CAPACITY BUILDING FOR SUSTAINABLE ENGINEERING PRACTICE: A CIVIL ENGINEERING EDUCATION PERSPECTIVE

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Abstract: Civil engineers play a critical role in the planning and design of the built environment around. As a result, they wield enormous influence over the use of earth's natural resources. At this pivotal juncture of increased globalization and accelerated, widespread economic development, demand for earth's natural resources and the impact of development on our ecosystem are increasing rapidly. This is creating an unsustainable scenario, and therefore, it is imperative for educators to prepare the future engineering workforce to become stewards of a sustainable global society. This paper presents some reflections of the author based on experience from developing and teaching a course titled "Material Systems for Sustainable Design" as part of a civil engineering curriculum. The overarching course objective is to provide students with the knowledge on sustainability and create an awareness of the tools that are both available and needed to apply sustainable material selection practices in their future design work.

Keywords: Sustainability, Design, Engineering, Education, Materials

1. Introduction

A near consensus has emerged within the scientific community on the strong links between the lifestyles of people and global ecological deterioration. It does not come naturally to most societies to think in terms of the long-term impacts of their decisions. Furthermore, globalization has prompted rapid development in many emerging countries that is introducing more people to consumerist lifestyles similar to that of the western world. This has prompted countries to develop creative and innovative ways to educate communities, the younger generation in particular, to understand the long-term impacts of their actions and to find ways to create a sustainable world order. The term sustainability has evolved from an ecology-based concept to one that calls for societies to develop and sustain resources and leave the natural ecosystem in a sustainable mode for future generations.

Sustainability requires living within the regenerative capacity of the biosphere, and it has been reported that the human demand could well have exceeded the regenerative capacity of the biosphere since the 1980s [Wackernagel et al., 2002]. According to preliminary and exploratory assessments, humanity's load corresponded to 70% of the capacity of the global biosphere in 1961, and grew to 120% in 1999. The alarming increase in the rate at which Earth's resources are being utilized prompted the United Nations to initiate a Millennium Ecosystem Assessment in 2001 to assess the consequences of ecosystem change for human wellbeing and the scientific basis for action needed to enhance the conservation and sustainable use of those systems. Evidence of the consequences of non-sustainable use of Earth's natural resources was highlighted 23 years ago [UNDP 1987]. The predictions of possible outcomes of the ecological change that has been taking place include reduced standards of living in the developed world, threats to food security in the developing world and widespread famine. These scenarios may lead to increasing risk of mass migration of populations, social injustice and unrest caused by struggles to share scarce resources. The predictions and the timing of such scenarios vary between sources, but it is clear that the future workforce must be educated more intensely on the impact of the utilization of Earth's natural resources and the manner in which they are used.

2. Sustainable Civil Engineering Education

Current global emphasis on sustainability has prompted engineers to design products and services by incorporating principles of sustainability. Sustainability is a multi-faceted and a multidisciplinary issue. Therefore, to work towards a sustainable future, it is important to educate future engineers to develop skills needed to effectively work in multidisciplinary teams. Many techniques may be used to include sustainability within the engineering curriculum. For example, students may be required to analyze case studies and present and discuss the topics learned [Paten et al., 2005]. Additionally, promoting student creativity is an important aspect of sustainability education.

The US Accreditation Board for Engineering and Technology (ABET) updated its accreditation criteria [ABET EC 2000] to allow university engineering programs to be more creative in their education mission. In EC 2000 Criterion 3, ABET reaffirmed a set of 'hard' engineering skills while introducing a second set of six 'professional' skills that were divided by Shuman et al. [2005] into process and awareness skills. This professional skill set has been somewhat controversial, particularly due to ambiguities associated with their assessment, but many advances have been made by institutions in the teaching and learning of these skills. The 'awareness' category of skills includes the following that can be associated with sustainability education.

- A broad education necessary to understand the impact of engineering solutions in a global, economic, environmental and societal context
- A recognition of the need for, and an ability to engage in life-long learning
- A knowledge of contemporary issues

Researchers have observed a much deeper understanding of what it means to include sustainability in design. Shekar (2007) indicated that engineering design projects are active learning tools that may be used to encourage the development of problem-solving skills of students while teaching the concepts behind other issues such as sustainability. Several authors have presented ideas on appropriate ways to teach engineering design within the context of sustainability. De Ciurana and Filho [2006] proposed a novel approach for "greening" of the curricula that included ten characteristics. Morris et al. [2007] suggested that engineering students must first be introduced to design concepts and then sustainability concepts can be gradually introduced into the design process. In addition to innovative design exercises, they recommend problem-based learning as an effective way to teach sustainable engineering design, and that past research has repeatedly shown that these approaches of teaching enhance students learning experiences that motivate them for deeper learning and better retention of learning content.

According to data collected by the US Geological Survey [Figure 1], the construction industry uses by far the largest quantity of natural resources as raw materials [USGS 1998]. Most of these natural resources can be categorized as non-renewable, and therefore, the construction industry has significant impacts on sustainability of Earth's natural resources. Designers of civil engineering projects can effectively contribute towards sustainability through more effective use of new and recycled materials. This will significantly slow down the utilization of non-renewable natural resources. Civil engineering students and the society in general can benefit immensely from course curricula that provide awareness on sustainability implications of various materials available at their disposal. These implications include material supply, recycling potential and ecological implications.

The current practice of specifying construction materials for projects is primarily driven by factors such as status quo and existing pricing mechanisms. However, with the increasing emphasis placed on sustainability and the preservation of biodiversity in all facets of the society, civil engineers must take a closer look at potential benefits to society from sustainable design and construction practices.

The Accreditation Board for Engineering and Technology (ABET) has included knowledge of sustainability in its general program evaluation criteria [ABET 2000]. In addition, the ASCE Body of Knowledge (BOK) for the 21st Century document includes knowledge of sustainability as one of 11 technical outcomes to be met at the bachelor's degree level [ASCE 2004]. The second edition of the BOK recommends the incorporation of sustainability concepts in design courses and to allow students to develop specialized knowledge and skills beyond traditional civil engineering-related subject areas.

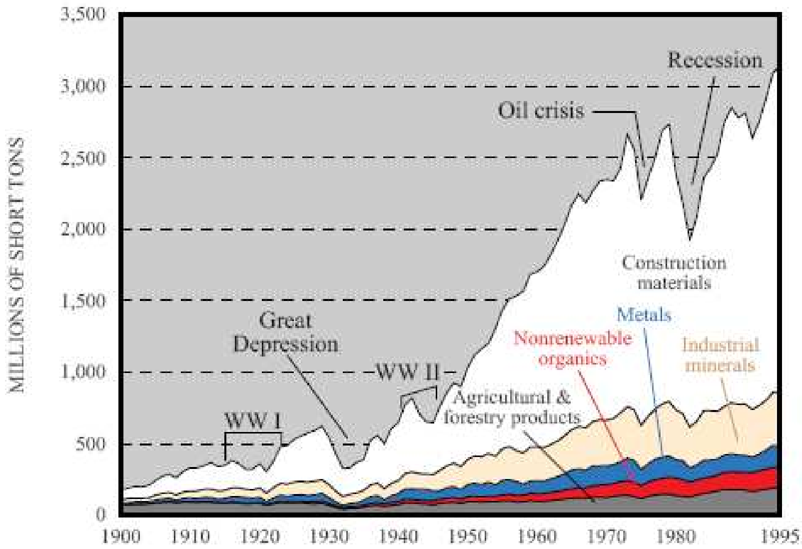

Figure 1. *Raw Materials Consumed in the United States, 1900-1995 [USGS, 1998]*

The development of sustainable built environment systems requires a coherent development strategy encompassing areas such as regional planning and development, engineering design, energy, transportation technologies, environmental quality and human health. It has been suggested that students must not only grasp the principles of these individual subject areas, but also develop skills to integrate such knowledge [Morris et al., 2007].

The typical product lifecycle in a civil engineering project consists of planning and design, material production/processing, construction, operation and disposal phases. Material selection for civil engineering projects is mostly influenced in the early phases of a project lifecycle, i.e. planning and design phases. In cultivating sustainable design practices, the amount of energy utilized and the ecological footprint of materials must be considered. During the material production/processing phase, the concerns are most notably on the energy utilized to produce the material (embodied energy) and the ecological footprint of that phase. The environmental impact is commonly expressed as the amount of greenhouse gas emissions and toxic material releases per unit mass or volume of material produced. During the construction phase, the energy consumed during the construction process (process energy), the greenhouse gas (i.e. carbon) footprint and localized pollution due to the construction process are major concerns. During the operation phase, conservation of energy and minimization of negative environmental impact are of paramount interest. During the disposal phase, it is important that material is non-toxic and recyclable.

In civil engineering design, the conventional approach to material selection typically involves maximizing the use of locally available materials due to the high transportation cost of bulky and heavy construction materials. In order to institute sustainable engineering design practices, the design process has to integrate sustainable development, environment, economy, society and the future [LSF-

LST 2007]. Students can be encouraged to take innovative approaches to material selection and the design of material systems based on a sustainability-based approach that includes material consumption availability and rate of utilization, use of energy to produce the material (embodied energy), process energy expended and the ecological footprint of the material and the related construction process. Sustainable design and material selection also requires the rational use of life-cycle analysis methods to make holistic decisions that incorporate the impact of all factors indicated above.

3. Material Systems for Sustainable Design: A New Course

A new course titled Material Systems for Sustainable Design was developed for graduating seniors and graduate students. This course was designed with the objective that it will meet either the senior elective or the design elective requirement for undergraduates. Additional course content was assigned to students who were taking it for graduate credit. The following factors highlighted in the literature review presented in this paper were incorporated in the design of this course curriculum and pedagogy.

1. The study of sustainability requires a systemic (global) approach.
2. Design of sustainable systems requires a holistic approach with a long-term outlook that takes into consideration the overall quality of life of societies.
3. Civil engineers can make a significantly positive impact in creating a sustainable society.
4. Sustainable engineering design is a non-linear process that requires a collaborative effort from a multidisciplinary team.
5. Sustainable design can be effectively taught by first introducing the basic principles of design, and then gradually adding sustainability concepts to the design process.
6. Case studies and team design projects greatly enhance the engineering design experience.
7. Problem-based learning (PBL) approach is an effective way to teach design.
8. The topic Sustainability satisfies the ABET ‘awareness’ professional skill category.

Considering the factors identified above, the course was divided into the following topics.

1. Engineering design process: Design criteria and constraints, working in design teams
2. Role of materials in design: Material characteristics, specifications and markets
3. Introduction to sustainability: Definitions, history, concepts, impacts
4. Sustainable use of materials: Energy, ecology and natural resources
5. Guidance documents on sustainable engineering practice
6. Material flow analysis
7. Sustainability metrics
8. Sustainable design
9. Specifications for sustainable material use
10. Design project
11. Life-cycle assessment (for graduate credit)

The above topics were selected by carefully considering the recommendations presented in the literature review conducted for this paper. Every effort was made to highlight the multidisciplinary nature of sustainable design and its impact to global sustainability. Table 1 outlines the sustainability-related topics and learning outcomes for this new course. The domains of human learning, as defined in Bloom’s Taxonomy, were used as the basis to organize student learning from this course. Learning outcomes identified in Table 1 were developed to ensure that the course addresses all domains of human learning. The course was delivered using a format that combined several techniques including the following.

1. Limited traditional classroom instruction to introduce basic concepts

2. Review magazine articles and books to understand global, holistic outlook of the topic
3. Develop a Material Flow Analysis charts for select materials
    - Each student was assigned a construction material
    - Materials selected to make comparisons for similar applications
4. Review of key publications related to sustainability
    - UN Brundtland Commission Report [UNDP 1987]
    - Sustainable Engineering Practice: An Introduction [ASCE 2004]
    - US Green Buildings Council LEED™ Certification
5. Review and discussion of journal articles on sustainable material use
6. Semester Design Project
    - Students worked in teams, with each team representing a particular application
    - Each student within group developed specifications and metrics for his/her material
7. Life-Cycle Assessment (for graduate credit)

There were twelve students enrolled in this class, and each student was assigned a commonly used civil engineering material, and each student was responsible for the development of a Portfolio for each material that included the following.

1. Existing material specifications (ASTM, AASHTO, etc.)
2. Material market information (market size, availability, pricing, sustainability)
3. Process chart for application-material combination
4. Material flow chart with inputs and outputs identified
5. Sustainability metrics for the material when used in the assigned application
6. Design of a structural component

The Read-Present-Discuss approach turned out to be a very effective method to create a highly collaborative learning environment. It was effectively used in the reading assignments of the Brundtland Commission Report and the journal articles on sustainable material use. Each student was assigned a topic to read, and each student was required to present the key points of the paper in class. Discussions followed each presentation and further discussions were also conducted at the end of all presentations. Each student was responsible for one chapter in the Brundtland Commission report, and one journal publication was also assigned to each student covering a different area of sustainable material use. The topics covered on sustainable material use are listed below.

1. Consumption of materials in the United States
2. Construction materials and the environment
3. Design principles for ecological engineering
4. Environmental taxation of raw materials
5. National materials flows and the environment
6. Natural resource requirements of commodities
7. Sustainable design and construction strategies
8. Socio-economically sustainable civil engineering infrastructures
9. Construction ecology and metabolism
10. Sustainable technologies for the building construction industry
11. Sustainable construction in the United States
12. Management of natural resources

The Project Development and Building Process for a civil engineering structure was presented to the students as comprising of three phases; Plan, Design, Build. Subsequently, the use of the construction product and a sustainable waste management strategy were introduced by using the framework shown in Figure 2. The sustainable waste management strategy presented to the students was developed based on the Reduce-Reuse-Recycle approach developed by the European Commission.

Student learning was assessed using the following assignments. The grading rubric used for this course included 25% for homework assignments, 30% for the design project, 25% for the mid-term exam and 20% for the final exam. The homework assignments included the calculation exercises indicated above as well as Read-Present-Discuss assignments.

1. Calculation of personal carbon and energy footprints
2. Calculation of sustainability metrics for materials
3. Read-Present-Discuss assignments
4. Design project
5. Exams

There were several Read-Present-Discuss assignments included in the curriculum. These included magazine articles, the UN Brundtland Commission report and Journal publications on sustainable material use. This format was a great success and it facilitated a very enriching learning process through dialogue and synergy.

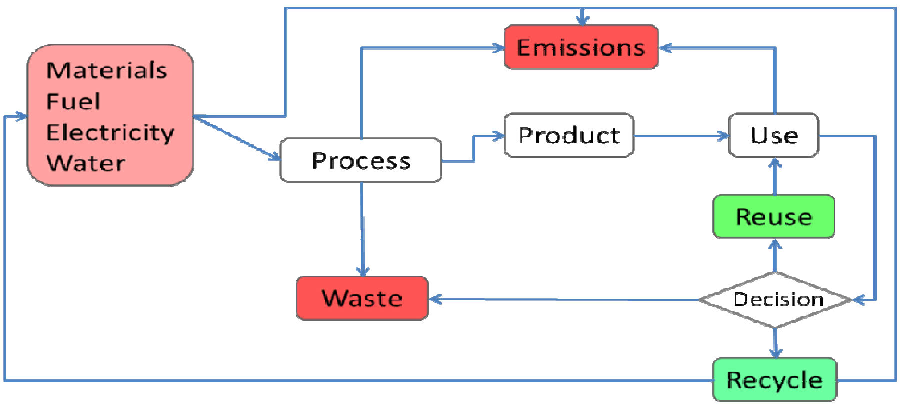

Figure 2. *Framework on Resource Utilization and Impacts for Sustainable Design*

Table 1. *Sustainability Concepts and Learning Outcomes for the Course Material Systems for Sustainable Design*

Subject Area	Sustainability Topic	Homework Activity	Outcome
Overview of Civil Engineering Materials	• Material properties • Material markets • Material Flow Analysis (MFA) • Embodied and process energies of materials • Impact on the Biosphere • Optimization of material use	For key materials; a. Draw MFA charts; b. Estimate embodied and process energies; c. Study impact on the biosphere d. Study of existing material selection practices	6. Define MFA 7. Design MFA charts 8. Calculate embodied and process energies 9. Analyze material impacts 10. Identify key factors in material selection
Sustainability Concepts	• Definitions • Impacts • Metrics	• Study key definitions • Paper review and class discussions on civil engineering design and material impacts on sustainability • Calculation of sustainability metrics for select materials	11. Define sustainability 12. Discuss impacts of civil engineering on sustainability 13. Identify parameters used in the calculation of sustainability metrics 14. Estimate sustainability metrics for select materials
Sustainable Civil Engineering Design Practice	• ASCE Policy on the Role of the Engineer in Sustainability • Other guidelines for sustainable design; • Sustainability metrics for materials	• Read report by ASCE Committee on Sustainability • Read LEED® and other sustainability guidelines • Calculate sustainability metrics for materials	15. Discuss ASCE sustainability outlook 16. Discuss LEED® and other guidelines 17. Estimate sustainability metrics for application-material combinations
Life-Cycle Assessment(LCA)	• Use of sustainability metrics in LCA	18. Selection of materials using LCA	19. Apply LCA to material selection
Material Specifications	• Components of a material specification • Sustainability-based material specifications	20. Develop specifications for sustainability	21. Apply sustainability concepts to specifications
Design Project	22. Application of sustainability concepts in a real project	23. Conduct sustainability-based material selection for a simple project	24. Integrate sustainability to select materials for a simple project

4. Student Feedback

The instructor prepared detailed questionnaires to assess student viewpoints. This questionnaire was in addition to the standard university-run evaluation of the course and the instructor. Where appropriate, student responses were collected both at the beginning and at the end of the course. The results presented below are based on student responses to the instructor's questionnaire. The questionnaires covered the following four areas.

1. Learning Outcomes from the Course
2. Student Outlook on Sustainable Practice
3. Assignment formats
4. Topics Covered

Summaries of student responses to the instructor's detailed anonymous questionnaires are presented in Figures 3-9.

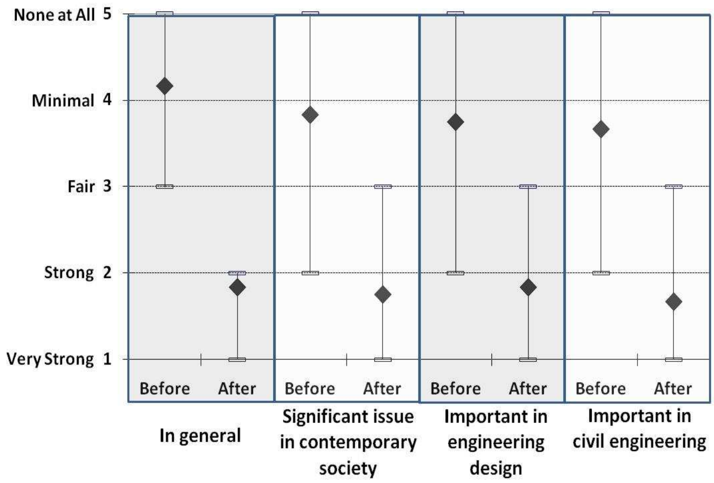

Figure 3. *Student Understanding of Sustainability "Before" & "After" the Course*

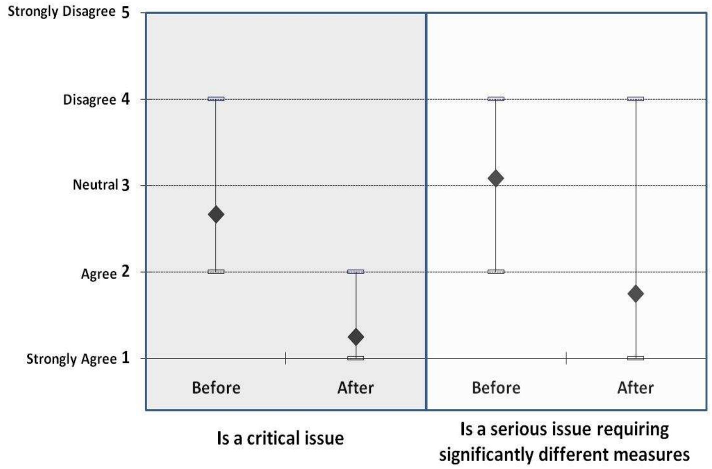

Figure 4. *"Before" & "After" Perceptions: Importance of Global Sustainability*

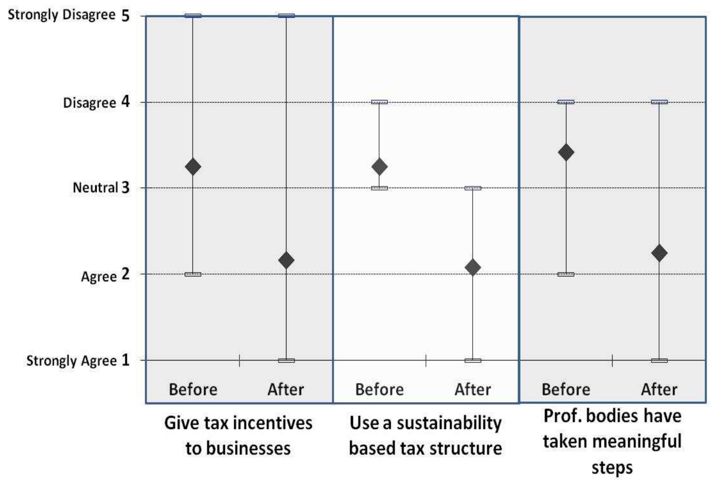

Figure 5. *"Before" & "After" Perceptions: Develop a Sustainability-Based Society*

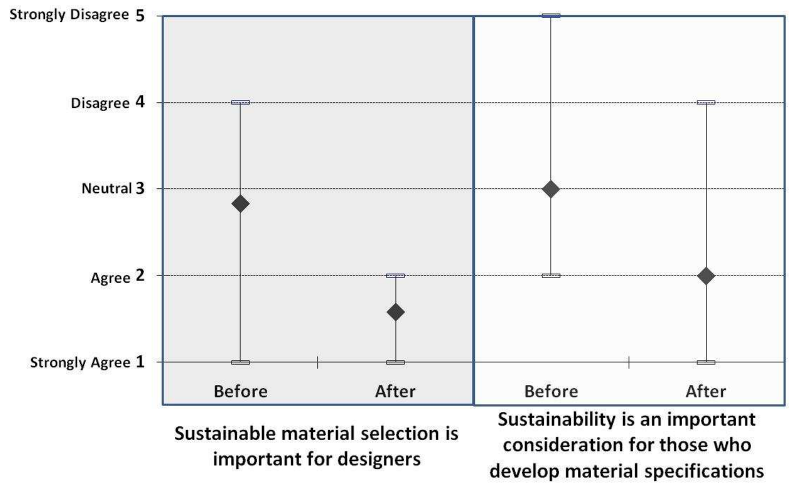

Figure 6. *"Before" and "After" Perceptions: Importance of Sustainability in Design*

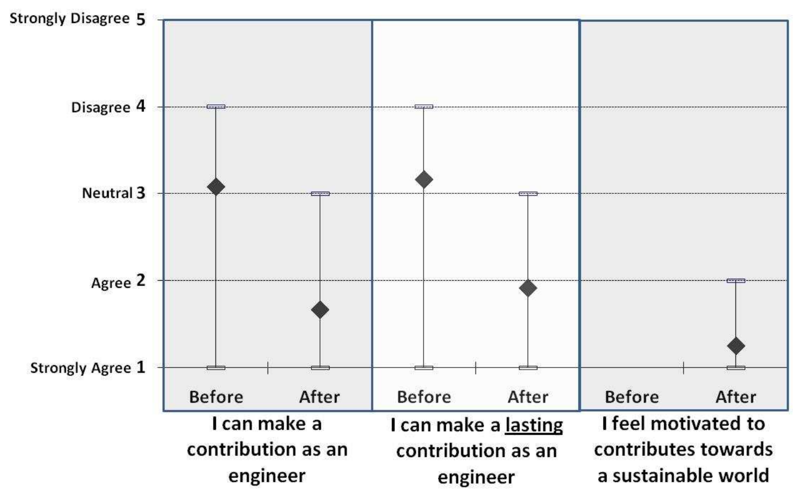

Figure 7. *"Before" & "After" Beliefs: Student's Role for a Sustainable Society*

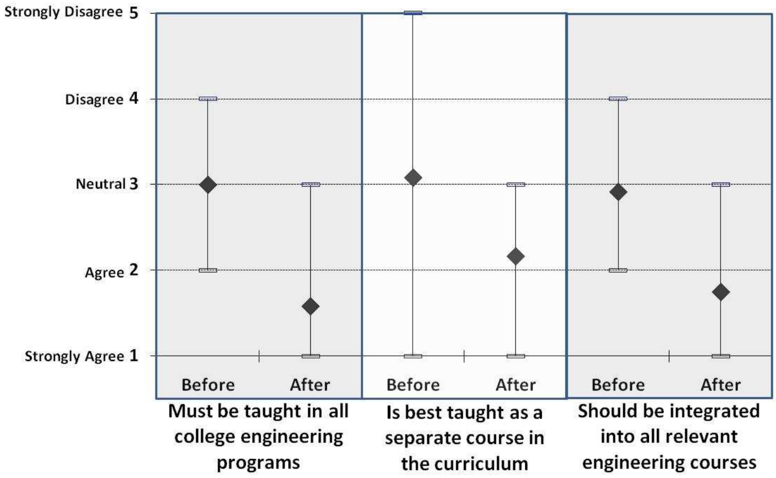

Figure 8. *"Before" & "After" Perceptions: Incorporate Sustainability in Curricula*

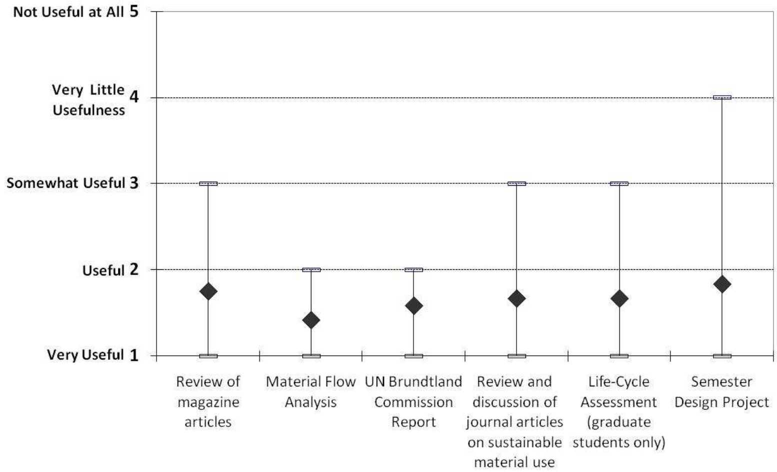

Figure 9. *Student Assessment of Course Delivery*

Based on student responses to the instructor's detailed questionnaire as presented in Figure 3-9 above, allow the following general conclusions to be made.

1. The student understanding of sustainability and its significance in the society in their chosen major field of study improved as a result of following this course [Figure 3].
2. The student group did not have disagreements on the importance of sustainability in the world today. Furthermore, as a result of following this course, students developed a more favorable perception of the importance of sustainability [Figure 4].
3. Students had diverse viewpoints on how to create a sustainable society, both at the beginning and at the end of the course. However, as a group, they seemed to look more favorably at some of the ideas currently prevalent in the literature (Figure 5].
4. The students generally agreed that sustainability is an important aspect of the design process including material selection. Student responses also indicated a strengthening of their outlook on the importance of sustainability in design [Figure 6].
5. The students indicated favorable opinions about their ability to contribute to the development of a sustainable society, and their opinions developed to a more favorable state after the course [Figure 7].
6. The students indicated that sustainability could be taught at the undergraduate level, either as modules in existing courses or as a separate course [Figure 8].
7. The Student assessment of the course generated very favorable responses [Figure 9].

The one significant negative comment the students provided was the difficulty in obtaining data needed to calculate sustainability metrics for individual materials. This course did not assign time for students to develop their own calculation metrics for the material-application combination, and therefore, the students had to rely on studies published by other researchers for such data. The students commented that data published by different researchers for the same material were often significantly different from one another. Not having either one or a few central data repositories to obtain sustainability-related data is a problem that teachers of sustainable material use have to overcome. An organized repository of data will allow students to draw from is an important resource for hands-on class projects.

5. Conclusions and Recommendations

This new course was well received by students, judging by student responses to the instructor's detailed questionnaire and from the student evaluations collected by the University. The instructor plans to offer this course on a regular basis.

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