineers, the National Research Council (NRC) speculates that there is a need for practioners from all engineering disciplines to promote sustainability through sustainable design[11]. Engineering design is fundamentally "a creative decision-making process that aims to find an optimal balance of trade-offs in the production of an artifact that best satisfies customer and other stakeholder preferences[12]". Sustainable design only requires that sustainability principles be incorporated into this complex decision-making process to promote consideration of and balance between the three sustainability pillars. Describing this innovative approach to design, Skerlos et.al.[12] states that sustainable design "brings focus" to the design process, while McLennan[13] says that sustainable design "expand[s] the definition of good design to include a wider set of issues". Overall, designing for sustainability is not an alternative to traditional engineering design; rather, it is a more holistic design paradigm. To train students to engage in sustainable design, efforts are needed to incorporate sustainability into undergraduate engineering courses.

Despite the need for sustainability-conscious engineers, undergraduate engineering programs may not properly equip students with the knowledge and skills necessary to engage in sustainable design. Specifically, curricula in higher education have been criticized as emphasizing disciplinary specialization and reductionist thinking[14,15,16]. As a result, many graduates are "unbalanced, over-specialized, and mono-disciplinary graduates" who use their narrow skill sets to solve problems by analyzing system components in isolation[16]. In contrast, the complex nature of global and local dilemmas necessitates that engineers exercise interdisciplinary and systems thinking to understand and balance the interrelated technical, economical, environmental, and social dimensions of a problem[17]. Thus, significant changes are needed to integrate sustainability content into the curricula of undergraduate engineering programs to effectively enable students to tackle complex global dilemmas.

Reform in engineering education can begin by instituting assessments and evaluations to benchmark the effectiveness of current course sequences. Tools for examining the sustainability content of curricula[18,19] and the quality of resulting student sustainability knowledge[20,21] have been discussed in the literature. However, techniques for capturing the extent to which students engage in sustainable design are not currently available. Given that the ultimate goal of sustainable engineering education is to train engineers to incorporate sustainability considerations into their professional practices, it is critical that a tool be developed to evaluate sustainable design skills.

Study Outline

The goal of this study is to develop and apply a sustainable design rubric that can be used to evaluate student abilities to incorporate sustainability principles into capstone design projects. Specifically, the rubric was designed to answer the following research questions: (1) What are the expectations related to sustainable design for student projects? (2) To what extent do students actually incorporate sustainability into their design projects? (3) What is the impact of sponsor expectations on student sustainable design performance? Afterward, the rubric was used to examine project reports compiled by civil and environmental engineering (CEE) students at the Georgia Institute of Technology (Georgia Tech) during a Fall 2011 capstone design course. Results were analyzed to provide insights for improving sustainability education in CEE at Georgia Tech and abroad.

Background

Curricular Reform to Support Sustainable Engineering Education

1. Endorsements for Curricular Reform

Given the potential for sustainability-conscious engineers to impact future developments, several organizations have endorsed integration of sustainability into engineering education. For instance, the Accreditation Board for Engineering and Technology (ABET) requires that students possess "the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context[22]". Furthermore, the American Association of Engineering Societies (AAES) state in their cannons of professional conduct that "engineers shall hold paramount the safety, health and welfare of the public and shall strive to comply with the principles of sustainable development in the performance of their professional duties[23]". In 2010, The National Science Foundation (NSF) created an investment area in Science, Engineering, and Education for Sustainability (SEES) to "promote the research and education needed to address the challenges of creating a sustainable human future[24]". In 1996, the American Society of Civil Engineers (ASCE) revised its Code of Ethics to include sustainability principles as part of the canon of civil engineering practices[25]. Other professional organizations, including the Institute of Electrical and Electronics Engineers (IEEE), the American Society of Mechanical Engineers (ASME), and the American Society of Chemical Engineers (AIChE) have endorsed sustainability education[26,27].

2. Types of Curricular Reform

Two common methods for effective incorporation of sustainability into university curricula include horizontal and vertical integration. Horizontal integration is a strategy where sustainability concepts are incorporated into several courses across a program, while vertical integration involves the addition of new sustainability courses into an existing curriculum[28]. Dissemination of a new course with sustainability content is essential for teaching students about fundamental concepts and principles related to sustainability[29]. However, vertical integration alone may be insufficient because only teaching students about sustainability in isolation from core engineering concepts does not encourage them to incorporate sustainability into their professional designs and practices[29]. Rather, integration of sustainability into existing courses may aid students in viewing sustainability holistically by demonstrating how sustainability and technical content can be blended to create sustainable designs[28,29].

3. Status of Curricular Reform

Engineering programs across the United States (US) have initiated a variety of reform efforts. As part of a study sponsored by the Environmental Protection Agency (US-EPA), course materials from a variety of engineering disciplines and institutions were examined[30]. Of the approximately 150 courses examined, only 23% aimed to integrate sustainable engineering concepts into traditional engineering courses (i.e. horizontal integration). In contrast, 77% of the courses represented vertical integration, either by having sustainable engineering as the dominant theme (48%), focusing on sustainable technologies for developing sustainable solutions (14%), or being interdisciplinary (co-taught by engineering and non-engineering faculty) (15%). Thus, this investigation shows that vertical integration is the most commonly implemented strategy of curricular reform. While it is certainly positive that many institutions are recognizing the need to train sustainability-conscious engineers, the emphasis on vertical integration may promote the misconception that sustainability is to be considered apart from or as an afterthought of the design process[31].

Using Rubrics to Evaluate Sustainable Design

1. Uses of Rubrics

Rubrics are simply scoring tools that detail the expectations and requirements for an assignment[32]. Specifically, rubrics are advantageous when a "judgment of quality" is required to critique a work, which is often the case for writing samples[33]. More generally, rubrics are used to judge the quality of constructs (e.g. reports, presentations, etc.) made by students during performance tests, which require students to exhibit high-level skills to complete an authentic (i.e. real-world) challenge[34]. As a result, rubrics are commonly used in the classroom as both assessment and teaching tools to enhance student learning[35]. For instance, an instructor may provide students with a rubric to guide them in completion of a task. Reflecting on the rubric helps students assess their own work and provides the instructor with a tool for grading the assignment and providing feedback[35]. Alternatively, rubrics may be used for evaluation purposes to track changes in educational programs over time due to reform efforts[32,36]. In engineering education, rubrics have been used widely to assess and evaluate many complex skills, including critical thinking [37] and integration of interdisciplinary knowledge[21].

2. Types of Rubrics

No matter the intended use, rubrics are generally classified into two categories. A holistic rubric is one that requires a judge to make a single, overall judgment about the quality of student work[38]. Alternatively, an analytic rubric includes specific criteria with more than one level of achievement to aid evaluators in scoring quality based on several aspects or components[39]. It has been argued that analytic scoring provides a more objective assessment of construct quality because it minimizes biases that may impact holistic judgments[38]. For examples of holistic and analytic rubrics, see Ralston & Bays[37].

3. Developing a Rubric

As summarized by Allen & Tanner[39], one common strategy for creating rubrics is to individually describe their defining components. For example, the four basic components of an analytic rubric are the task description, dimensions, scale, and dimension descriptors[36,37]. The task description captures the overall purpose of the assignment or task, while the dimensions encompass those criteria by which the task will be judged. The scale defines different achievement levels for student performance and may be reflected by numbers (e.g. 1, 2, 3, 4) and descriptors (e.g. exemplary, competent, developing, unacceptable). Finally, the dimension descriptors describe clearly the requirements for meeting each performance level for each criterion. See Ralston & Bays[37] for a rubric diagram with labeled components. In addition to these four components, it is critical that performance levels for criteria are observable and measureable. In essence, developers must have a "clear picture" of what attaining each performance level for a criterion "looks like[39]".

4. Potential Frameworks for a Sustainable Design Rubric

Developing a sustainable design rubric requires a set of criteria by which to judge design performance. A number of rating systems are available for quantifying the sustainability of large infrastructure projects, including Leadership in Energy and Environmental Design (LEED) and Envision™, which may provide insights for judging student projects. Alternatively, the 9 Principles of Sustainable Engineering may serve as the foundation for an evaluation tool.

LEED encompasses a suite of rating systems developed by the US Green Building Council (USGBC) that can be used to measure the sustainability of a variety of buildings, including homes, schools, and even neighborhoods. The basic concept behind the LEED framework is that projects earn points for meeting green building criteria that fall within five main credit categories: sustainable sites, water efficiency, energy and atmosphere, materials and resources, and indoor environmental quality. Depending on the project type, points may be required in additional credit categories. For example, LEED-certified neighborhoods must earn points in smart location and linkage, neighborhood pattern and design, as well as green infrastructure and buildings credit categories. Bonus credits are also available, including incentives for innovation in design. Once a specified number of points are earned, then the project can become certified. Buildings earning at least 40 points are considered "certified," while projects earning at least 80 points are "platinum-certified." For more information on LEED, readers are referred to the USGBC website[40] or Kubba[41].

Envision™, developed by the Zofnass Program for Sustainable Infrastructure at Harvard University and the Institute for Sustainable Infrastructure (ISI), is a newer system that provides a "holistic" framework for evaluating the sustainability of infrastructure projects. In fact, the rating system evaluates the community, environmental, and economic benefits of projects, which is in alignment with the three sustainability pillars proposed in the Johannesburg Declaration[2]. More specifically, the rating system includes 60 sustainability criteria that comprise five sections: quality of life, leadership, resource allocation, natural world, as well as climate and risk. Like the LEED systems, additional credits can be earned for innovative strategies and technologies. For each criterion, there is a set of metrics, levels of achievement (improved, enhanced, superior, and conserving), and explanations for how to advance in achievement level. For additional details, please consult the Envision™ website[42].

While a number of detailed rating systems are available for guiding sustainable development of civil infrastructure, the Nine Principles of Sustainable Engineering may serve as a more general framework for engaging in sustainable design (Table 1). These Principles were developed by a group of sustainable engineering experts gathered at a 2002 Green Engineering Conference held in Sandestin, FL. The intent of proposing the Principles were to "provide a paradigm in which engineers can design products and services to meet societal needs with minimal impact on the global ecosystem[43]". While the Principles do not outline a sustainable design methodology, they can be used with existing design strategies to produce sustainable projects[43]. In fact, many of the Principles are reflected in both the LEED and Envision™ rating systems. For instance, both systems provide criteria for resource use and allocation, which broadly align with the Principle "minimize depletion of natural resources." In addition, both LEED and Envision™ provide extra points for particularly innovative projects. Indeed, one of the sustainable engineering principles directs engineers to "create engineering solutions beyond current or dominant technologies." Overall, the Nine Principles of Sustainable Engineering provide broad and generalizable guidance for engaging in sustainable design.

Table 1. Sustainable engineering principles [Adapted from Abraham[43]].

No.	Description of Principle
1.	Engineer processes and products holistically using system analysis.
2.	Conserve and improve natural ecosystems, while protecting human health and well-being.
3.	Use life cycle thinking in all engineering activities.
4.	Ensure that all material/energy inputs/outputs are as inherently safe and benign as possible
5.	Minimize depletion of natural resources.
6.	Strive to prevent waste.
7.	Develop/apply engineering solutions, while considering local circumstances and cultures.
8.	Create engineering solutions beyond current or dominant technologies.
9.	Actively engage communities and stakeholders in development of engineering solutions.

Context: Civil and Environmental Engineering at the Georgia Institute of Technology

The School of CEE at Georgia Tech confers Bachelor of Science degrees in both Civil and Environmental Engineering. Home to over 60 tenure-track faculty, CEE programs conferred degrees to over 200 undergraduates during the 2011-2012 academic year. The CEE faculty and administration pride themselves in their commitment to "balanc[ing] the built environmental and the natural environment, while addressing the complex challenges of globalization in the 21st century[44]". Related to this endeavor, CEE faculty members have begun to enhance undergraduate engineering education through the incorporation of sustainability concepts and principles into their courses. One approach for gauging the effectiveness of these efforts is to examine the ability of seniors enrolled in the capstone design course to incorporate sustainability into the design process.

Sustainability Education in CEE at Georgia Tech

Two sustainability-focused courses have been vertically integrated into the CEE curriculum at Georgia Tech. First, the Civil Engineering Systems course (CEE 3000) was created in 1999 in response to a university-wide sustainability initiative. Required for all CEE undergraduates, CEE 3000 is intended to introduce students to sustainability from a systems perspective. The course includes three modules: Systems and Sustainability Perspectives, Systems Performance Analysis, and Economic Decision-Making Tools and Project Evaluation. In addition, students are required to complete a final project that requires a sustainability analysis of an existing civil infrastructure system. More recently, a new elective entitled Sustainable Engineering (CEE 4803/8813) was created for students to further enrich their knowledge of sustainability. Topics include industrial ecology, earth systems engineering and management, integration of environmental/social/ economic issues, life cycle assessment, and material flow analysis. Students also collaboratively work to develop and apply class principles to a problem of interest. Thus, the CEE curriculum exposes all students to sustainability, while providing opportunities for motivated students to engage in more in-depth learning[45,46].

Many instructors have also sought to horizontally integrate sustainability into the program by adding sustainability content to existing courses. In a 2008 Self-Study Report prepared for the Accreditation Board for Engineering and Technology (ABET), faculty were asked to indicate the contribution of their courses to providing students with "a broad education and knowledge of contemporary issues necessary to understand the impact of civil engineering solutions in a global, social, and environmental context." Instructors from over 15 of the approximately 40 courses said that their courses provided a "high" contribution to sustainability education. Examples of courses whose instructors have indicated a high level of sustainability content include Environmental Engineering Principles (CEE 2300), Geosystems Engineering Design

(4410), and Transportation Planning, Operations, and Design (CEE 4600)[47]. Additional details about the Self-Study Report are available[48].

Capstone Design

After students complete core CEE courses, they are required to participate in a capstone design experience to practice application of their engineering knowledge. First, students form "companies" by self-organizing into groups of 4-5 students. Students may create specialized companies by joining with students from similar concentrations (construction, environmental, geotechnical, structures, transportation, or water resources), or create general civil engineering firms by including students from multiple concentrations.

Within the first three weeks of class, students compile and submit a statement of qualifications (SOQ) in response to a real request for qualifications (RFQ). For example, one semester students recently prepared SOQs in response to an RFQ from Barrow County, GA for preliminary and final design of a local bypass. Completion of the SOQ assignment is intended to encourage groups to quickly learn about the expertise of group members and overall group dynamics.

Student companies may select from a variety of authentic projects provided by design firms, industries, and government agencies. Typical projects include design and/or modification of bridges, roadways, wastewater treatment plants, multi-use paths, and stormwater management systems. After selecting a project, students meet with the project sponsor to discuss project goals and expectations. Throughout the semester, design teams meet regularly with project sponsors and a faculty mentor. At the end of the semester, student groups present final projects to sponsors, faculty, and classmates. Final grades are determined by faculty and sponsor panels.

Methods: Development of a Sustainable Design Rubric

An analytical sustainable design rubric was developed to aid quantifying students' abilities to incorporate sustainability into capstone design projects. In designing the rubric, one goal was to produce a tool that could be easily applied to a variety of CEE-related student projects. Because of the structure of the capstone design, the rubric needed to capture not only the extent to which students engage in sustainable design, but also the influence of project sponsors and/or course instructors on sustainable design expectations. Development of this tool was completed using a three-phase process.

Phase 1: Researching Existing Sustainability Evaluation Frameworks

In Phase 1, existing frameworks potentially applicable for evaluating sustainability content of student design projects were investigated. LEED, which provides a comprehensive rating system for quantifying the sustainability of buildings[41], was deemed inappropriate because it would not allow for evaluation of wide range of CEE student projects, such as those related to transportation or environmental engineering. While Envision™ was developed to be applicable for a variety of infrastructure projects[49], it requires scoring of 60 criteria, which would be tedious to apply to student projects. Even if time were available to complete the evaluation, many of the criteria are too detailed to be addressed in a semester- or year-long project. For instance, to meet the "assess climate threat" criterion (CR2.1) students would have to complete a Climate Impact Assessment and Adaptation Plan. Similarly, to meet the "reduce net embodied energy" criterion (RA1.1), students would have to complete a life-cycle energy assessment. Overall, existing project-level assessment frameworks were concluded to be too narrow in scope and/or require unreasonably detailed design analysis for student capstone projects.

Although no existing frameworks were found to be applicable to student projects, the 9 Principles of Sustainable Engineering were found to be a promising foundation for developing a set of sustainable design criteria (Table 1). Not only are the 9 Principles applicable to a range of CEE capstone projects, they are also relevant for other engineering disciplines. Second, basing project evaluation criteria on expert-derived sustainability principles is advantageous because it helps promote content validity of the evaluation tool. Thus, the 9 Principles were identified as a more suitable framework for evaluating student design projects than existing tools for large-scale projects.

Phase 2: Developing a Preliminary Project Evaluation Rubric

During Phase 2, a preliminary project evaluation rubric was developed based on the 9 Principles of Sustainable Engineering and the four basic components of an analytical rubric, as suggested by Allen & Tanner[39]. Since many of the 9 principles are complex and incorporate multiple ideas, each principle was decomposed into discrete design criteria to aid in ease of rubric application. For instance, the second principle (Table 1) was separated into two sustainable design criteria: (1) conserve natural ecosystems and (2) protect human health and well-being. Deconstruction of the 9 Principles yielded 13 sustainable design criteria. Since the economic dimension of sustainability is not explicitly represented by the 9 Principles, the set of 13 criteria was supplemented with three economic design criteria. As a result, a system of 16 sustainable design criteria by which to judge the sustainability content of student capstone projects was established (Table 2).

To aid judges in identifying application of criteria in project reports, a set of examples for how the 16 criteria may be met in CEE projects was compiled. This phase was essential for elucidating what each criterion "looks like" in student projects, as suggested by Allen & Tanner[39]. First, capstone design reports completed by Georgia Tech CEE students in Fall 2010 were evaluated using the rubric, and instances of criteria consideration were recorded. Afterward, Fall 2007 projects were examined using the amended rubric and any new examples were recorded. This process was repeated for Fall 2004 and Fall 2001 projects. As a result, a comprehensive list summarizing how CEE students may incorporate sustainable design criteria into capstone projects was developed to supplement the rubric.

Two four-point rating scales were created to aid evaluators in judging capstone reports based on the 16 sustainable design criteria (Table 3). The earned points scale captures the extent to which students consider each sustainable design criterion in their capstone projects. A score of 0 corresponds to a project that shows no evidence of incorporating the design criterion, while a score of 3 is assigned if the project shows evidence of extensive criterion application. Application of the earned points scale for some criteria requires additional specifications (Table S1). The potential points scale describes the extent to which each sustainable design criterion is applicable to a given capstone project. A score of 0 is awarded if the criterion is not applicable to the project, while a score of 3 is assigned if the criterion is not only applicable, but consideration was dictated by an instructor or project sponsor. Rating projects on both the extent of consideration and level of applicability allows for differentiation between sustainability application due to student motivation and sponsor requests.

Several metrics were designated to evaluate and compare rubric scores (Table 4). Raw scores for each criterion (i), including earned (E_i) and potential (P_i) points, were used to provide insights into the extent of criterion consideration and level of criterion applicability, respectively. Using raw scores, means for each rubric category (environmental, social, sustainable design tools, and economic) were also computed. The final sustainable design index was quantified as the difference between mean potential (M_{pot}) and mean earned (M_{earn}) scores. As a result, a sustainable design index of +3 represents a project with high sustainable design expectations and low student performance. Conversely, an index of -3 is characteristic of a project with low sustainable design requirements and high student performance. A sustainable design index near zero represents a project that largely met sustainable design expectations (Figure 1).

Table 2. Sample scoring rubric, including the 16 sustainable design criteria, used to evaluate capstone design projects.

Design Criteria	Potential Points[a]	Earned Points[a]
Environmental Design Criteria	1-3	0-3
Minimizes natural resource depletion	1-3	0-3
Prevents waste	1-3	0-3
Protects natural ecosystems	1-3	0-3
Uses renewable energy sources	1-3	0-3
Uses inherently safe and benign materials (to environment)	1-3	0-3
Social Design Criteria		
Addresses community and stakeholder requests	1-3	0-3
Considers local circumstances and cultures	1-3	0-3
Protects human health and well-being	3	0-3
Uses inherently safe and benign materials (to humans)	1-3	0-3
Use of Sustainable Design Tools		
Incorporates life cycle analysis	1-3	0-3
Incorporates environmental impact assessment tools	1-3	0-3
Incorporates systems analysis	1-3	0-3
Uses innovative technologies to achieve sustainability	1-3	0-3
Economic Design Criteria		
Consider economic impacts of promoting environmental sustainability.	1-3	0-3
Consider economic impacts of promoting social sustainability.	1-3	0-3
Conduct a cost and/or cost-benefit analysis	2	0-3

[a]See Table 3 for potential and earned points rating scales. Values shown below were conventions used for the current investigation.

Table 3. Rating scale for extent of consideration of sustainable design criteria (earned points) and the level of applicability of sustainable design criteria (potential points).

Score	Descriptor	Dimension Description
Earned Points Scale		
0	Unacceptable	Criterion not at all considered in project report.
1	Developing	Criterion mentioned or discussed in the project report, but not applied in design process.
2	Competent	Project report shows evidence that the criterion was adequately applied in design process (1-2 instances of criterion application).
3	Exemplary	Project report shows evidence that the criterion was extensively applied in the design process (3 or more instances of criterion application).
Potential Points Scale		
0	Inapplicable	The criterion is not at all valid for the project.
1	Valid	Although the sponsor does not require application of the criterion, it is still applicable to the project.
2	Required	The sponsor requires some application of the criterion in the project (1-2 instances of requiring criterion application).
3	Critical	The sponsor requires extensive application of the criterion in the project (3 or more instances of requiring criterion application).

Table 4. Sustainable design metrics for use with the Sustainable Design Rubric.

	Range	Potential Scale	Earned Scale
Environmental Design Mean	[0, 3]	$M_{env,pot} = \sum_{i=1}^{5} P_i \big/ 5$	$M_{env,pot} = \sum_{i=1}^{5} E_i \big/ 5$
Social Design Mean	[0, 3]	$M_{soc,pot} = \sum_{i=6}^{9} P_i \big/ 4$	$M_{soc,pot} = \sum_{i=6}^{9} E_i \big/ 4$
Sustainable Design Tools Mean	[0, 3]	$M_{tools,pot} = \sum_{i=10}^{13} P_i \big/ 4$	$M_{tools,pot} = \sum_{i=10}^{13} E_i \big/ 4$
Economic Design Mean	[0, 3]	$M_{tools,pot} = \sum_{i=14}^{16} P_i \big/ 3$	$M_{tools,pot} = \sum_{i=14}^{16} E_i \big/ 3$
Potential or Earned Score Mean	[0, 3]	$M_{pot} = \sum_{i=1}^{16} P_i \big/ 16$	$M_{earn} = \sum_{i=1}^{16} E_i \big/ 16$
Sustainable Design Indicator	[-3, 3]	$SD_{score} = M_{pot} - M_{earn}$	

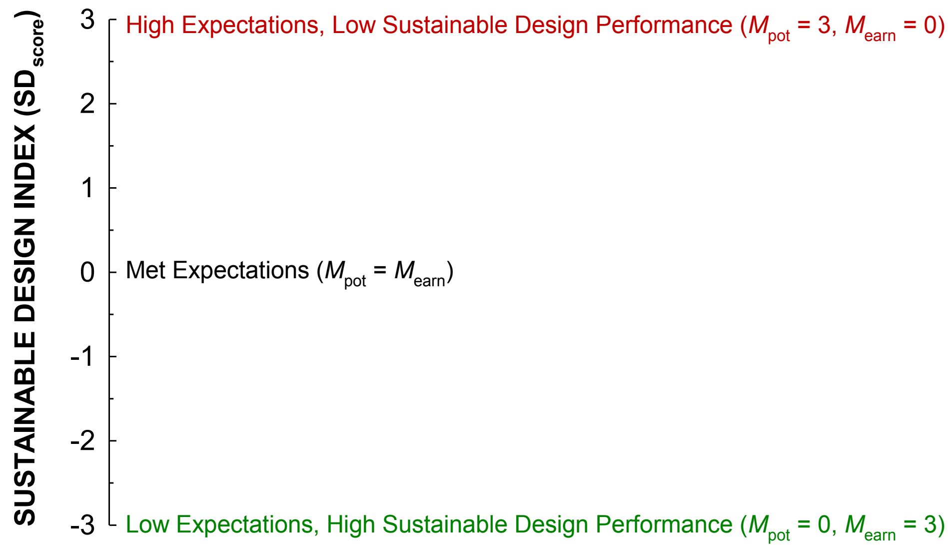

Figure 1. Scale for Sustainable Design Index (SD_{score}).

Phase 3: Validation of Sustainable Design Rubric

Content validity of the rubric was established through assessment by an expert panel, which has been endorsed by other researchers[50,51,52]. Graduate student panelists included three students from civil, environmental, and aerospace engineering, each conducting research broadly associated with sustainability. Faculty panelists consisted of two CEE faculty members who had experience facilitating capstone design, as well as an educational psychologist. Each panelist reviewed the sustainable design rubric, including the 16 sustainable design criteria (Table 3), two rating scales (Table 3), and supplementary examples (Tables S3-S6), and then responded to several questions related to the appropriateness of the rubric for capstone projects (Table S.2). Panelists were also encouraged to provide open-ended feedback. Suggestions, especially related to classification of sustainable design examples, were incorporated into the final rubric.

Methods: Application of Sustainable Design Rubric

A study was conducted to demonstrate application of the sustainable design rubric. CEE capstone projects completed during the Fall 2011 semester were analyzed by three judges using the sustainable design rubric. Scores were analyzed to provide insights for improving sustainability education in CEE at Georgia Tech.

Student Population and Projects

During Fall 2011, 66 students were enrolled in CEE capstone design. Of these students, most were males (84%) and civil engineers (83%). To complete their semester projects, students self-organized themselves into 14 groups of four or five students. Projects encompassed the full range of civil engineering sub-disciplines, including transportation, geotechnical, structural, construction, and environmental engineering. All research methods were approved by the Institutional Review Board (IRB) at Georgia Tech.

Judge Training and Scoring Calibration

Three graduate students served as judges to evaluate capstone projects. The lead judge was the developer of the rubric, as well as a PhD candidate in environmental engineering. Both additional judges were PhD candidates in civil engineering at the time the research was completed. All judges were designated as "experts" due to their extensive knowledge of sustainability gained through completion of relevant coursework and/or research.

To ensure competency and consistency in scoring, all three judges participated in a training session to encourage interrater reliability, as suggested by Bresciani et al.[53]. Judges were first familiarized with the sustainable design criteria and related rating scales (Tables 2-3). Some rating conventions were specified during the training periods. For "protects human health and well-being" judges were to give a default potential rating of "3," due to ethical requirements for all CEE projects specified by ASCE[54]. Similarly, judges awarded a standard potential score of "2" for "conducts a cost and/or cost-benefit analysis," since student groups were required to complete economic analysis as part of the course requirement. In the event that no evidence was found to suggest that the group was required to meet a criterion and no special scoring consideration applied (Table S.1), judges were directed to give potential scores of "1" for all criteria, since they are broadly applicable to all CEE projects.

To calibrate scoring, judges examined several projects that were not being used as part of the research study. First, the group discussed application of the potential and earned points scale using a project that was pre-scored by the lead judge. Afterward, each judge practiced applying the rubric to three capstone design projects. The lead judge met individually with other judges to discuss discrepancies and reach a set of consensus scores.

Scoring Capstone Projects

After judges were trained, the group used the rubric to score Fall 2011 capstone projects. The lead judge evaluated each project, while additional judges each examined seven different projects. As a result, each project was reviewed by two different judges. Individual scores were recorded and any discrepancies were discussed to reach a set of consensus scores, as per Besterfield-Sacre et al.[55]. Thus, for each project, data included judges' individual potential and earned ratings for each criterion, as well as consensus potential and earned scores for each criterion.

Inter-Rater Reliability

Inter-rater reliability was calculated using Krippendorff's alpha, because it can be used for any number of judges and any type of data. Krippendorff argues that reliability statistics above 0.80 are adequately acceptable, while values above 0.67 are acceptable for exploratory research[56,57]. A custom dialog created for the Statistical Package for the Social Sciences (SPSS) was employed to calculate Krippendorff's alpha[56]. For the current study, inter-rater reliability for the potential and earned points scales were 0.728 and 0.742, respectively.

Statistical Analysis of Consensus Scores

Judge's consensus scores were used for all subsequent statistical analyses. To provide insight into areas of student design proficiency and deficiency, SPSS was employed to conduct paired-samples *t*-tests to compare mean potential and earned points for each of the 16 sustainable design. Significant differences were identified as those yielding *p*-values less than or equal to 0.05.

Results

Sustainable Design Expectations (Potential Points)

Potential points were computed and analyzed to capture the extent to which sustainable design criteria could reasonably have been applied in student projects, given instructor/sponsor requests and requirements (Figure 2; Table 5). The mean potential points for all 16 sustainable design criteria and 14 projects was 1.3. Across the projects, 78% of criteria were awarded a 1, 18% were awarded a 2, and 7% were awarded a 3 for potential points. Several trends were also noted for each of the four rubric dimensions.

CEE capstone design projects required students to consider social aspects of sustainable design (Figure 2; Table 5) more than other aspects. In fact, the mean potential score for all social criteria was 1.7 out of a possible 3 points. More specifically, as designated by the scoring convention, all projects required students to "protect human health and well-being" ($M = 3.0$). In addition, 12 out of 14 project sponsors required students to "address community and stakeholder requests" ($M = 1.9$) during the design process. Despite the emphasis on safety and incorporating stakeholders, no sponsor explicitly requested students to “consider local circumstances and cultures” or “use inherently safe materials.”

After the social dimension, economic considerations were most requested by sponsors (*M* = 1.4) (Figure 2; Table 5). Related to economic sustainability, all students were required to “conduct a cost and/or cost-benefit analysis” (*M* = 2.0) as part of the course requirement. One sponsor also mandated that students “consider the economic impacts of promoting environmental sustainability” (*M* = 1.1).

Both the environmental and sustainable design tools were the dimensions least emphasized by project sponsors (*M* = 1.1) (Figure 2; Table 5). In the environmental dimension, six sponsors made requests that required students to “protect natural ecosystems” (*M* = 1.4), while three sponsors required students to “minimize natural resource depletion” (*M* = 1.2). For sustainable design tools, three sponsors suggested that students “incorporate systems analysis” (*M* = 1.2), while one sponsor specified for students to “incorporate environmental impact assessment tools” (*M* = 1.1) and “use innovative technologies to achieve sustainability” (*M* = 1.1).

Student Application of Sustainable Design Criteria (Earned Points)

Earned points were calculated and examined to describe the extent to which students actually addressed sustainable design criteria, regardless of instructor/sponsor influence (Figure 2; Table 5). The mean earned score was 0.9 out of a maximum of three points. Overall, students considered 14 out of the 16 criteria across all four rubric dimensions, with 55, 13, 21, and 11% of criteria being awarded earned points of 0, 1, 2, and 3, respectively.

During the design process, students emphasized social sustainability more than other dimensions (Figure 2; Table 5). Specifically, the mean earned score for all social criteria was 1.4. All groups “considered human health and well-being” (*M* = 2.8), while 13 groups also “addressed community and stakeholder requests” (*M* = 2.2). Only six groups “considered local circumstances and cultures” (*M* = 0.6), while no evidence of “using inherently safe and benign materials (to humans)” was found by judges in project reports (*M* = 0.0).

The economic dimension was the second most addressed rubric dimension, with a mean earned score of 0.9 for all economic criteria. Again, due to course requirements, all students “conducted a cost and/or cost benefit analysis” (*M* = 2.6). Only 3 groups “considered the economic impacts of promoting environmental sustainability” (*M* = 0.4), while four groups “considered the economic impacts of promoting social sustainability” (*M* = 0.4). Thus, few groups addressed economic sustainability beyond what was required.

Table 5. Comparison between potential and earned scores for sustainable design criteria (n = 14 projects).

	Potential		Earned		Paired Samples *t*-Test	
	M	*SD*	*M*	*SD*	*t*(13)	*p*
Environmental Design Criteria						
Minimizes natural resource depletion	1.2	0.4	0.6	0.9	2.51	0.026*
Prevents waste	1.0	0.0	0.4	0.6	3.31	0.006**
Protects natural ecosystems	1.4	0.5	1.6	1.2	-0.62	0.547
Uses renewable energy sources	1.0	0.0	0.0	0.0	-[a]	-
Uses inherently safe materials (to environment)	1.0	0.0	0.2	0.6	5.08	0.000***
Average for Environmental Design Criteria	1.1	0.1	0.6	0.3	8.33	0.000***
Social Design Criteria						
Addresses community and stakeholder requests	1.9	0.5	2.2	0.9	-1.75	0.104
Considers local circumstances and cultures	1.0	0.0	0.6	0.8	1.59	0.136
Protects human health and well-being	3.0	0.0	2.8	0.4	1.88	0.082
Uses inherently safe and benign materials (to humans)	1.0	0.0	0.0	0.0	-[a]	-
Average for Social Design Criteria	1.7	0.1	1.4	0.4	3.63	0.003**
Use of Sustainable Design Tools						
Incorporates life cycle analysis	1.0	0.0	0.5	0.7	2.88	0.013*
Incorporates environmental impact assessment tools	1.1	0.3	0.4	0.7	3.68	0.003**
Incorporates systems analysis	1.2	0.4	1.4	1.0	-0.62	0.547
Uses innovative technologies to achieve sustainability	1.1	0.3	0.7	1.0	1.44	0.174
Average for Sustainable Design Tools Criteria	1.1	0.1	0.7	0.5	2.64	0.021*
Economic Design Criteria						
Considers economic impacts of environmental criteria	1.1	0.3	0.4	0.7	4.37	0.001***
Considers economic impacts of social design criteria	1.0	0.0	0.4	0.9	2.51	0.026*
Conducts a cost and/or cost-benefit analysis	2.0	0.0	1.9	0.7	0.81	0.435
Average for Economic Design Criteria	1.4	0.1	0.9	0.4	4.58	0.001***
Average for all Design Criteria	1.3	0.1	0.9	0.3	6.62	0.000***

[a]No Fall 2011 project reports contained evidence that criterion was applied.

*$p \le 0.05$; $p \le 0.01$; $p \le 0.001$

Next, the mean earned score for the sustainable design tools category was 0.7 (Figure 2; Table 5). Most notably, 10 student groups "incorporated systems analysis" (M = 1.4), while 6 groups each "incorporated life cycle analysis" (M = 0.7) and "used innovative tools to promote sustainability" (M = 0.7). However, only 3 groups "incorporated environmental impact assessment tools (M = 0.4). Overall, most reports showed evidence of one or more types of sustainable design tools and/or thinking.

Finally, the environmental dimension was the least addressed by students, with a mean potential score of 0.6 (Figure 2; Table 5). Even so, 10 groups showed evidence of "protecting natural ecosystems," which was the criterion with the overall fourth highest score (M = 1.6). In addition, five groups each developed designs that "minimized natural resource depletion" (M = 0.6) and "prevented waste" (M = 0.4). Two groups "used inherently safe and benign materials (to environment)" (M = 0.2), while no projects showed evidence of "using renewable energy sources" (M = 0.0). While some criteria were largely neglected, most student groups incorporated some aspect of environmental sustainability into their projects.

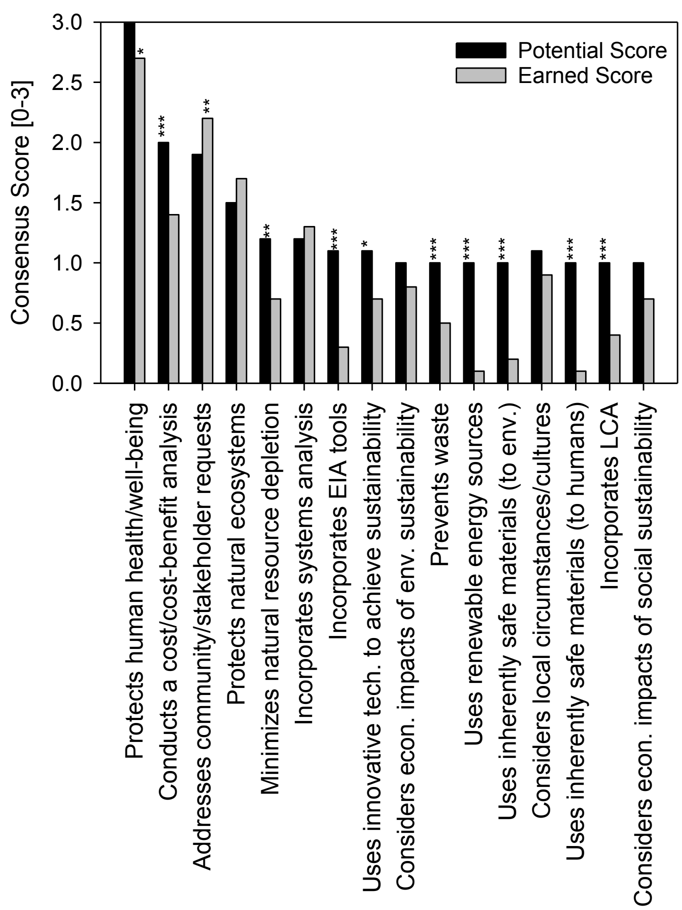

Figure 2. Mean consensus potential and earned scores for design criteria
(*$p \leq 0.05$; **$p \leq 0.01$, ***$p \leq 0.001$).

Comparing Project Potential and Student Actions (Potential versus Earned Points)

Generally, mean earned scores were lower than mean potential scores, indicating that students could have more extensively addressed sustainability criteria in their projects (Table 5). In fact, when comparing the totals for all design criteria, the mean earned score ($M = 0.9$) was significantly lower ($p \leq 0.001$) than the mean potential score ($M = 1.3$). In addition, earned means were statistically ($p \leq 0.05$) lower than potential means for 8 of the 16 criteria across all four of the rubric categories. The mean sustainable design index (Table 4) was 0.43, on a scale of -3.0 to +3.0 (Figure 1), indicating that student groups primarily "met the expectations" of their project sponsors and course instructors, but did not exceed them.

Nearly all of the environmental design criteria were not fully considered by student groups (Table 5). In fact, mean earned scores for "minimizes natural resource depletion," "prevents waste," and "uses inherently safe materials (to environment)" were significantly ($p \leq 0.05$) less than mean potential points. Even still, "uses renewable energy sources" was not demonstrated in any project. However, mean potential and earned scores for "protects natural ecosystems" were not statistically different, which suggests that student efforts related to this criterion were sufficient to meet sponsor expectations.

Few differences were demonstrated between potential and earned points for social design criteria (Table 5). In fact, only "uses inherently safe and benign materials (to humans)" was not addressed in any project. No statistical differences were found for any other social design criterion.

Some deficiencies were identified for the economic dimension (Table 5). Specifically, earned scores were significantly lower ($p \leq 0.05$) for "consider economic impacts of promoting environmental sustainability" and "consider economic impacts of promoting social sustainability." However, students largely met expectations for "conduct a cost and/or cost-benefit analysis," since no difference was demonstrated between potential and earned scores.

Students sufficiently applied some sustainable design tools in their projects (Table 5). For example, no differences between potential and earned points were found for "incorporates systems analysis" or "uses innovative technologies to achieve sustainability." Conversely, earned points were significantly ($p \leq 0.05$) lower than potential points for "incorporate life cycle analysis" and "incorporate environmental impact assessment tools." Thus, student analysis could benefit from use of more diverse design tools and thinking.

Discussion

Examining Sustainable Design in CEE at Georgia Tech

1. To what extent can sustainability reasonably be incorporated into student projects?

Expectations for students to engage in sustainable design during capstone design were somewhat limited (Table 5). In fact, 7 out of 16 design criteria from across all four rubric categories were not directly or indirectly requested by any project sponsor. However, instructor and/or sponsor requirements did prompt students to consider some sustainable design criteria, including "protect human health and well-being," "conduct a cost and/or cost-benefit analysis," "address community and stakeholder requests," and "protect natural ecosystems" (mean potential scores of 1.4 or higher). Despite the limited scope of sponsor requests, the variety of criteria among those receiving the top four highest potential scores were balanced, with at least one criterion from each the economic, environmental, and social rubric categories being represented. This is in accordance with Lozano[8] that supports a holistic perspective of sustainability with balance among relevant dimensions. Additional criteria, especially those from the sustainable design tools category, were incorporated into sponsor requirements, although to a much lesser extent (mean potential scores of 1.1-1.2). Thus, while sponsor requests largely correspond to only a few sustainable design criteria, at least one criterion from each of the three major sustainability dimensions were substantially emphasized.

Despite the balance among the most emphasized design criteria, instructor/sponsor requirements overall most incorporated the social dimension of sustainability. However, the social dimension exhibited the highest potential score in part because of the decision by judges to award a potential score of 3.0 for "protects human health and well-being" due to the ethical requirement for civil and environmental engineers to ensure safety during the design process[54]. Even so, "consider local circumstances and cultures" also received an impressive potential score and was specified by 12 sponsors, even though it was not classified as fundamental to all CEE projects. This contradicts numerous reports that stakeholders, including undergraduates[58,59] and facilities management directors[60], over-emphasize the environmental aspects of sustainability.

2. To what extent do students actually incorporate sustainability into their design projects?

While 14 of the 16 criteria were incorporated into at least one student project, five criteria were substantially addressed across many student projects. In addition to being among the criteria with the highest potential scores, "protect human health and well-being," " address community and stakeholder requests," "conduct a cost and/or cost-benefit analysis," and "protect natural ecosystems" also received the highest earned scores ($M = 1.9 – 2.8$). In addition, "incorporate systems analysis" was also among the criteria with the top five earned scores, with over 70% of student groups addressing this criterion. Demonstration of systems thinking may be prevalent in student projects due to earlier completion of a mandatory civil engineering systems course[45,46]. Student incorporation of sustainability into their projects was even more balanced than sponsor requests, with at least one criterion from each rubric category being represented among the five criteria with the highest earned scores.

When examining criteria beyond the five most prevalently applied, students most extensively addressed the social dimension of sustainability. Not only did students "protect human health and well-being" and "address community and stakeholder requests," but almost half of groups "considered local circumstances and cultures." This contradicts reports by previous authors that social sustainability is the least emphasized dimension[7], especially within civil engineering education[61] and among undergraduates[20].

3. What is the impact of sponsor expectations on student sustainable design performance?

Student performance was largely aligned with instructor and/or sponsor requests. First, criteria with the highest potential scores were also awarded the highest earned scores. In fact, there was no statistical difference between potential and earned scores for "protects natural ecosystems," "addresses community and stakeholder requests," "protects human health and well-being," and "conducts a cost and/or cost-benefit analysis." Conversely, those criteria that were not emphasized by any sponsors (mean potential score of 1.0), received some of the lowest earned scores. In fact, the earned scores for "prevents waste," "uses renewable energy sources," "uses inherently safe materials (to environment and humans)", "incorporates life cycle analysis," and "considers economic impacts of promoting social sustainability" were statistically lower than potential scores. Notable exceptions where students considered criteria in the absence of sponsor influences were demonstrated for "considers local circumstances and cultures" and "uses innovative technologies to achieve sustainability." For both criteria there was no significant difference between potential and earned points. Thus, elevated sponsor and instructor expectations may correspond with improved student demonstration of sustainable design capabilities.

4. What do sustainable design scores suggest for CEE sustainability education at Georgia Tech?

Based on evaluation of student projects using the rubric, it is evident that efforts are needed to encourage students to incorporate a wider variety of sustainable design criteria into their projects. Specific emphasis should be given to the 11 criteria that yielded earned scores of less than 1.0; these criteria spanned all four rubric categories. One mechanism for encouraging application of these criteria may be to explicitly incorporate them into the project requirements. For instance, "conduct a cost and/or cost-benefit analysis" was specified as a requirement for all projects by the sponsors and/or course instructors. As a result, all students met this criterion and it was awarded an earned score of 1.9. Similarly, student performance generally responded to sponsor expectations for other sustainable design criteria, since the criteria with the highest potential scores also exhibited the highest earned scores. While the desires and influences of external sponsors may be difficult to manipulate, it could be possible for course instructors to explicitly require groups to address all or some sustainable design criteria. In fact, the sustainable design rubric could be provided to students to serve as a general framework for incorporating sustainability into design projects.

Broad Application of Sustainable Design Rubric

While the sustainable design rubric was applied to capstone design projects from CEE at Georgia Tech, it can also be applied by other departments and institutions to benchmark student capabilities to engage in sustainable design. If utilized by other CEE departments, the rubric, including the 16 design criteria (Table 3), two rating scales (Tables 3-S1), and numerous examples (Table S3-S6), may be directly applicable. While specific sustainable design examples may not be relevant for engineering programs beyond CEE, the design criteria and accompanying rating scales are still applicable to many engineering disciplines, since they are based on general sustainable design principles (Table 1) and related criteria (Table 2). Finally, the rubric may be helpful for instructors leading design courses other than capstone design. Using the sustainable design rubric to weave sustainability into multiple undergraduate courses may facilitate horizontal integration, which could encourage students to incorporate sustainability into their professional designs and practices[29].

Study Limitations

Several limitations to these research methods are acknowledged. Foremost, when assigning potential and earned scores for each criterion, judges only had access to final student reports. As a result, an accurate evaluation of sponsor and/or instructor requests is only achieved if students make these requirements explicit in the reports. In the design reports reviewed, students were often very clear, especially when defining their project objectives and special instructions from sponsors. Similarly, when awarding earned points, judges could only give credit for consideration or application of those design criteria that were evident in the final report. However, just because a sustainable design element does not make it into the report, does not mean that the group did not consider it. Nevertheless, the elements of research and analysis that the group deemed most important and spent the most time on would be evident in the final report. An additional limitation is related to the repeatability of judges' scores, due to the somewhat subjective nature of the rubric. For instance, depending on the context presented in the final report, some design activities could be classified as meeting different design criteria. As a result, a different set of judges evaluating the same set of projects may yield slightly different results. However, efforts were made to ensure the generation of reliable data, including training of judges and reporting of interrater reliability statistics. In addition, the extensive database of design examples for each criterion (Tables S3-S6) was developed to help aid in reproducibility of rubric application.

Summary and Conclusions

A rubric was developed to capture the applicability of sustainable design criteria to student capstone projects, as well as student incorporation of sustainability principles during the design process. After validating the rubric using a faculty and graduate student panel, three judges used the rubric to score capstone design projects completed by students enrolled in a Fall 2011 CEE capstone course at Georgia Tech. The following conclusions were made based on the results.

1. While the 16 sustainable design criteria are fundamentally applicable to almost all CEE projects, instructor and/or sponsor requirements dictated that students most substantially "protected human health and well-being" and "conducted a cost and/or cost-benefit analysis."
2. Although student incorporation of sustainable design criteria was limited (11 criteria received earned scores of less than 1.0), students most extensively "protected human health and well-being" and "addressed community and stakeholder requests."
3. Overall, both sponsor requirements and student design activities incorporated the social design criteria into their projects more than those related to the environment, economy, or sustainable design tools.
4. In general, criteria that were most related to instructor and/or sponsor requirements were most extensively addressed student groups. One exception was "incorporates systems analysis," which was not commonly specified by sponsors but may have been addressed due to students completing an undergraduate sustainability-related course.

Results from the evaluation of student projects suggest that efforts are needed to encourage students to incorporate a wider variety of sustainable design criteria into their capstone projects. Due to the influence of sponsor and instructor requests on student performance, it is suggested that sustainable design requirements be made explicit in the capstone design course. Broadly, the sustainable design rubric can be used by other CEE and engineering departments to quantify student design abilities in any design course. Given that engineers will be increasingly called upon to develop and implement innovative solutions that serve a growing population, while simultaneously exploiting fewer resources and minimizing environmental impacts, it is essential that undergraduate engineering education guide students in developing sustainable design skills. After all, the design decisions made by engineers have the potential to impact both current and future generations.

Future Work

This study is part of a larger project in CEE at Georgia Tech to evaluate and improve the quality of undergraduate sustainability education. Using the sustainable design rubric detailed in this manuscript, the authors aim to evaluate capstone projects from the past decade to infer whether or not departmental efforts to incorporate sustainability into CEE programs have impacted student abilities to apply sustainability principles during design. In addition, the rubric is being used as a tool to track potential changes in student design performance as a result of initiatives to enhance CEE capstone design[62]. Also, the rubric is being used to evaluate capstone projects at another institution in order to determine its applicability to other disciplines beyond CEE. The authors hope that other educators will also find the rubric helpful in guiding course and curricular reform efforts.

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Supplemental Material

Table S1. Interpretation of earned points rating scale for selected criteria.

Criteria	Score = 1	Score = 2	Score = 3
Incorporates life cycle analysis (LCA)	Mentions need for LCA and/or considers 1 stage[1] beyond immediate use.	Considers 2-3 stages[1] beyond immediate project use.	Considers more than 3 stages[1] beyond immediate project use.
Incorporates environmental impact assessment (EIA) tools	Mentions the need for EIA and/or begins to formulate EIA through description of potential impacts.	Develops abbreviated EIA through estimation of environmental impacts of multiple design alternatives.	Completes full EIA OR fulfills score 2 requirements and recognizes need for extended EIA.
Incorporates systems analysis	Understands project is part of a larger system. Demonstrated by defining boundaries or project context.	Considers 1-2 linkages (economic, environmental, or social) that connect project to larger system.	Considers more than 3 linkages (economic, environmental, or social) that connect project to larger system.
Economic analysis	Completes a cost estimate for only one design alternative.	Completes a cost estimate for more than one design alternative.	Meets score 2 criterion and incorporates cost/benefit analysis.

[1]Stages: raw materials acquisition, manufacturing, use, reuse, maintenance, recycle, disposal.

Table S.2. Questions used to guide panelists in providing feedback on the rubric.

After reviewing the sustainable design rubric:
1. Are the 9 Sustainable Design Principles (Table 1), developed by experts at the 2002 Green Engineering Conference, an appropriate framework for a sustainable design rubric?
2. Are the 16 sustainable design criteria (Table 2) appropriate for evaluating student projects?
3. Are the earned points and potential points rating scales comprehendible (Tables 3-4)?
4. Are the special considerations for application of potential points rating scale reasonable?
5. Are examples of sustainable design criteria consideration properly classified (Tables 5-8)?
6. Are sub-scores (equation 1) and total scores (equation 2) appropriate for comparing sustainability content of capstone projects?

Table S3. Example applications of environmental design criteria in capstone projects.

Environmental Design Criteria	Examples
Minimizes natural resource depletion (quantity)	• Collecting and using rainwater for non-consumption purposes (e.g. green roof to collect irrigation water). • Promoting use of non-fossil-fuel-based transportation (e.g. providing bike racks, reducing number of parking spaces, or other techniques that do not include using renewable energy sources). • Decreasing fossil fuel consumption by using local materials. • Limiting disturbed land area. • Reducing conversion of land area to impervious surfaces. • Maximize available flow rate from dam or through culvert. • Promoting water and/or energy efficiency practices (e.g. water efficient landscaping)
Prevents waste (material)	• Designing project to use as much of existing structures (roadways, buildings, etc.) as possible. • Minimizing material waste during construction. • Providing opportunities for users of a project to recycle. • Recycling materials from structures that cannot be rehabilitated. • Using recycled materials for design (e.g. building a roadway with recycled concrete)
Protects natural ecosystems (quality)	• Implementing erosion control measures to protect water quality and aquatic habitats. • Preventing release of pollutants into water sources. • Using vegetation to preserve water quality (e.g. use of green spaces, stream buffers, landscaping islands). • Choosing a site to minimize interference with ecosystems or ecosystems components (e.g. water sources, wetlands, trees, etc.) • Consideration of endangered species in design process. • Limiting disruption of stream floor, contours, or flow. • Minimizing overall impacts on natural environments.
Uses inherently safe and benign materials (to environment)[1]	• Use of natural building materials (e.g. compressed earth block) • Use of materials whose production as low environmental impacts (e.g. construction concrete and steel). • Use of rapidly-renewable plant materials (e.g. bamboo). • Use of certified environmentally-safe materials.
Uses renewable energy sources	• Incorporation of on-site renewable energy (wind, hydropower, solar, bio-based, geothermal) into design. • Use of renewable energy during construction. • Providing alternative fueling stations. • Providing preferred parking for alternative fuel vehicles.

[1]Use of standard civil engineering materials (e.g. wood, steel, etc.) is not sufficient to satisfy this criteria *unless* the report suggests that the group made a conscious decision about material choice based on environmental concerns.

Table S4. Example applications of social sustainability design criteria in capstone projects.

Social Design Criteria	Examples
Addresses community and stakeholder requests	• Improvements to traffic congestion (e.g. minimizing queuing at traffic signals, improving level of service). • Sequencing construction to minimize impact on traffic flow. • Avoiding routing traffic through residential areas. • Including green spaces (or other features) to increase local property values. • Holding charettes or other community events to solicit local concerns and opinions about design project. • Incorporating concerns or suggestions voiced during charettes or other community events into design. • Improving access to public transportation. • Improving access to public amenities for pedestrians and bicyclists. • Increasing vehicular access to public amenities (e.g. more parking spaces) • Including accommodations for handicapped or elderly patrons (e.g. facilitating transport across steep hill using pedestrian bridge, adding extra handicapped parking spaces). • Providing recreational amenities. • Considering aesthetic appeal of designs. • Providing opportunities to enjoy scenic surroundings. • Choosing site to minimize disruption or acquisition of private property. • Promoting community atmosphere (e.g. building retail community rather than box shopping center)
Considers local circumstances and cultures	• Designing projects to blend in with the aesthetic qualities of the community. • Considering future needs of community (e.g. future population growth). • Preserving historical sites. • Honoring historical sites that must be altered during design (e.g. adding commemorative plaques). • Minimizing land excavation for sites that may have archeological value. • Providing designs that allow community to maintain small-town atmosphere. • Honoring community requests for LEED certification or environmental protection. • Considering local demographic during design.

Protects human health and well-being	• Addressing driver expectancy issues and/or minimizing driver confusion (e.g. with appropriate signs, signals, etc.). • Adding features to protect pedestrians (barriers to roadways, crosswalks, etc.). • Adding appropriate measures to prevent flooding (e.g. detention ponds, drainage improvements). • Providing appropriate amenities or access for fire rescue (e.g. water lines) or other safety services. • Compliance with laws, regulations, or codes (e.g. AASHTO). • Considering safety at any time during project life cycle (construction, use, etc.). • Adding retaining walls to stabilize slopes and promote safety. • Adding barriers and/or fences to prevent cars from leaving roadway. • Designing project with consideration of extreme events (e.g. designing for a 100 year storm, staying above 10 year flood plain, etc.). • Ensuring proper lighting for proper use of project. • Ensuring structural integrity of designs (e.g. controlling crack propagation, ensuring suitability of soil for construction). • Including methods for monitoring and/or improving indoor and outdoor air quality. • Minimizing entry of pollutants into buildings.
Uses inherently safe and benign materials (to humans)[1]	• Use of low emitting adhesives, sealants, paints, coatings, and/or flooring systems. • Use of low or non-toxic materials (e.g. non-carcinogens, non-irritants, etc). • Use of moisture-resistant materials that reduce biological contaminants. • Use of materials that require non-toxic cleaning procedures.

[1]Use of standard civil engineering materials (e.g. wood, steel, etc.) is not sufficient to satisfy this criteria *unless* the report suggests that the group made a conscious decision about material choice based on health concerns.

Table S5. Example applications of sustainable engineering tools and strategies in capstone projects.

Sustainable Engineering Tool/Strategy	Example
Incorporates life cycle analysis	• Considering impacts of project over its lifecycle, rather than just its useful life. • Using results from a life cycle analysis. • Conducting a simplified life cycle analysis using a Materials, Energy, Toxicity (MET) matrix, Eco-Indicator 99, or other appropriate tool. • Defining the project lifecycle.
Incorporates environmental impact assessment tools	• Recommending that an environmental impact assessment be completed. • Using results from an environmental impact assessment.
Incorporates systems analysis	• Defining the project system by setting boundaries, defining system components and attributes, and explaining links between system components and attributes. • Determining project impacts (economic, environmental, social) within and outside of system boundaries.
Uses innovative technologies to achieve sustainability	• Developing a design that cannot be analyzed using traditional engineering software (e.g. diverging diamond interchange). • Applying new design/development paradigms (e.g. new urbanism). • Designing for LEED certification. • Using non-typical solutions for a geographical area (e.g. roundabouts uncommon in GA). • Using a sustainable design tool, such as a design abacus.

Table S6. Example applications of economic sustainability design criteria in capstone projects.

Economic Design Criteria	Example
Considers economic impacts of executing environmental principle(s)	• Calculating costs for enacting an environmental sustainability principle. • Finding cost-effective methods for enacting an environmental sustainability principle. • Suggesting mechanisms for creating a profit while enacting an environmental sustainability principle (e.g. charge extra for residential units located near green space). • Completing environmental sustainability principle to decrease costs (e.g. material, energy, and/or water efficiency). • Implementing environmental sustainability principle to receive tax break (e.g. LEED certification). • Comparing costs of design alternatives with different levels of environmental consideration/protection.
Considers economic impacts of executing social principle(s)	• Calculating costs for enacting a social sustainability principle (e.g. cost to improve safety, aesthetics, etc). • Finding cost-effective methods for enacting an environmental sustainability principle. • Suggesting mechanisms for creating a profit from enacting a social sustainability principle (e.g. adding commercial space near residential areas to increase property values). • Maximizing social benefit, while minimizing costs (e.g. maximizing number of parking spaces while minimizing cost). • Increasing factor safety/margin of error to both ensure public safety and prevent expensive re-designs in the event of project failure.
Quantifies economic costs and benefits.	• Estimation of project costs. • Use of cost-benefit analyses.