Validating a Sustainable Design Rubric by Surveying Engineering Educators

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Validating a Sustainable Design Rubric by Surveying Engineering Educators:

Comparing Professional Viewpoints with Established Sustainability Frameworks

Abstract

Previously, researchers developed and applied a sustainable design rubric, based on the Nine Principles of Sustainable Engineering, to civil engineering student design projects. The rubric is being updated for use across engineering disciplines based on insights from the pilot application phase and a three phase validation process. This paper reports on expert validation through a survey and comparisons with sustainability frameworks. Paper and web-based surveys were used to gather perspectives from engineering education professionals with different disciplinary perspectives, including civil, environmental, mechanical, electrical/computer, and other engineering or related disciplines, from the United States and abroad (N = 55). Specifically, participants ranked their ten most important sustainable design criteria from a list of 34 criteria that were generated based on the original rubric and a systematic review of literature. Participant rankings were converted into scores then sorted based on quartiles, with criteria in the first, second, third, and fourth quartiles designated as very important, important, slightly important, and not important, respectively. Of the eight criteria designated as very important, most were related to the environmental or social dimensions of sustainability. A few economic design criteria were designated as important, although most were designated as slightly or not important. Ultimately, expert feedback substantiated parallel validation efforts to identify and reduce the number and type of design criteria comprising the rubric. The completed rubric will provide engineering educators and students with a learning and assessment tool to enhance sustainable design outcomes of projects.

Introduction

During the 2016 ASEE Annual Conference, a special session posed a question about how engineering educators can assess “difficult to measure” learning outcomes like sustainability, ethics, entrepreneurship, etc. Panelists presented numerous examples of assessment tools and methods that could be used to benchmark and measure learning gains in each difficult area. A follow-up systematic literature review focused on “sustainability assessments” in ASEE proceedings identified twenty-nine recent publications describing various tools and methods for assessing knowledge, design skills, beliefs/attitudes/interests [1]. While there are many sustainability assessment options available to engineering educators, the review revealed opportunities for rigorously validated assessment instruments and direct assessments, as opposed to self-report instruments, for capturing application of sustainable design skills [1].

We are engaged in an ongoing effort to refine and validate a cross-disciplinary sustainable design rubric to promote learning during and assessment of student-level design projects. Our original sustainable design criteria (Table 1) were based on the Nine Principles of Sustainable Engineering [2] and were used in an initial pilot study of civil and environmental engineering capstone projects [3, 4]. Since then, we have conducted a systematic literature review to expand our list of cross-disciplinary criteria [5] (Table 1).

Table 1: Draft criteria for cross-disciplinary sustainable design rubric (pilot phase criteria [3, 4] are shown in *italics*; others resulted from systematic literature review [5]).

Category	Code	Criterion
Environmental	A1	*Minimizes natural resource depletion*
	A2	*Prevents waste*
	A3	*Protects natural ecosystems*
	A4	*Uses renewable energy sources*
	A5	Provides for low-energy production
	A6	Provides for technological adaptability
	A7	*Uses inherently safe and benign materials (to environment)*
	A8	Uses footprint analysis to estimate impact
	A9	Analyzes embedded energy of alternatives
Social	B1	*Addresses stakeholder or client requests*
	B2	*Considers local circumstances and cultures*
	B3	Incorporates public/stakeholder participation
	B4	Incorporates user experience
	B5	*Protects human health and well-being*
	B6	*Uses inherently safe and benign materials (to humans)*
	B7	Demonstrates ethics/ethical reasoning
	B8	Reflects social responsibility
	B9	Manufacturing complies with safety regulations
Economic	C1	*Considers economic impacts of environmental design criterion*
	C2	*Considers economic impacts of a social design criterion*
	C3	*Conducts a cost and/or cost-benefit analysis*
	C4	Demonstrates cost competitiveness or cost reduction
	C5	Stimulates labor/jobs
	C6	Considers affordability
	C7	Promotes low-carbon economy
Other, including Design Tools	D1	*Incorporates life cycle analysis*
	D2	Uses DfX in design process (indicate "X")
	D3	Reflects cradle-to-cradle design
	D4	Uses industrial ecology principles
	D5	*Incorporates environmental impact assessment tools*
	D6	*Incorporates systems analysis*
	D7	Incorporates uncertainty analysis
	D8	*Uses innovative technologies to achieve sustainability*
	D9	Reflects leadership

Currently, we are iteratively refining and validating our sustainable design criteria based on a survey of multi-disciplinary experts [6], as well as comparison to existing sustainable design frameworks [7]. Once rubric criteria are finalized, rubric rating scales and criteria weightings will be refined, perhaps using analytic Hierarchy Process, a multi-objective decision-making methodology, or another formal methodology [8] (Figure 1).

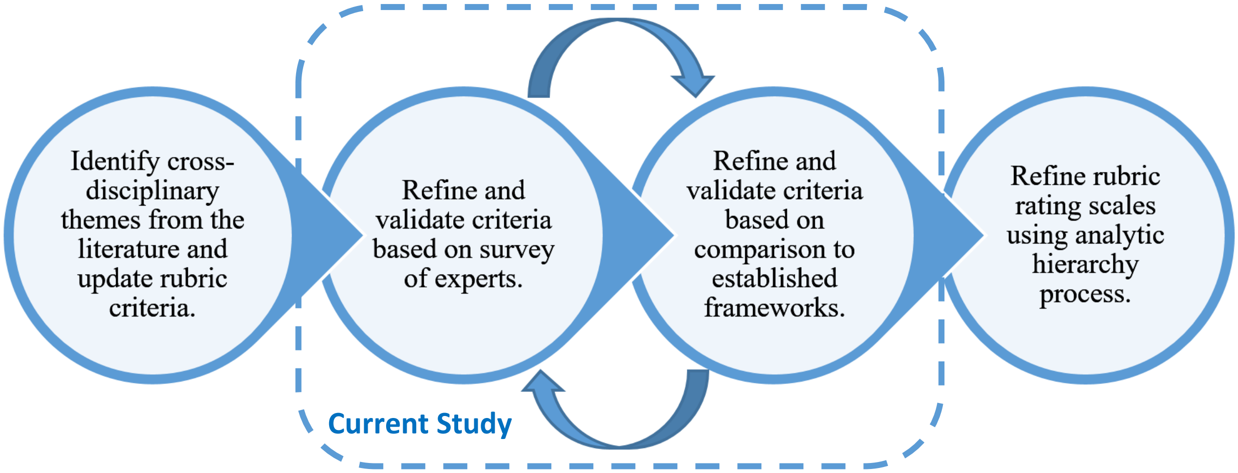

Figure 1: Process to refine and validate a sustainable design rubric for student-level projects [7].

Text Mapping of Existing Sustainable Design Frameworks

Prior to this study, we compared our revised sustainable design criteria to three established sustainable design frameworks [7]. The Envision™ framework, containing 60 items, is a resource for planning, designing, building, and maintaining civil infrastructure. STAUNCH© is a framework consisting of 36 criteria divided into economic, environmental, and social dimensions that is used to evaluate universities' integration of sustainability into curricula, via the evaluation of course descriptions [9]. Finally, the UN Sustainable Development Goals (UNSDG) contains 17 items and was developed to provide guidance to the global community on how to develop sustainably.

To refine our rubric, three researchers scored the overlap between our sustainable design criteria and the items/criteria from the three established frameworks [7]. Overall, our sustainable design criteria mapped well to all three frameworks, although eight criteria were identified for possible omission or incorporation into other criteria (A8, B4, B7, B9, C6, D2, D4, D7). Some items/criteria in the established frameworks, however, were not adequately reflected in our rubric. For instance, our rubric universally failed to address issues of policy and regulation, including environmental impacts and climate action. Surprisingly, our rubric lacked inclusion of topics related to environmental conservation, especially as captured in Envision™ and the UNSDG. Furthermore, our rubric was missing diversity-related topics included in STAUNCH©. While text mapping provided rich insights into the strengths and weaknesses of our rubric, we believe that insights from professionals are needed to substantiate decisions on adding, retaining, or omitting sustainable design criteria.

Survey of Sustainable Design Educators

To further refine and validate our sustainable design criteria, a survey was developed and distributed to a variety of engineering and non-engineering educators from domestic and international communities [6]. As part of this survey, participants were asked to rank the importance of our existing criteria using a 1-10 scale.

While early analysis of the survey data demonstrated that the survey was functionally effective at assessing expert feedback on the importance of our sustainable design criteria, the sample size was too small to make any final decisions on inclusion or omission. The present study sought to expand the reach of this survey to a larger pool of engineering and non-engineering education professionals. Results from the full survey will be discussed in a subsequent section and then compared to the text-mapping results.

Research Objectives

In the context of our larger effort to produce a multi-disciplinary sustainable design rubric (Table 1), the goal of this study was to analyze expert survey data and compare results to previous text mapping of established sustainable design frameworks to aid in iteratively condensing the existing rubric. Consequently, we will address the following research questions (RQs) in this paper:

RQ 1. Which draft sustainable design criteria are most and least valued by engineering education professionals across disciplines?
RQ 2. Which draft sustainable design criteria are most and least supported by both existing sustainable design frameworks and engineering education professionals?
RQ 3. Which sustainable design criteria should be retained, refined, or omitted based on overlapping outcomes from text mapping of existing frameworks and a survey of professionals?

Methods

Survey of Engineering and Non-Engineering Educators

Previously, a survey was developed and deployed to collect educators' perspectives on sustainable design and our draft criteria [6]. The survey asked participants to provide information on their professional background, including disciplinary affiliations. Within environmental, social, economic, and other (including design tools) categories, the survey asked participants to choose at least five, and up to ten, criteria that they felt were the most important overall to the rubric. Participants had the option to write in additional criteria, if the participant felt the rubric excluded an important item. If a participant wrote in a criterion, it would be grouped under one of our four categories and the participant could then choose to rank it in their top criteria. Only responses to the question asking participants to rank existing criteria are presented here, although other sections of the survey are discussed elsewhere [6].

Following both organizational and IRB approval, the survey (in Qualtrics) was distributed via mass email to the members of several engineering organizations; subsequent distribution utilized a snowball sampling approach. A paper version of the survey was also implemented as a pilot and then entered in digitally, though this reflected a very small portion of our sample size (n = 10). In total, 55 participants fully completed the criteria ranking question (as compared to only 16 in our preliminary report). Respondents represented a variety of disciplines, including civil engineering (14.5%), electrical/computer engineering (9.1%), environmental engineering (16.4%), mechanical engineering (30.1%), and other engineering or non-engineering fields

(29.1%). Additional participants partially completed the survey, specifically the open-ended questions defining sustainable design criteria. All responses to the open-ended questions are being qualitatively analyzed to better understand engineering educators' definitions of sustainability and sustainable design.

For data processing, all Qualtrics responses were exported into Microsoft Excel and paper-responses were manually added to the spreadsheet. Descriptive statistics and comparisons across disciplines were performed using IBM Statistical Package for the Social Sciences (SPSS). Participants' responses to the ranking question were converted into a binary variable to represent inclusion or non-inclusion in a participant's ranked criteria. This transformation was performed to analyze which items were generally considered important to participants, as inferential statistics with small sample sizes is both problematic and generally impractical.

Text Mapping with Established Sustainable Design Frameworks

As part of an earlier study, we compared our sustainable design criteria with items/criteria from the existing Envision™, STAUNCH©, and UNSDG frameworks [7]. Three researchers completed the text mapping process, including an educator from an interdisciplinary engineering program, an educator in a civil engineering program, and a psychology graduate student.

First, each researcher used a matrix to record overlaps between our criteria and those from each of the three frameworks. For example, if a researcher considered the *minimizes natural resource depletion* criterion to correspond with STAUNCH©'s *biodiversity* criterion, then he or she recorded a "1" in the appropriate matrix cell in her/his individual scoring matrix. After individual completion of matrices, the three researchers met over several sessions to compare and contrast scores. Subsequently, each researcher re-evaluated his or her matrices to make amendments based on group conversations.

Finally, individual matrices were compiled and totaled to produce a collaborative matrix for each framework. For instance, if two researchers found that Rubric Criterion A (e.g., *minimizes natural resource depletion*) corresponded with Framework Item B (e.g., STAUNCH©'s *biodiversity* criterion), then a "2" was recorded in the appropriate matrix cell. Totals for each criterion were computed based on the collaborative matrices. A generic, sample collaborative matrix is included below (Table 2**Error! Reference source not found.**).

Table 2. Sample collaborative matrix used to summarize overlaps between sustainable design criteria and items/criteria from existing frameworks*.

Rubric Criteria	Framework Items/Criteria			SUM
	A	B	C	
A	1	2	3	6
B	1	2	1	4
C	3	0	0	3

*A "1," "2," and "3," indicates that one, two, or three researchers (out of three total reviews), respectively, identified overlap between the rubric criterion and the framework item/criterion.

Normalizing and Comparing Survey Data and Text Mapping Data

Quartile analysis was used to normalize the text mapping and survey data to facilitate comparison of criteria validation methods. It was important to normalize the data sets because the type of data and relative scales resulting from each of the text mapping and survey studies differed. For the text mapping study, the outcome was a collaborative matrix for each framework that included a *sum* score for each of our criteria. For the survey study, the outcome was the *percentage* of participants ranking each of our criteria.

For text mapping data, sum scores for each criterion and collaborative matrix were converted to quartiles. Within each of the three collaborative matrices, the sums for each of our criteria were sorted according to quartiles. To compile results from each of the three frameworks, the quartiles for each criterion within each collaborative matrix were summed. Finally, the sum of quartiles was again sorted by quartile to yield a total text mapping score for each criterion (ranging from 1 to 4). Criteria ranked overall in the first, second, third, or fourth quartiles were assigned to categories of *Very Important*, *Important*, *Slightly Important*, or *Not Important*, respectively.

For survey data, the percentage of participants prioritizing each criterion was ranked according to quartiles. Ultimately, each criterion was assigned a score of 1-4, depending on its quartile. Criteria ranked overall in the first, second, third, or fourth quartiles were assigned to categories of *Very Important*, *Important*, *Slightly Important*, or *Not Important*, respectively.

Finally, the text mapping and survey outcomes were compared based on quartiles. The total text mapping score [1-4] and the survey score [1-4] were summed and ranked by quartile to yield a final score [1-4]. Criteria ranked overall in the first, second, third, or fourth quartiles were assigned final designations of *Very Important*, *Important*, *Slightly Important*, or *Not Important*, respectively. For a final designation of *Very Important*, the criterion was either categorized as *Very Important* in both the text mapping and survey studies or *Very Important* in one and *Important* in the other. For a final designation of *Not Important*, the criterion was either categorized as *Not Important* in both the text mapping and survey studies or *Not Important* in one and *Slightly Important* in the other (Table 3). Please note that the total sum (Σ) value is relative to only that particular framework, while quartile (Q) is comparable between frameworks.

Table 3: Interpretation of final criteria designations based on text mapping and survey studies.

Final Designation	Interpretation
Very Important	Both Very Important OR Very Important, Important
Important	Never Not Important
Slightly Important	Never Very Important
Not Important	Both Not Important OR Not Important, Slightly Important

Results

Expert Survey Data

Based on all professionals' rankings of sustainable design criteria, the most commonly ranked criteria were from the Social and Environmental categories, while the least commonly ranked were from the Economic and Other (Including Design Tools) categories (Table 4**Error! Reference source not found.**). Specifically, “protects human health and well-being” (51%) and “minimizes natural resource depletion” (47%) were ranked by approximately half of participants. “Addresses stakeholder or client requests” (38%) and “protects natural ecosystems” (35%) were ranked by approximately one-third of participants. In contrast, no participant ranked “stimulates labor/jobs” and few participants ranked “uses industrial ecology principles” (2%), “demonstrates cost competitiveness or cost reduction” (4%), “promotes low-carbon economy” (4%), “used DfX in design process” (4%), “uses innovative technology to achieve sustainability” (4%), and “reflects leadership” (5%).

When ranking criteria by quartiles for all participants, criteria from the Social and Environmental categories again emerged as especially important, while criteria from the Economic and Other (Including Design Tools) categories were less important (Table 4**Error! Reference source not found.**). Within the social category, four criteria were designated as *Very Important* and none were designated as *Not Important*. Within the environmental category, three criteria were designated as *Very Important* and two were designated as *Not Important*. Within the economic category, no criterion was designated as *Very Important* and three were designated as *Not Important*. Within the other/tools category, one criterion was designated as *Very Important* and four were designated as *Not Important*. Ultimately, the social and environmental categories contained the most *Very Important* criteria, while the economic and other/tools category contained the most *Not Important* criteria.

Text Mapping Data

Data resulting from the text mapping study, in which we collaboratively compared our sustainable design criteria with items/criteria from the STAUNCH©, Envision™, and UNSDG frameworks, were normalized according to quartiles (Table 5). Within the environmental category, three criteria were designated as *Very Important* and four were designated as *Not Important*. Within the social category, four criteria were designated as *Very Important* and three were designated as *Not Important*. Within the economic category, no criteria was designated as *Very Important* and two were designated as *Not Important*. Within the other/tools category, no criteria were designated as *Very Important* and five were designated as *Not Important*. Ultimately, the social and environmental categories contained the most *Very Important* criteria, while the other/tools category contained the most *Not Important* criteria.

Comparing Survey and Text Mapping Data

Normalized text mapping and survey data (for all disciplines) were summed and sorted by quartiles to determine the relative importance of each sustainable design criteria (Table 6). Within the environmental category, three criteria were designated as *Very Important* and three were designated as *Not Important*. Within the social category, four criteria were designated as *Very Important* and one was designated as *Not Important*. Within the economic category, no criterion was designated as *Very Important* and three were designated as *Not Important*. Within the other/tools category, one criterion was designated as *Very Important* and four were designated as *Not Important*. Ultimately, the social and environmental categories contained the most *Very Important* criteria, while the environmental, economic, and other/tools categories contained several *Not Important* criteria.

Table 4: Normalizing survey data by quartiles[1] to designate criteria importance for all participants.

		% Ranked	Q	Decision
Environmental	Minimizes natural resource depletion	47.27	4	Very important
	Prevents waste	27.27	4	Very important
	Protects natural ecosystems	34.55	4	Very important
	Uses renewable energy sources	14.55	2	Slightly Important
	Provides for low-energy production	16.36	2	Slightly Important
	Provides for technological adaptability	9.09	1	Not Important
	Uses inherently safe and benign materials (to enviro)	25.45	3	Important
	Uses footprint analysis to estimate impact	16.36	2	Slightly Important
	Analyzed embedded energy of alternatives	9.09	1	Not Important
Social	Addresses stakeholder or client requests	38.18	4	Very important
	Considers local circumstances and cultures	29.09	4	Very important
	Incorporated public/stakeholder participation	18.18	3	Important
	Incorporated user experience	18.18	3	Important
	Protects human health and well-being	50.91	4	Very important
	Uses inherently safe and benign materials (to humans)	14.55	2	Slightly Important
	Demonstrates ethics/ethical reasoning	20.00	3	Important
	Reflects social responsibility	27.27	4	Very important
	Manufacturing complies with safety regulations	20.00	3	Important
Economic	Consider economic impacts of enviro design criterion	25.45	3	Important
	Consider economic impacts of a social design criterion	10.91	2	Slightly Important
	Conduct a cost and/or cost-benefit analysis	12.73	2	Slightly Important
	Demonstrates cost competitiveness or cost reduction	3.64	1	Not Important
	Stimulates labor/jobs	0.00	1	Not Important
	Considers affordability	18.18	3	Important
	Promotes low-carbon economy	3.64	1	Not Important
Other, Incl. Design Tools	Incorporates life cycle analysis	27.27	4	Very important
	Used DfX in design process (indicate "X")	3.64	1	Not Important
	Reflects cradle-to-cradle design	21.82	3	Important
	Uses industrial ecology principles	1.82	1	Not Important
	Incorporates environmental impact assessment tools	12.73	2	Slightly Important
	Incorporates systems analysis	23.64	3	Important
	Incorporates uncertainty analysis	10.91	2	Slightly Important
	Uses innovative technologies to achieve sustainability	3.64	1	Not Important
	Reflects leadership	5.45	1	Not Important

Table 5: Normalizing text mapping data by quartiles to designate the relative importance of each sustainable design criterion.

		STAUNCH		Envision		UNSDG		Tot		Decision
		Σ	Q	Σ	Q	Σ	Q	Σ	Q	
Environmental	Minimizes natural resource depletion	26	3	15	4	13	3	10	4	Very important
	Prevents waste	24	3	21	4	14	4	11	4	Very important
	Protects natural ecosystems	29	4	50	4	24	4	12	4	Very important
	Uses renewable energy sources	23	2	4	2	8	3	7	2	Slightly Important
	Provides for low-energy production	22	2	8	3	2	2	7	2	Slightly Important
	Provides for technological adaptability	21	1	4	2	12	3	6	1	Not Important
	Uses inherently safe and benign materials (to enviro)	21	1	6	2	8	3	6	1	Not Important
	Uses footprint analysis to estimate impact	21	1	2	1	1	1	3	1	Not Important
	Analyzed embedded energy of alternatives	23	2	6	2	0	1	5	1	Not Important
Social	Addresses stakeholder or client requests	19	1	12	4	5	2	7	2	Slightly Important
	Considers local circumstances and cultures	36	4	20	4	15	4	12	4	Very important
	Incorporated public/stakeholder participation	27	4	14	4	17	4	12	4	Very important
	Incorporated user experience	7	1	3	2	3	2	5	1	Not Important
	Protects human health and well-being	35	4	26	4	26	4	12	4	Very important
	Uses inherently safe and benign materials (to humans)	21	1	7	3	7	2	6	1	Not Important
	Demonstrates ethics/ethical reasoning	32	4	1	1	14	4	9	3	Important
	Reflects social responsibility	40	4	5	2	33	4	10	4	Very important
	Manufacturing complies with safety regulations	21	1	1	1	1	1	3	1	Not Important
Economic	Consider economic impacts of enviro design criterion	21	1	12	4	12	3	8	3	Important
	Consider economic impacts of a social design criterion	22	2	7	3	17	4	9	3	Important
	Conduct a cost and/or cost-benefit analysis	25	3	4	2	0	1	6	1	Not Important
	Demonstrates cost competitiveness or cost reduction	21	1	4	2	2	2	5	1	Not Important
	Stimulates labor/jobs	25	3	6	2	18	4	9	3	Important
	Considers affordability	25	3	3	2	11	3	8	3	Important
	Promotes low-carbon economy	22	2	9	3	4	2	7	2	Slightly Important

Other, Incl. Design Tools	Incorporates life cycle analysis	25	3	14	4	0	1	8	3	Important
	Used DfX in design process (indicate "X")	20	1	3	2	0	1	4	1	Not Important
	Reflects cradle-to-cradle design	23	2	10	3	1	1	6	1	Not Important
	Uses industrial ecology principles	23	2	0	1	1	1	4	1	Not Important
	Incorporates environmental impact assessment tools	27	4	5	2	4	2	8	3	Important
	Incorporates systems analysis	32	4	4	2	1	1	7	2	Slightly Important
	Incorporates uncertainty analysis	27	4	2	1	0	1	6	1	Not Important
	Uses innovative technologies to achieve sustainability	22	2	7	3	12	3	8	3	Important
	Reflects leadership	15	1	5	2	11	3	6	1	Not Important

Table 6: Combined quartile scores from survey and text-mapping to designate the relative importance of each sustainable design criterion.

		Sum[1]	Q	Final Decision
Environmental	Minimizes natural resource depletion	8	4	Very important
	Prevents waste	8	4	Very important
	Protects natural ecosystems	8	4	Very important
	Uses renewable energy sources	4	2	Slightly Important
	Provides for low-energy production	4	2	Slightly Important
	Provides for technological adaptability	2	1	Not Important
	Uses inherently safe and benign materials (to enviro)	4	2	Slightly Important
	Uses footprint analysis to estimate impact	3	1	Not Important
	Analyzed embedded energy of alternatives	2	1	Not Important
Social	Addresses stakeholder or client requests	6	3	Important
	Considers local circumstances and cultures	8	4	Very important
	Incorporated public/stakeholder participation	7	4	Very important
	Incorporated user experience	4	2	Slightly Important
	Protects human health and well-being	8	4	Very important
	Uses inherently safe and benign materials (to humans)	3	1	Not Important
	Demonstrates ethics/ethical reasoning	6	3	Important
	Reflects social responsibility	8	4	Very important
	Manufacturing complies with safety regulations	4	2	Slightly Important
Economic	Consider economic impacts of enviro design criterion	6	3	Important
	Consider economic impacts of a social design criterion	5	3	Important
	Conduct a cost and/or cost-benefit analysis	3	1	Not Important
	Demonstrates cost competitiveness or cost reduction	2	1	Not Important
	Stimulates labor/jobs	4	2	Slightly Important
	Considers affordability	6	3	Important
	Promotes low-carbon economy	3	1	Not Important
Other, Including Tools	Incorporates life cycle analysis	7	4	Very important
	Used DfX in design process (indicate "X")	2	1	Not Important
	Reflects cradle-to-cradle design	4	2	Slightly Important
	Uses industrial ecology principles	2	1	Not Important
	Incorporates environmental impact assessment tools	5	3	Important
	Incorporates systems analysis	5	3	Important
	Incorporates uncertainty analysis	3	1	Not Important
	Uses innovative technologies to achieve sustainability	4	2	Slightly Important
	Reflects leadership	2	1	Not Important

[1]Sum of the Tot Q from Table 5 and Q from Table 4**Error! Reference source not found.**.

Discussion

Professionals' Perspectives Across Disciplines

To aid in refinement of the draft sustainable design criteria, those criteria that were identified as *Very Important* by at least one discipline and those criteria that were identified as *Not Important* by all disciplines were examined. In developing a cross-disciplinary rubric, it is essential that the most important criteria for each discipline are reflected. However, if all disciplines find a criterion to be *Not Important*, then it should not be reflected in the rubric.

Across all disciplines, eight criteria were designated as *Very Important* based on quartile analysis (shaded dark green in Table 4). Most agreement across disciplines was observed for "minimizes natural resource depletion," "addresses stakeholder or client requests," and "protects human health and well-being." Of the *Very Important* criteria across disciplines, most were from the social and environmental categories, with fewer from the economic and other/tools categories.

Five criteria, shaded in orange in Table 4Table 6**Error! Reference source not found.**, were considered *Not Important* across disciplines. None of the criteria were from the environmental or social categories, while two were from the economic category and three were from the other/tools category.

Comparing Established Frameworks with Professional's Perspectives

Overall, criteria designations determined from the text mapping and surveyed students were similar. In fact, designations for 17 of the 34 criteria were identical (Table 7), while designations differed by only one level for 10 of the 34 criteria.

Table 7: Criteria that received matching designations from text mapping and survey studies.

A1	Minimizes natural resource depletion	*Very Important*
A2	Prevents waste	
A3	Protects natural ecosystems	
B2	Considers local circumstances and cultures	
B5	Protects human health and well-being	
B8	Reflects social responsibility	
B7	Demonstrates ethics/ethical reasoning	*Important*
C1	Consider economic impacts of environmental design criterion	
C6	Considers affordability	
A4	Uses renewable energy sources	*Slightly Important*
A5	Provides for low-energy production	
A6	Provides for technological adaptability	*Not Important*
A9	Analyzed embedded energy of alternatives	
C4	Demonstrates cost competitiveness or cost reduction	
D2	Used DfX in design process (indicate "X")	
D4	Uses industrial ecology principles	
D9	Reflects leadership	

Combined, 79.4% of criteria received exact, or near exact, designations from each of the two studies. Perfect agreement between studies was most common for the environmental category, with seven criteria receiving matching designations. In comparison, four criteria from the social category received matching designations, while three criteria from each the economic and other/tools categories matched exactly.

Despite overall similar outcomes from the text mapping and survey studies, some criteria received differing designations (Table 8). In total, seven criteria received designations that differed by two levels between the two studies, including one from the environmental category, three from the social category, one from the economic category, and two from the other/tools category. Ultimately, when finalizing the set of sustainable design criteria, special attention may be needed for these criteria. No criterion received designations that differed by more than two levels between the two studies.

Table 8: Criteria that received differing designations by two levels from the text mapping and survey studies.

		Text Mapping	Survey
A7	Uses inherently safe & benign materials (to env)	Not Important	Important
B1	Addresses stakeholder or client requests	Slightly Important	Very Important
B4	Incorporated user experience	Not Important	Important
B9	Manufacturing complies with safety regulations	Not Important	Important
C5	Stimulates labor/jobs	Important	Not Important
D3	Reflects cradle-to-cradle design	Not Important	Important
D8	Uses innovative technologies to achieve sustainability	Important	Not Important

Identifying Sustainable Criteria to Retain, Refine, or Omit

Final designations from the text mapping and survey studies (Table 6) were used to identify criteria that may need to be retained, refined, or omitted in compilation of the final sustainable design rubric. Recommendations below are pending analysis of additional survey questions and pilot testing with student design projects.

1. Criteria to Retain or Refine

Overall, eight criteria were ultimately designated as *Very Important*, including three from the environmental category, four from the social category, and one from the other/tools category (Table 9). To receive this designation, the criteria were categorized as *Very Important* by both the text mapping and survey studies or *Very Important* by one study and *Important* by the other. Agreement between the two studies suggests that the eight criteria should be retained in the final rubric.

Seven criteria were ultimately designated as *Important*, including two from the social category, three from the economic category, and two from the other/tools category (Table 9). To receive this designation, the criteria were never designated as *Not Important* by either of the two studies. Consequently, these seven criteria should either be retained or refined for the final rubric, pending further validation work. For example, the three *Important* economic criteria (C1, C2, C6) should be considered for inclusion in the final rubric, since no economic criteria were designated as *Very Important*. Conversely, the two *Important* criteria from the other/tools category related to environmental impact assessment and systems analysis (D5 and D6) could be refined and consolidated as part of "incorporates life cycle analysis" (designated as *Very Important*). Only "addresses stakeholder or client requests" (B1) received significantly differing designations from the text mapping and survey studies (Table 8). B1's *Very Important* designation from the survey study supports that it should be explicitly reflected in the final rubric.

2. Criteria to Refine or Omit

Eight criteria were ultimately designated as *Slightly Important*, including three from the environmental category, two from the social category, one from the economic category, and two from the other/tools category (Table 9). To receive this designation, the criteria were never designated as *Very Important*. Consequently, it is likely that the eight *Slightly Important* criteria will not be individually included in the final rubric, although they may be reflected as part of other unique criteria. For instance, "manufacturing complies with safety regulations" (B9) could be included as an example of "protects human health and well-being" (B5; designated as *Very Important*). Of note, six of the eight *Slightly Important* criteria received significantly different designations between the two studies (Table 8). While future validation phases should examine these six criteria, considering them for refinement or omission is likely acceptable since neither study supported them as *Very Important*.

Finally, 11 criteria were ultimately designated as *Not Important*, including three from the environmental category, one from the social category, three from the economic category, and four from the other/tools category (Table 9). To receive this designation, the criteria were categorized as *Not Important* by both the text mapping and survey studies or *Not Important* by one study and *Slightly Important* by the other. Agreement between the two studies suggests that the 11 criteria should be omitted from the final rubric, although some may serve as useful examples of retained criteria. While each omitted criterion is still an important facet of sustainable design, they collectively were more specific than the highest ranked criteria and also tended to overlap with others. For example, "promotes a low carbon economy" (C7) could be an example of "minimizes natural resource depletion" (A1; designated as *Very Important*). As another example, "uses inherently safe and benign materials" (B6) should be necessary for addressing "protects human health and well-being" (B5; designated as *Very Important*).

Table 9: Suggestions for retaining, refining, or omitting criteria based on final designations from text mapping and survey studies.

A1	Minimizes natural resource depletion	*Very Important* Likely Retain Some text refinement may be appropriate.
A2	Prevents waste	
A3	Protects natural ecosystems	
B2	Considers local circumstances and cultures	
B3	Incorporated public/stakeholder participation	
B5	Protects human health and well-being	
B8	Reflects social responsibility	
D1	Incorporates life cycle analysis	
B1[1]	Addresses stakeholder or client requests	*Important* Likely Retain or Refine Refinement would likely be as unique criteria or examples of other criteria.
B7	Demonstrates ethics/ethical reasoning	
C1	Consider economic impacts of environmental design criterion	
C2	Consider economic impacts of a social design criterion	
C6	Considers affordability	
D5	Incorporates environmental impact assessment tools	
D6	Incorporates systems analysis	
A4	Uses renewable energy sources	*Slightly Important* Likely Refine or Omit Refinement would likely be as examples of other criteria.
A5	Provides for low-energy production	
A7[1]	Uses inherently safe and benign materials (to environment)	
B4[1]	Incorporated user experience	
B9[1]	Manufacturing complies with safety regulations	
C5[1]	Stimulates labor/jobs	
D3[1]	Reflects cradle-to-cradle design	
D8[1]	Uses innovative technologies to achieve sustainability	
A6[2]	Provides for technological adaptability	*Not Important* Likely Omit Some may still be used as examples of other criteria.
A8	Uses footprint analysis to estimate impact	
A9[2]	Analyzed embedded energy of alternatives	
B6	Uses inherently safe and benign materials (to humans)	
C3	Conduct a cost and/or cost-benefit analysis	
C4[2]	Demonstrates cost competitiveness or cost reduction	
C7	Promotes low-carbon economy	
D2[2]	Used DfX in design process (indicate "X")	
D4[2]	Uses industrial ecology principles	
D7	Incorporates uncertainty analysis	
D9[2]	Reflects leadership	

[1]Designations for these criteria differed by two levels between the text mapping and survey studies; [2]These criteria were designated as *Not Important* by all disciplines and text mapping analysis and may be omitted from the rubric.

Conclusions and Future Work

As part of a broader effort to create a cross-disciplinary sustainable design rubric for student-level projects, the goal of this work was to normalize data from prior text mapping of existing sustainable design frameworks and a survey of professionals to aid in iterative refinement of design criteria. In the text mapping study, three researchers mapped items/criteria from the STAUNCH©, Envision™, and UN Sustainable Development Goals to the draft design criteria. In the survey study, professionals from a variety of disciplines selected and ranked the 10 most important criteria from the set of draft criteria. Subsequently, data from each of the text mapping and survey studies were sorted by quartiles (and importance). The sorted data from each separate study were combined and used to designate the relative importance of each design criteria (*Very Important*, *Important*, *Slightly Important*, *Not Important*). The following conclusions were made based on the results.

1. Given that 27 of the 34 criteria (79.4%) received identical or similar rankings between the text mapping and survey studies, convergence of final importance designations was established for most criteria.
2. The eight criteria that were ultimately designated as *Very Important* and the 11 criteria that were ultimately designated as *Not Important* will likely be retained and omitted from the final rubric, respectively.
3. The seven criteria that were ultimately designated as *Important* will likely be retained or refined for the final rubric, pending further validation phases.
4. The eight criteria that were ultimately designated as *Slightly Important* will likely be refined or omitted from the final rubric, pending further validation phases.

This study is the first phase in iteratively comparing different techniques (in this case, text-mapping and expert survey) to examine and validate our draft sustainable design criteria. Ultimately, the analysis presented will allow us to reduce the number of criteria by omitting those that are less important and/or by merging related criteria. However, future work is still needed to supplement our rubric with criteria that reflect topics not currently covered by the draft set. For instance, the prior text mapping study identified several topics included in the STAUNCH©, Envision™, and UNSDG frameworks that were not adequately captured by our draft criteria. In addition, as part of survey completion, professionals were asked to provide topics or criteria that are not currently reflected in our rubric and describe examples of how students would satisfy criteria in their projects. Consequently, future efforts will focus on further analysis of these data sets to provide a validated set of sustainable design criteria. Concurrently, we are examining different scoring approaches and rating scales for applying the rubric to student projects. A scoring approach and supporting documentation should support consistent use of the rubric by different engineering educators and students while also allowing flexibility for customization and recalibration over time.

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