Measuring engineering students' conceptual and empirical understanding of sustainability

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Abstract- Engineering professionals are in a pivotal position to influence the way societies function and as problem solvers, their primary responsibility is to produce solutions that work in the real world, with all the attendant constraints. Traditionally, engineers have tackled most problems pertaining to individual dimensions of sustainability retroactively, but current challenges facing society require a more proactive orientation to the teaching and practice of the profession. There are currently many efforts to introduce sustainability concepts in various classes across engineering departments. However, these efforts tend to simply promote the appreciation of sustainability as an ideal rather than introduce specialized technical content necessary for providing engineering based solutions. If engineers are to be effective participants in sustainable development, sustainability must become part of the engineering practice paradigm. This, on the other hand, can only be achieved if it becomes an integral part of engineering education programs, not a mere 'add-on' to the 'core' parts of the curriculum. Embedding sustainability within the curriculum does not simply mean including new content. There is currently no available assessment instrument to gauge the competencies acquired by students in the variety of sustainable engineering education efforts. More so, there is no data that tells us if any of the learning objectives developed by various programs are truly in line with what will be expected of the next generation of engineers. This work proposes a framework for assessing the changes in the conceptual and empirical understanding of sustainability by engineering students as wells as determining the degree to which engineering graduates are being imparted with the requisite skills to solve engineering problems in the context of sustainable development by first, determining and articulating what these skills should be. A model for the development of a research track on measuring the degree of attainment of sustainability learning objectives is proposed. The ultimate goal is to develop a basis for curricula and pedagogical changes to engineering education in preparation for sustainability challenges.

Keywords: sustainability, curriculum, assessment

INTRODUCTION

Current trends and ongoing discussions suggest potential redefinitions of the future roles of engineers in society. There are calls for a departure from the current "detached" mentality of the various engineering disciplines and a return to synergistic orientations in the teaching and practice of the profession [Turner, 30]. These new paradigms demand that engineers work comfortably within a holistic multidisciplinary context to solve contemporary challenges like sustainable development. However, ambiguities in definitions and methodologies across disciplines have hampered collaborative efforts because many problem statements and preferred solutions have been restricted to rather narrow scopes heavily influenced by the perspectives of the various stakeholders. Three dimensions of sustainability have traditionally been identified: economic, environmental, and social. Other dimensions are often proposed when considering standards or guiding principles of various professions and specializations [Pawlowski, 18]. Hence from an engineer's perspective, a technical dimension is also to be considered. Engineering professionals, in their role as technology providers, are in a pivotal position to influence the way societies function [Carew, 5] and as problem solvers; their primary responsibility is to produce solutions that work in the real world, with all the attendant constraints.

The principles of sustainable engineering and design of processes, products and services, life cycle design, sustainable flows of materials, adequate management of energy resources, industrial ecology, and pollution prevention have been touted by various professional engineering bodies and the challenges inherent are constantly being identified and defined in cross-disciplinary contexts [Wallace, 31]. However, there have not been many

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tangible ideas on how to make these principles operational in practice. As noted by Ivan Amato, Managing Editor of Chemical & Engineering News, “The sustainability ethic may be infiltrating the mind-set of a widening swath of humanity, but there also is a collective shoulder-shrug about how to realize it” [Amato, 3].While recognition and acknowledgement of a problem is a crucial step, formulating and implementing the solutions is even more imperative especially considering the multi-faceted nature of the sustainability model. A major gap exists between theory and practice and no clear protocols have been developed for achieving this ideal. Arguably, some flux currently exists regarding what defines sustainable engineering and how these definitions fit into future roles for engineers. Since the introduction of the term “sustainable development” there has been a continuous effort to clearly define what it means and how it can be achieved. It has been theorized by some that at the core of sustainability is an unachievable ideal that can only be aspired to and that, “without a particular frame of reference, the concept of sustainability has virtually no meaning at the practical problem-solving level” [Thornton, 29]. Allenby et al. contend that sustainability began as, and some would argue that it still is, a cultural non-scientific or non-technological construct and that it refers to lofty and qualitative ideals, which are difficult to define and measure in terms that engineers are familiar with [Allenby, 2].Therefore, “a new kind of engineer is needed, an engineer who is fully aware of the systemic nature of the challenges we face” [De Graaff, 9].

In response to this and recently revised accreditation requirements, there are currently many efforts to introduce sustainable development concepts in various classes across engineering departments to promote an awareness of sustainability and environmental impact issues and produce sustainability conscious engineers. In general, though, these efforts are not aimed at producing engineers with specific technical expertise to appreciate the systemic nature of the challenges and to provide engineering based solutions. Embedding sustainability within the curriculum does not simply mean including new content [Holmberg, 13]. If engineers are to contribute truly to sustainable development, sustainability must become part of their paradigm and effect every day thinking. This, on the other hand, can only be achieved if it becomes an integral part of engineering education programs, not a mere ‘add-on’ to the ‘core’ parts of the curriculum [Sterling, 26].

In a special report titled “The Research Agenda for the New Discipline of Engineering,” the Steering committee of the National Engineering Education Research Colloquies contends, “Will the U.S. have engineers prepared to collaborate and lead in a rapidly changing world? The answer to that question, in part, relies on our ability to transform how we educate our future engineers. Our premise is that we need fundamental knowledge of how engineers learn to under-gird these transformational decisions” [The Steering Committee, 28].

RELEVANT LITERATURE

Education in sustainability has been contemplated by many engineering departments since the late 1990s [Segalas, 21]. In the past, few engineering schools have made major updates to their courses and curricula due to the significant amount of time and effort needed as well as the probable lack of impetus, but to meet the challenges of sustainability, the scope of engineering practice is expanding and *ipso facto,* the engineering curriculum has to be overhauled. New courses are being introduced and old courses are being changed to respond to industry needs.

Recent conferences on Engineering Education and Sustainable Development have focused on integrating sustainability in engineering education, thereby beginning the development of a body of knowledge and experience [Boks, 4]. As “Energy and Power Generation,” “Water,” “Industrial Processes,” “End of Life and Waste Management,” “Life Cycle Assessment,” and “Business and Economics” begin to emerge as themes in various sustainable engineering curricula, Allen et. al., poses a pertinent question, “What relevant competencies should engineering students obtain from college training and instruction?”[Allen, 1]. Some studies suggest that these competencies should be mainly related to critical thinking, systems thinking, an ability to work across disciplinary frameworks, and values consistent with the sustainability paradigm [Segalas, 23, Svanstrom, 27].

A consortium of the Univ. of Texas at Austin, Arizona State University, and Carnegie Mellon University called Center for Sustainable Engineering, recently completed an EPA-funded project on the status of sustainable engineering education at four-year colleges and universities in the U.S.. 1,368 engineering departments (or the equivalent) at 364 US universities and colleges were invited to partake in a survey on the extent to which sustainable engineering was being integrated into the various existing curricula. More than 20% responded, of which more than 80% reported teaching either sustainable engineering focused courses or integrating sustainable engineering material into existing courses. A total of 155 course titles from a variety of engineering disciplines focusing on sustainable engineering were identified as having been offered by (or in cooperation with) an engineering department. They are as follows:

- Civil, Architectural, and/or Environmental Engineering, 64 courses
- Mechanical, Aero-, and/or Manufacturing, 32 courses
- General Engineering and Other (including Electrical and Nuclear), 28 courses
- Chemical, Bio-, and/or Materials Engineering, 18 courses
- Industrial, Systems, and/or Sustainable Engineering, 13 courses [Allen, 1]

Based on survey responses, as of 2008, at least 33 departments (12% of respondents) from 26 universities were granting both bachelor's and master's degrees related to sustainable engineering. An additional 17 departments (corresponding to 17 institutions) offered bachelor's degree programs, 15 departments (corresponding to 15 institutions) offered only master's degree programs making a total of at least 65 departments (23% of respondents) and 53 institutions (29% of respondents) [Allen, 1].These findings indicate that engineering schools are actively engaged in incorporating sustainable engineering concepts into the curriculum. The report also showed that while there is significant diversity in the nature of the courses being taught, there are several themes and features common to many programs. Ultimately, the researchers concluded that there is an urgent need for the development of a set of community standards for learning objectives. "What is needed in addition to a uniform set of terminology and standards is a tool to assess the quality of the output from these programs and hence, provide a basis for modifications and continuous improvement." [Allen, 1]

Considering the fact that every year, approximately 70,000 new engineering graduates are produced in the U.S. (corresponding to over 1,500 engineering units and departments at more than 350 colleges and universities), while Europe, China and India produce 100,000, 215,000 and 350,000 graduates respectively, the need for standards and metrics become imperative as the global demand for the specific skills afforded by engineers trained in sustainability increases [Davidson, 8].

While there may be broad agreement about the need for sustainable engineering outcomes, the literature suggests that engineering academics feel that sustainability requires differing actions [Carew, 5]. Research shows that sustainable engineering content and concepts are currently being introduced into the engineering curriculum in four ways [Davidson, 8],

1. Dedicated sustainable engineering courses typically focused on the use of tools designed to address complex systems. This seems to be the dominant approach.
2. Integrating sustainable engineering concepts into traditional engineering courses.
3. Courses that focus on technologies touted as sustainable engineering solutions.
4. Cross-listed courses with non-engineering departments that focus on some aspect of sustainability.

To teach sustainability a three-tier approach was developed at the University of Surrey comprising of the following elements:

1. Dedicated lectures and tutorials on sustainable development;
2. Specific case studies;
3. Integration of sustainability into the overall curriculum [Segalàs-Coral, 24]

Indeed, a wealth of literature exists to support the notion that active, student-centered learning is more effective than passive, teacher-centered instruction. To evaluate the effectiveness of different pedagogical approaches in teaching sustainability, ten courses from five European technological universities were analyzed using conceptual maps (Cmaps) [Novak, 17, Segalas, 22] as assessment tools. With over 500 student participants, the study was designed to assess students' *understanding* of the concept of sustainability and not necessarily the *technical skills and abilities* acquired. This assessment was structured as a pretest–posttest experiment comparing results before and after the course to evaluate the degree of learning. The researchers concluded that courses applying a more community-oriented and constructive, active-learning pedagogical approach, increased students' general knowledge of sustainability but they also observed that students disproportionately perceived sustainability as a mere technological problem which could be resolved accordingly. This perception was only partially readdressed after taking the courses. Despite acknowledged shortcomings, the study presented useful information that helped in gauging how well the original objectives of the courses were being achieved and consequently, the need for restructuring the course in terms of content and delivery [Segalas, 22].

A review of ABET accreditation requirements suggests that ABET is already addressing the issue of sustainability in engineering education. Criterion 3 of ABET accreditation requirements for all engineering programs states that "…students in the program must attain an ability to design a system, component, or process to meet desired needs within realistic constraints, such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability"[Kumar, 15].

However, successful integration of sustainability principles into engineering requires that students achieve an understanding of how various subjects relate to one another and fit into the bigger picture. This is arguably not emphasized nor required by ABET [Kumar, 15]. Research also suggests that what a teacher already knows, thinks, and feels about a topic will influence the way in which he or she structures teaching and learning activities for students [Prosser, 19]. For example, according to Fletcher and Dewberry, two extremes exist in the implementation of sustainability into the curricula of industrial design schools [Fletcher, 10]. For some, design is viewed as a dimension of sustainability, where design takes place to achieve the objectives of sustainability. For others, sustainability is a dimension of design and is understood within the frame of reference of current design activities and priorities [Boks, 4].

Learning outcomes are statements of what a learner (i.e. the student) is expected to know, understand and/or be able to demonstrate after completion of the learning activity. Assessment is integral to effective learning and is defined as measurement of the learner's achievement and progress in a learning process. Used to refer to operations associated with measuring achievements in relation to desirable outcomes [Keeves, 14], it can also be essential in developing and testing pedagogical approaches [Gikandi, 11]. For sustainable engineering education, undoubtedly, new forms of assessments will be necessary to help in gauging the efficacy of programs and methods. The National Science Foundation (NSF) has already taken the lead by granting funds to universities that are focusing on new and innovative pedagogical topics and methods. An investment in assessment tools is a necessary corollary.

Because summative assessments measure what students have learned at the end of an instructional unit, end of a course, or after some defined period [Hargreaves, 12], it can also help in ascertaining that the desired goals of learning have been met or certifying that the required levels of competence have been achieved [Challis, 6]. Assessment inevitably shapes how students approach learning, including what they focus on and how they go about learning it. Assessment instruments may be designed to emphasize lower-order cognitive outcomes (memorization knowledge, understanding, and application) versus higher-order cognitive outcomes (analysis, critique, design, and synthesis) [Sadler, 20].Objective assessments include short answer completion, multiple-choice, and true-false tests. These types of assessments capture information about recall of factual knowledge but are less useful for assessing higher-order thinking as they typically allow for only one best answer. Performance assessments however, allow for more than one correct answer. They require students to respond to questions by selecting, organizing, creating, performing and/or presenting ideas. Hence, performance assessments are better at measuring higher-order thinking [Stanford, 25]. Performance assessments may be used to assess what students can demonstrate or produce and allows for the evaluation of both process and product. Demonstrated evidence of student learning can be obtained through direct measures of assessment using standardized instruments. Standardized assessments are generally developed relying on standard sets of administration and scoring procedures and are generally more reliable. Standardized assessments may provide information about how students in a program compare to students at other peer institutions or to national/regional norms and standards [Stanford, 25].

THEORY AND APPROACH

In dealing with the challenges of curricula revision to accommodate sustainability, some programs simply include modules that create the awareness of sustainability issues within existing curricula. Other programs aspire to produce professionals that will be equipped with the skills to actually proffer and execute solutions. One approach, which is used by the engineering curriculum at James Madison University (JMU), emphasizes the incorporation of systems analysis and lifecycle assessment instruction in the traditional design sequences [Nagel, 16]. Hence, the engineer graduating from the program will aim to reduce social and environmental stresses while maintaining acceptable functionality as well as economic considerations.

Foundational Concepts

In general, these varied approaches to sustainably in engineering curricula are seemingly based on a few identifiable paradigms, namely:

- Sustainability involves science
- Sustainability can be taught
- Sustainability can be learned
- Sustainability learning can be assessed

These paradigms then necessitate that an acceptable working set of attributes be developed for sustainability and sustainable engineering. These include

- Definition
- Parameters
- Scope/Boundaries
- Content
- Pedagogic Tools
- Assessment Tools

The peculiar nature of the idea of sustainability makes traditional assessment techniques ineffective. This peculiarity stems from the varied definitions and scopes of sustainability.

Relevant Problem Statements

Certain relevant questions are needed to guide the development of any framework for assessing the needed changes in engineering education. These include:

1. What is sustainable engineering and should it be regarded as a particular kind of engineering or a competence that all engineering students need to have?
2. What is demanded of engineers when stakeholders require sustainable engineering?
3. What technical sustainability competencies should a graduating engineer possess?
4. How can these sustainability competencies acquired be measured?
5. What curricular features are effective in providing students sustainable engineering training?
6. What pedagogical strategies are effective in imparting these competencies?
7. What recommendations can be given to institutions and instructors to improve engineering education regarding sustainability?

A diagrammatic representation of the interrelationships between various dimensions of sustainable engineering education is presented in Figure 1

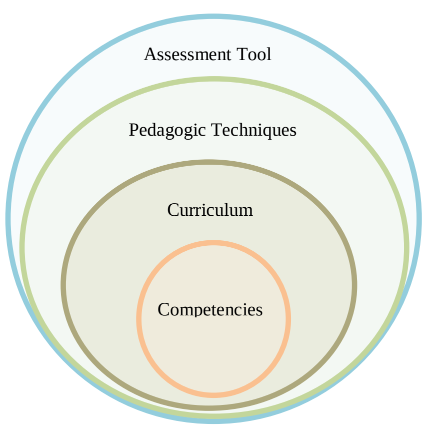

Figure 1.Dimensions of Sustainable Engineering Education

Research Method and Data Collection

Mixed research methodology combines quantitative and qualitative research strategies in a single study. As described by [Creswell, 7], concurrent procedures are those in which the researcher converges quantitative and qualitative data in order to provide a comprehensive analysis of the research problem. A nested concurrent strategy utilizes a predominant data collection method (qualitative or quantitative) that guides the project while the other method is nested within the predominant method. This nesting may mean that the embedded method addresses a different question to the dominant method or seeks information from different levels. The data collected from the two methods are mixed during the analysis phase of the project.

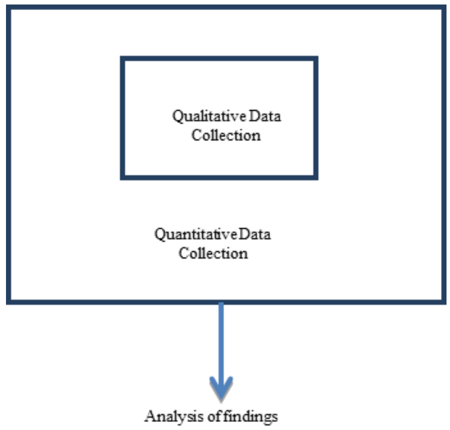

Figure 2. Concurrent nested research strategy (after Creswell [Creswell, 7])

A *mixed concurrent nested* data collection and analysis strategy where the qualitative method is nested within the quantitative one is deemed appropriate by the authors for this endeavor. This approach is illustrated in Figure 3. Qualitative data collection methods can be employed to identify descriptions of competencies and learning objectives as well as current curriculum structure and pedagogic techniques. These can be used as the framework for the development of a quantitative performance assessment instrument to measure the achievements of the learning objectives, identify areas of deficiencies and the role of curriculum structure and pedagogic techniques in meeting the objectives. The mixed research strategy provides the advantages of both quantitative and qualitative data, and deeper perspectives can be gained from different types of data or from different levels within the study. Data sources and their relationships are shown in Table 1.

Table 1. Information and data sources relevant to each dimension of Sustainable Engineering Education.

Competencies	**Curriculum**	**Pedagogic Techniques**	**Assessment Tool**
Employers	Academic Instructors	Academic Instructors	Academic Instructors
Reference Publications	Academic Administration	Reference Publications	Reference Publications
Professional Bodies		Students	Professional Bodies
Academic Instructors			Students
Academic Administration			

All of the identified information and data sources are recognized as stakeholders in sustainable engineering education. The initial focus should be on identifying and defining the competencies that are required from engineers trained in sustainability. The use of data gathering methods such as surveys, semi-structured interviews, focus groups and questionnaires can be employed. The target source of information will be potential employers, academics, members of professional engineering bodies and policy leaders. In addition structured interviews can be conducted with recognized experts in sustainable engineering. Information on the existing programs, curriculum structures as well as pedagogical techniques currently in place at various institutions should also be gathered with a view to forming identifiable categories. The data obtained can be synthesized into learning objectives that will serve as a basis for the development of an assessment instrument. Development, testing, and refinement of a performance assessment instrument using test groups and traditional pretest-posttest assessment methodologies will be necessary. The best approach will be to select institutions with similar and dissimilar programs as well as varying pedagogic techniques.

Assessment Instrument Development

An illustrative cycle of interlinked activities that are part of the assessment process is shown in Figure 3.

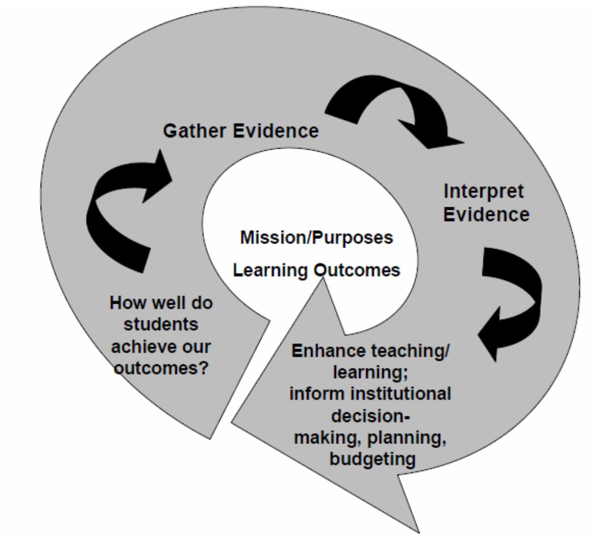

Figure 3. The assessment process (adapted from Maki, 2004)

A properly designed and developed assessment instrument will help evaluate

- Competency: Do students achieve sustainable engineering learning objectives?
- Relationships: Are there relationships between performances and curriculum structure/pedagogical techniques?
- Group Differences: Are there differences in performances by students in different groups i.e. gender, race, economic background etc.?
- Relevance: Are there significant differences from students who have had no sustainable engineering education.

A working set of Learning Objectives to guide the development of the assessment instrument is defined as follows:

Graduates will possess the knowledge and skills required to:

1. Assess the environmental, social, and economic impact of given engineering and technical systems.
2. Identify the interdependences and inter-relatedness of these sub-systems in environmental, socio-economical and technical contexts.
3. Propose optimized functional technical solutions.
4. Propose flexibilities within the system to account for perturbations while maintaining optimal functionality.

The assessment instrument to be developed should be concerned with technical skills and competencies acquired in the program as opposed to mere awareness of sustainability issues. The description of competencies embraces three strands which describe basic cognitive domains:

- *Knowledge and understanding*: the theoretical knowledge of an academic field, the capacity to know and understand.
- *Skills and abilities*: the practical and operational application of knowledge to certain situations.

- *Attitudes*: values as an integral element of the way of perceiving and living with others in a social context.

Competencies represent a dynamic combination of cognitive and meta-cognitive skills, knowledge and understanding, interpersonal, intellectual and practical skills, and ethical values. In this context, a competence means that a person puts into play a certain capacity or skill and performs a task, where he/she is able to demonstrate that he/she can do so in a way that allows evaluation of a level of achievement. The assumption is that competencies can be assessed and developed. This means that, normally, persons do not either possess or lack a competence in absolute terms, but command it to a varying degree, so that competences can be placed on a continuum and can be developed through exercise and education [Segalàs-Coral, 24]

To meet this goal, instruments for behavioral and attitudinal measures are inadequate. Likewise, due to the nature of the technical skills to be measured, simple multiple-choice instruments will be ineffective. Performance assessment instruments testing cognition and skills will be used as the framework for developing this assessment instrument. Bloom's Taxonomy provides a useful structure in which to categorize test questions when assessing student learning outcomes. A general blueprint of the assessment instrument will test students on their:

- Ability to adopt systems level thinking/tools to define problems and propose solutions
- Ability to identify the environmental, social, economic and technical considerations of a given problem scenario
- Ability to assess the impacts associated with these considerations
- Ability to identify the constraints these considerations place on functionality
- Ability to propose solutions grounded in appropriate scientific data

A grading rubric accompanies a performance assessment test. Rubrics are criterion-referenced, rather than norm-referenced. Hence, rather than specify how well a student performs compared to other students, they indicate how well a student performed in a particular content area. A framework for a scoring rubric would include the identification of specific content areas and descriptive objectives associated with each content area as well as a scoring mechanism. The rubric will resemble the one shown in Table 2.

Table 2. Rubric for scoring Sustainable Engineering Performance Assessment test

Content Area	**Objective**	**Score**
Systems Analysis	Ability to relate given problem to spatial and temporal considerations	
Design/Technical Principles	Ability to apply design principles and technical/engineering parameters to solve problem	
Problem Solving	Ability to propose feasible/viable solutions	
Environmental Considerations	Ability to identify/incorporate relevant environmental concerns	
Social Considerations	Ability to identify/incorporate relevant social concerns	
Economic Considerations	Ability to identify/incorporate relevant economic concerns	

CONCLUSIONS

As the competency requirements for the next generation of engineers change in line with changing global challenges and foci, the presented framework can guide the research that ultimately helps ensure that we are indeed preparing engineering students to competently address the problems of today and tomorrow. The proposed model can be adopted in the development of a research track aimed at the formulation of sustainability learning objectives in engineering curricula as well as methods of measuring the attainment of these objectives. It argues for the convergence of the various definitions and perspectives of sustainability in engineering education programs by identifying the true role different stakeholders play in sustainable engineering education and practice. The fact that many professional bodies acknowledge this necessity attests to the broad impact this line of research can have on engineering education. A primary objective of this work is to induce research that promises to improve scholarship in sustainable engineering education and practice as well as produce national baseline data on sustainable engineering education.

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