AC 2009-2054: A COURSE ON SUSTAINABLE MATERIALS USE IN CIVIL ENGINEERING: SYLLABUS, DELIVERY, AND STUDENT FEEDBACK

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A Course on Sustainable Materials Use in Civil Engineering: Syllabus, Delivery and Student Feedback

Abstract

Civil engineering construction projects use by far the largest quantity of natural resources, both renewable and non-renewable, consumed in the world. Civil engineers wield enormous influence over the utilization and conservation of these valuable resources. Therefore, civil engineering educators have a responsibility to prepare tomorrow's engineers on a path towards sustainable practices in their material selection decisions. This paper presents a comprehensive overview of the syllabus, delivery and student feedback from a new course after its first semester of teaching. The course is titled "Material Systems for Sustainable Design", and it was developed as a senior-level undergraduate elective. Advanced course content was added to also create a new graduate course on the same topic. The overarching course objective is to provide students with the knowledge on sustainability and create an awareness of the tools that are needed to apply sustainable material selection practices in their future design work. The teaching pedagogy was designed for problem-based learning (PBL) combined with limited conventional classroom instruction at the beginning of each new topic followed by focused reading assignments involving the latest technical literature on the subject. The course was delivered in a highly collaborative learning environment.

The instructor first conducted a review of conventional materials, basic material properties, specifications and the design process. Sustainability concepts were introduced through focused reading assignments and included sustainable design practice, sustainability metrics, life-cycle analysis as well as energy, water and other natural resource use implications in civil engineering projects. The students also gain an awareness of several sustainability-related calculators. This is followed by an extensive discussion on sustainability issues applicable to civil engineering materials. Each student was then asked to select a construction material from a list prepared for the class for which he/she developed a portfolio throughout the semester. The students applied sustainability concepts to their material of choice and calculate relevant sustainability metrics for the material process. The portfolio included a process chart for a specified application for each material, a material flow chart that identified the inflow of raw materials, energy and water to the production process as well as output, emissions and waste and sustainability metrics for each material-application combination. The final segment of the portfolio was a design project for the assigned material-application combination which allowed each student to apply the concepts they learned in the course to a design exercise.

Towards a Sustainable Society

After decades of increasing consumerism and consumption, a near consensus has emerged within the scientific community on the strong links between the lifestyles of people in the industrialized world 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 a similar lifestyle. This has prompted countries to collectively initiate a shift towards a more ecologically conscious and sustainable social and political order in order to arrest the potentially rapid deterioration in the ecosystem and escalating scarcity of resources. Societies must 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 generally been used in natural resource situations where 'long term' is the focus. The US EPA (2007)[1] defined sustainability as "the ability of an ecosystem to maintain a defined/desired state of ecological integrity over time". However, sustainability has evolved to encompass a wider group of disciplines including economic development, environment, agriculture, energy, and infrastructure. Taken in a global context, sustainability is now presented as a concept that allow societies to develop and sustain resources such that their members can use creative and innovative means to achieve their full potential and leave the natural ecosystem in a sustainable mode for future generations. This is reflected in the most widely quoted definition of stating that sustainable development means "meeting the needs of the present without compromising the ability of future generations to meet their own needs" [2].

Wackernagel et al. (2002)[3] suggested that sustainability requires living within the regenerative capacity of the biosphere. They believed that the human demand may well have exceeded the regenerative capacity of the biosphere since the 1980s. According to their preliminary and exploratory assessment, 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 the Earth's resources are being utilized prompted the United Nations to initiate a *Millennium Ecosystem Assessment*[4] in 2001 to assess the consequences of ecosystem change for human well-being and the scientific basis for action needed to enhance the conservation and sustainable use of those systems. This followed a series of UN initiatives including the Kyoto Protocol[5] in 1997, the Rio Conference on Environment and Development[6] in 1992, the Brundtland Commission Report[2] in 1987 and the Stockholm Declaration[7] in 1972. Evidence of the consequences of non-sustainable use of Earth's natural resources can be seen all around the globe and was highlighted 22 years ago in the UN Brundtland Commission Report[2]. A notable example of this phenomenon is the *Fertile Crescent* of ancient Mesopotamia and Syria. Jared Diamond, the Pulitzer prize-winning author and professor of geography at UCLA, noted in his book *Collapse*[8], that non-sustainable agriculture and irrigation practices have turned the once known fertile crescent in the middle east into the desert that it is today. 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.

Preparing Engineers for a Sustainable Future

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[9]). Additionally, promoting student creativity is an important aspect of sustainability education.

The US Accreditation Board for Engineering and Technology (ABET) updated its accreditation criteria (EC 2000[10]) towards developing a more flexible set of guidelines 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)[11] into process and awareness skills. These 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

Engineering design is a process that conceives ideas and develops products and processes for the benefit of society by utilizing the creativity, innovation, skill and experience of the engineer to apply principles in engineering and basic sciences. The design engineer has to operate under a set of design constraints while adhering to relevant codes, standards and applicable laws.

Dym et al (2005)[12] indicated that even though *design* is agreed by many to be of paramount importance in engineering education, the subject of engineering design remains ill-defined and not well understood. They defined engineering design as "a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specific set of constraints". Dym et al. also indicated evidence that design courses using problem-based learning appear to improve student learning and satisfaction, retention and the appreciation of the benefits from a diverse set of viewpoints. They also emphasized that the purpose of engineering education is to graduate engineers who can design, that design thinking is complex, and highlight the following skills often associated with the ability of good designers.

- Tolerate ambiguity that shows up in viewing design as inquiry or as an iterative loop of divergent-convergent thinking
- Maintain sight of the big picture by including systems thinking and systems design
- Handle uncertainty
- Make decisions
- Thinks as a member of a 'team' within a social process
- Think and communicate in the several languages of design

The conventional engineering design process is often driven by functionality, cost and aesthetics. Morris et al., (2007) [13] indicated that design is often perceived as itemized, linear and lecture-based, and is not conducive to creativity and innovation in the design process. Other researchers have suggested that engineering programs need to shift away from such a design model if integrated interdisciplinary processes such as sustainable design are to be promoted (Riley et al., 2006[14]).

Several authors have presented ideas on appropriate ways to teach engineering design within the context of sustainability. As it was mentioned previously, sustainability is inherently multidisciplinary, and students must be direct to cultivate the characteristics highlighted by Dym et al. that were indicated above. De Ciurana and Filho (2006) proposed a novel approach for "greening" of the curricula that included ten characteristics[15]. Morris et al. (2007) [13] 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. 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[16].

The Civil Engineer's Role

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[17]. 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[10]. 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[18]. 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.

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. Morris et al.

(2007) suggest that students must not only grasp the principles of these individual subject areas, but also develop skills to integrate such knowledge[13].

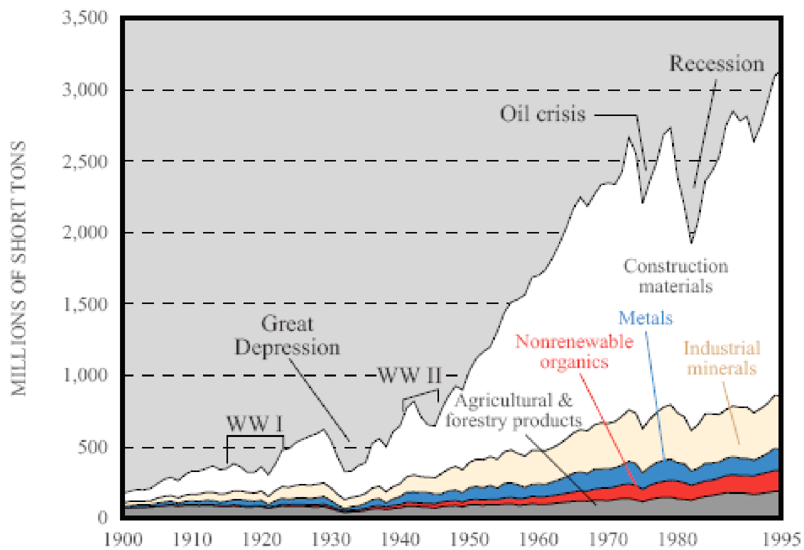

Figure 1. Raw Materials Consumed in the United States, 1900-1995 (USGS, 1998)[17]

The typical product life-cycle 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) [19]. 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. The importance of this holistic approach was well articulated by Senge et al. (2008) in their book *The Necessary Revolution*[20]. Senge, founder of the Society for Organizational Learning, explains the critical need for organizations to look at all impacts of their business decisions including economy, ecological health, human health and sustainability on the overall quality of life in societies.

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.

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

By 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: Important 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 section of this paper. Every effort was made to highlight the multidisciplinary nature of sustainable design and its impact on 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 outcomes from this course[21]. Bloom organized human learning into six domains; Knowledge, Comprehension, Application, Analysis, Synthesis and Evaluation. The learning outcomes identified in Table 1 were developed to ensure that the course addresses all domains of human learning to the extent possible.

The course was delivered using a format that combined several methods and techniques including the following.

- Limited traditional classroom instruction to introduce basic concepts
- Review of magazine articles and books to understand the global, holistic outlook of the topic
  - Article on proposal for an eco-friendly city in Dongtan, near Shanghai, China, conceptualized for design by *Arup and Partners* (McGray 2007)[22]
  - **TED®** conference video presentations[23]
- Develop a *Material Flow Analysis* charts for the material assigned
  - Each student was assigned a construction material
  - Materials were selected in such a way that comparisons can be made for applications for which same material is used
- Review of key publications related to sustainability
  - UN Brundtland Commission Report (1987)[2]
  - Sustainable Engineering Practice: An Introduction (ASCE 2004)[24]
  - US Green Buildings Council LEED Certification[25]
  - Review and discussion of journal articles on sustainable material use
- 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
- Life-Cycle Assessment (for graduate credit)

There were twelve civil engineering 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.

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

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; • Draw MFA charts; • Estimate embodied and process energies; • Study impact on the biosphere • Study of existing material selection practices	• Define MFA • Design MFA charts • Calculate embodied and process energies • Analyze material impacts • 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	• Define sustainability • Discuss impacts of civil engineering on sustainability • Identify parameters used in the calculation of sustainability metrics • 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	• Discuss ASCE sustainability outlook • Discuss LEED® and other guidelines • Estimate sustainability metrics for application-material combinations
Life-Cycle Assessment(LCA)	• Use of sustainability metrics in LCA	• Selection of materials using LCA	• Apply LCA to material selection
Material Specifications	• Components of a material specification • Sustainability-based material specifications	• Develop specifications for sustainability	• Apply sustainability concepts to specifications
Design Project	• Application of sustainability concepts in a real project	• Conduct sustainability-based material selection for a simple project	• Design a structural component by integrating sustainability concepts

The *Read-Present-Discuss* approach turned out to be effective in creating a highly collaborative learning environment by enriching learning process through dialogue and synergy. It was used in the reading assignments of the Brundtland Commission Report and the journal articles on sustainable material use. 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. Discussions followed each presentation and further discussions were also conducted at the end of all presentations. The topics covered on sustainable material use are listed below.

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

The *Project Development and Building Process* for a civil engineering structure was presented to the students as comprising of three phases: *Plan, Design and 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.[26]

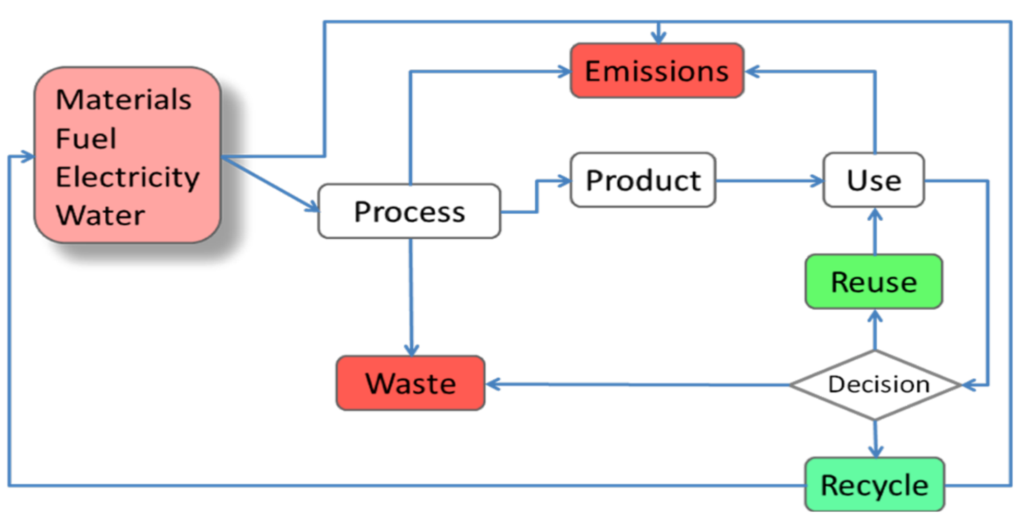

Figure 2. Framework on Resource Utilization and Impacts for Sustainable Design

Assessment of student learning was conducted using the following assignments. The grading rubric used for this course comprised of 25% for homework assignments, 30% for the design project, 25% for the mid-term exam and 20% for the final exam. The homework included the *Read-Present-Discuss* assignments as well as the calculation exercises indicated below.

- Calculation of personal carbon and energy footprints
- Calculation of sustainability metrics for materials
- *Read-Present-Discuss* assignments

Student Feedback

The instructor prepared detailed questionnaires to assess student feedback on the course content and instruction. This questionnaire was given 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 questions included in surveys conducted by the instructor. The questionnaires covered the following four areas. Summaries of student responses to the instructor's detailed anonymous questionnaires are presented in Figures 3-9.

- Learning Outcomes from the Course
- Student Outlook on Sustainable Practice
- Assignment formats
- Topics Covered

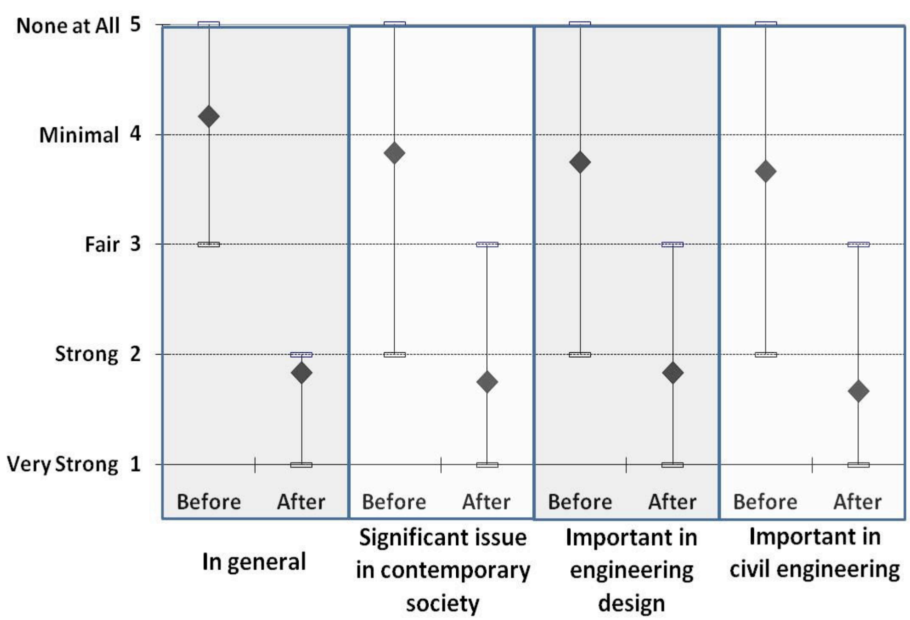

Figure 3. Student Understanding of Sustainability "Before" and "After" the Course

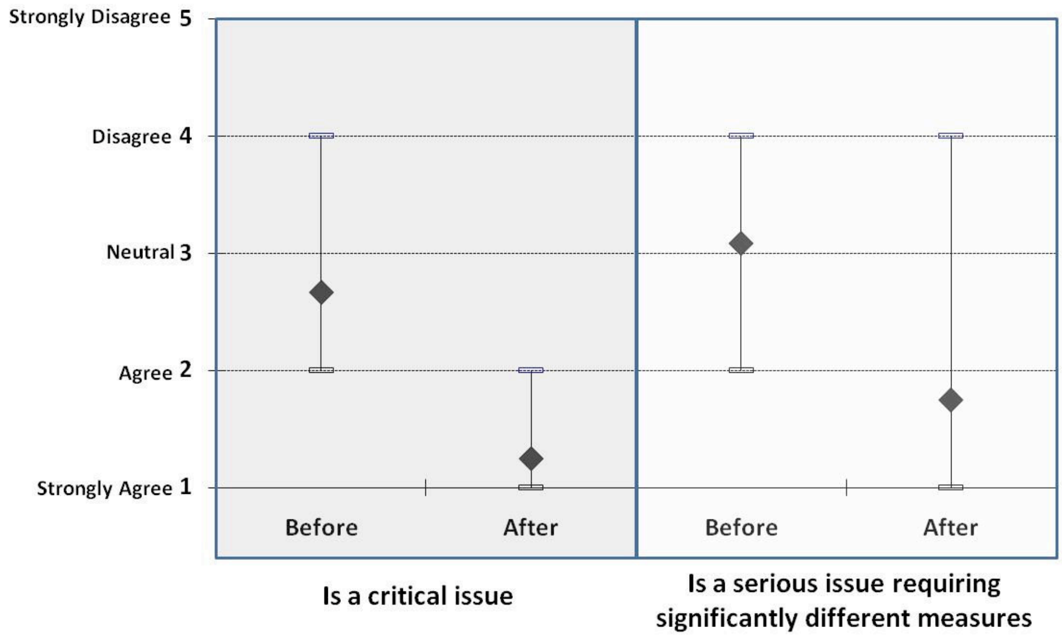

Figure 4. Student Perceptions "Before" and "After" the Course, on the Importance of Sustainability in the World Today

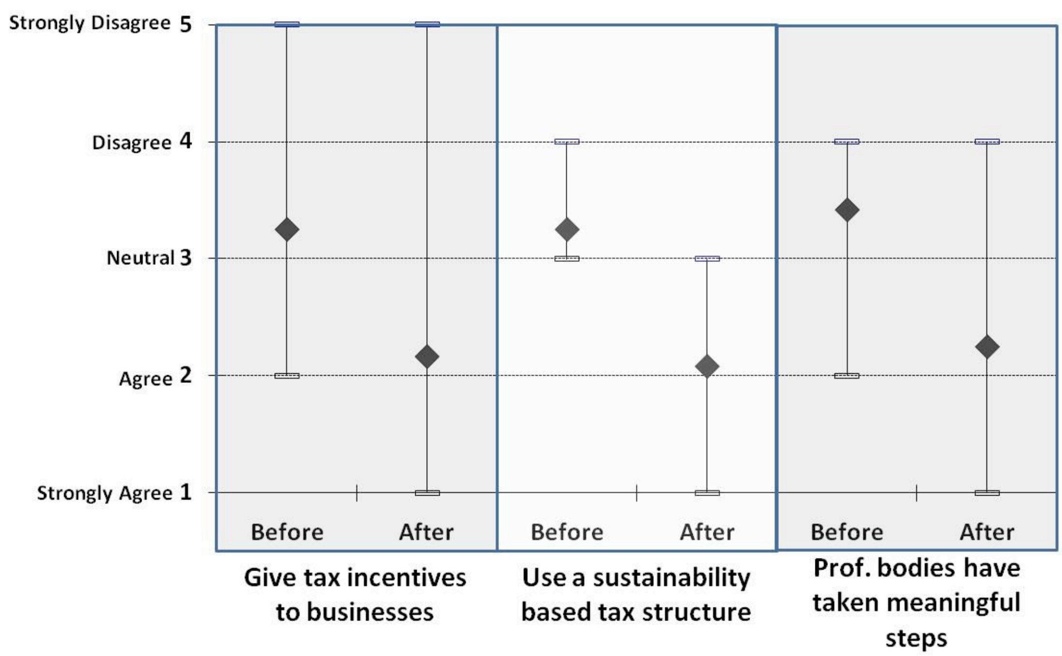

Figure 5. Student Perceptions "Before" and "After" the Course on How to Develop or Promote a Sustainability-Based Society

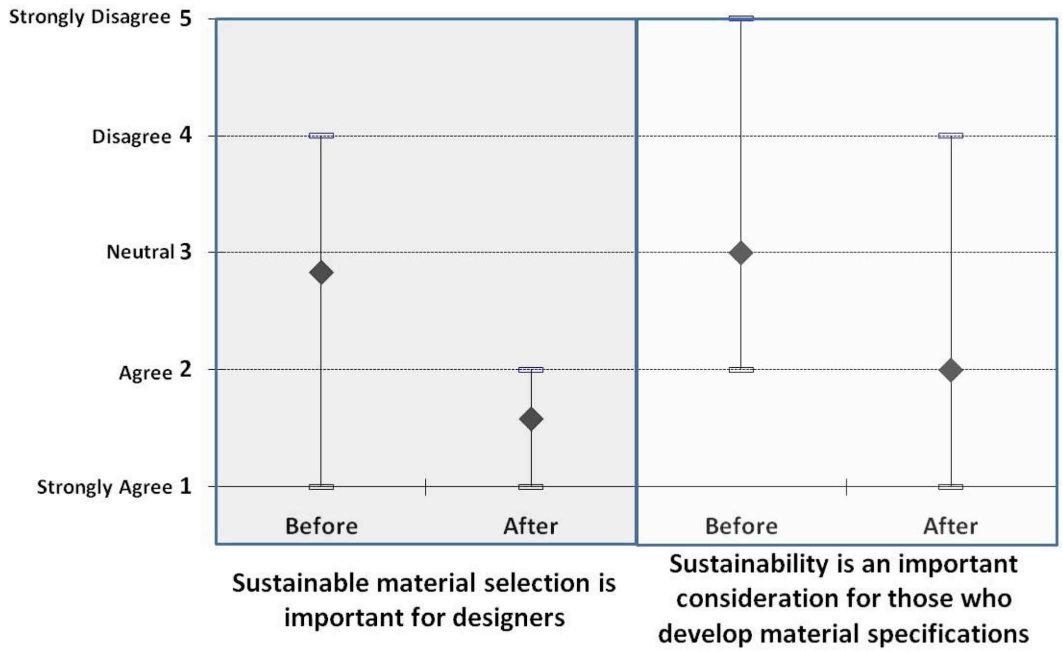

Figure 6. Student Perceptions "Before" and "After" the Course on the Importance of Sustainability in Engineering Design

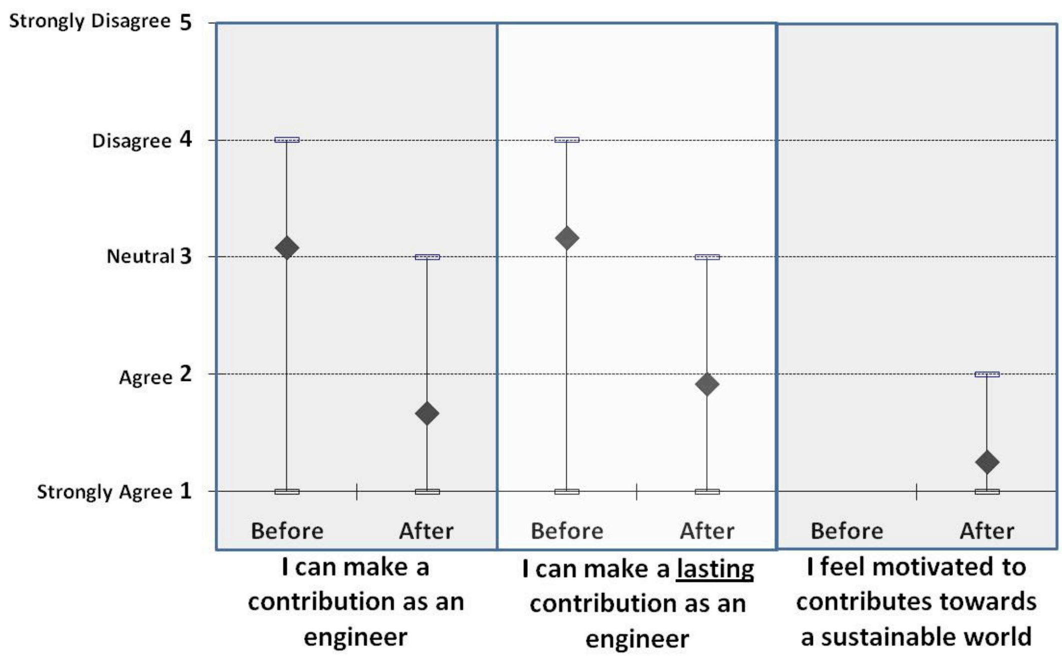

Figure 7. Student Beliefs "Before" and "After" the Course on their Role to Develop a Sustainable Society

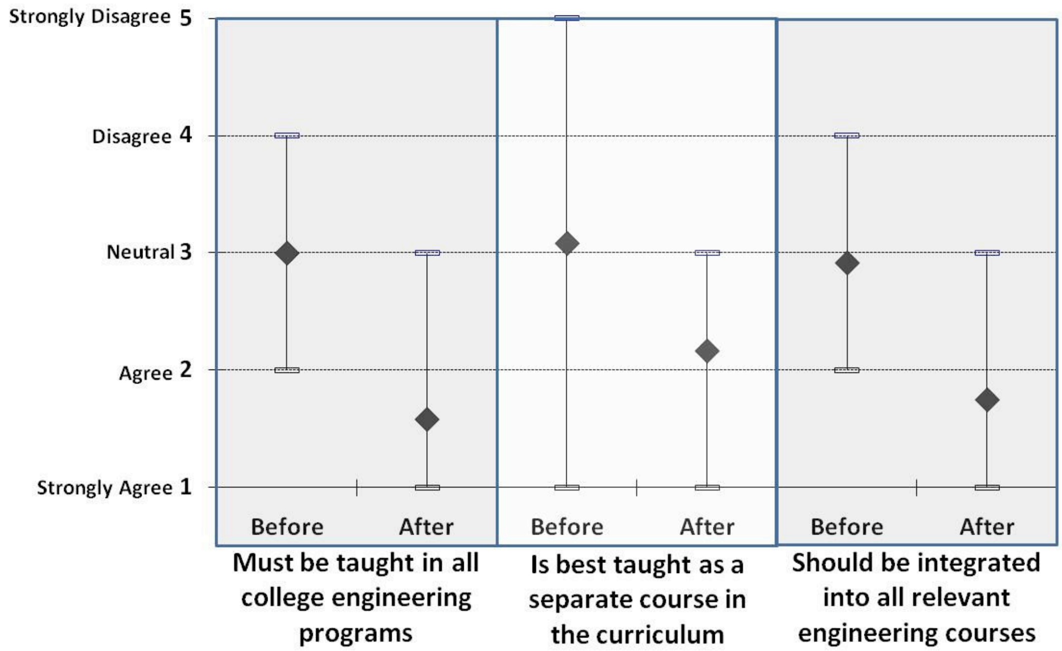

Figure 8. Student Perceptions "Before" and "After" the Course on Incorporating Sustainability into Engineering Curricula

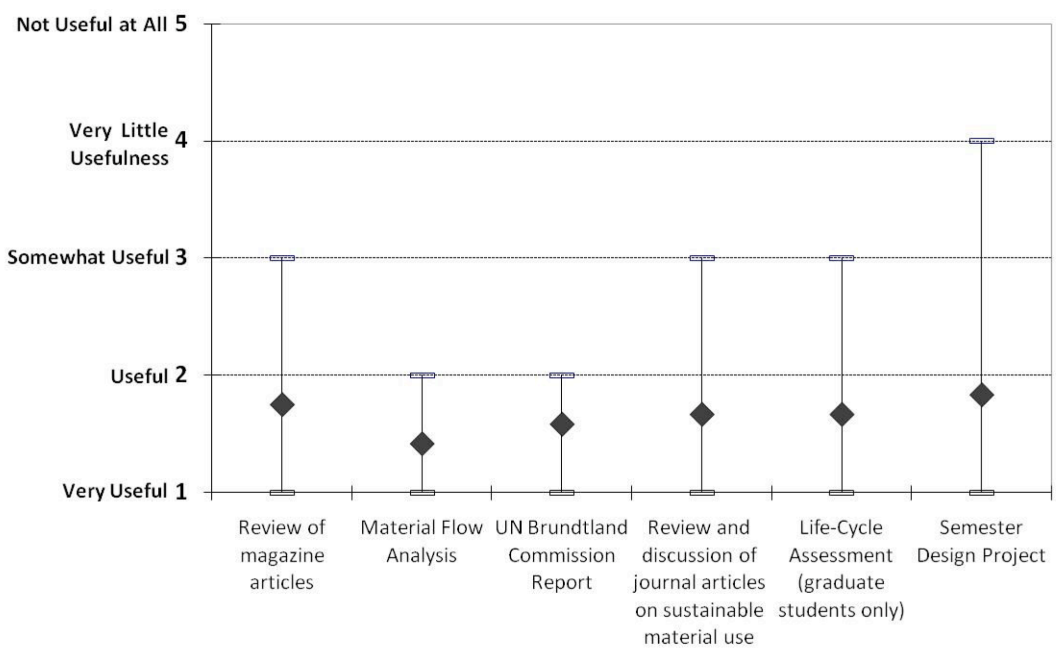

Figure 9. Student Assessments of Course Delivery Methods and Usefulness of Class Assignments in their Learning

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.

- The student understanding of sustainability and its significance in the society and in their chosen major field of study significantly improved as a result of following this course. (Figure 3)
- The students as a group did not have disagreements on the importance of sustainability in the world today. Furthermore, as a result of following this course, the students developed a more favorable perception of the importance of sustainability. (Figure 4)
- 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)
- Students generally agreed that sustainability is an important aspect of the design process and in material selection. Student responses also indicated a strengthening of their outlook on the importance of sustainability in design. (Figure 6)
- Students indicated favorable opinions about their ability to contribute to the development of a sustainable society, and their opinions evolved to a more favorable state at the end of the course. (Figure 7)
- Students were also of the opinion that sustainability concepts should be taught at the undergraduate level, either in the form of separate modules in existing courses or as a separate course. (Figure 8)
- 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 various construction 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 has to be overcome if sustainability-based curricula are to be developed. Having an organized repository of data the students can draw from is an important resource in conducting hands-on projects for classes such as this one.

Conclusions are Recommendations

This new course on *Material Systems for Sustainable Design* 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. Several changes will be made to the curriculum and the way this class is going to be taught in the future. The instructor's university is in the process of developing a minor on sustainable design for undergraduate students in the colleges of engineering and architecture, and the course is likely to attract a multidisciplinary group of students in the future. This will create a truly positive multi-disciplinary learning environment that will be good for student learning. In the course curriculum used for the first semester of teaching, the course time was divided as 40 percent for materials, 30 percent for sustainability principles and 30 percent for design. However, the course time assignment will be re-allocated to a 30-30-40 split for materials, sustainability and design respectively to have more time for design. This additional for design will be used to give the students a more comprehensive background on LEED certification and guidelines.

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