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Sustainable Design in a Second Year Engineering Design Course*

WARREN STIVER
Professor & NSERC Chair in Environmental Design Engineering, School of Engineering, University of Guelph, Guelph, Ontario, Canada, N1G 2W1, E-mail: wstiver@uoguelph.ca

Engineers have a primary responsibility to help society develop sustainably. Engineering education has an obligation to integrate sustainable design principles into the curriculum of all engineers. This paper describes the integration of sustainable design principles into a second year engineering design course taken by all engineering students at the University of Guelph. The approach requires students to develop and measure their design-build-test project from three specific measures to reflect economic, societal and environmental dimensions of their system. Many students are able to understand the challenges associated with succeeding by all three measures within the same design. These students see the importance of creativity and innovation in overcoming the apparent conflicts. However, it is also evident that the efforts to date are not sufficient to deeply embed sustainable design thinking in all of the students.

Keywords: sustainable development; design; second year

1. INTRODUCTION

OUR COMMON FUTURE put Sustainable Development openly and directly on the world stage [1]. The concept of Sustainable Development has been articulated in a number of different ways including 'Humanity has the ability to make development sustainable. To ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs' [2]. Sustainable development has also been stated as meeting the *Triple Bottom Line* and satisfying the *3 P's* (People, Place and Profit).

Progress towards sustainable development can only be achieved with the full participation of engineers. Professional engineering bodies have recognized this important role while accreditation bodies have moved to advance engineering education. For example, the Canadian Engineering Accreditation Board (CEAB) added a requirement that the 'concepts of sustainable development must be an integral component of the engineering curriculum' for all engineering programs [3]. The Washington Accord requires all graduates to be capable of designing solutions that 'meet specified needs with appropriate consideration for public health and safety, cultural, societal, and environmental considerations' and to 'demonstrate knowledge of and need for sustainable development' [4]. The Canadian accreditation requirements have subsequently shifted to align with the Washington Accord's phrasings [5].

It has been argued that no one would disagree with the pursuit of sustainable designs. Manzini goes further to state that it should be the main objective of all design research and by implication all designs [6]. If this is true then it is hard to understand why sustainable design is not integral to all engineering design practice and to all engineering design education. Academia changes slowly with the average innovation requiring 26 years to be implemented by the median institution [7]. There are barriers to change within the academic structures and culture [8]. Holmberg and colleagues draw from their experiences at three European universities to identify five areas in which a strong foundation will increase likelihood of success [9]. The five areas for education for sustainable development (ESD) success are: legitimacy (is focusing on ESD legitimate), commitment by university administration, responsibility is spread throughout the university, skilled teachers with ESD experience, and an effective structure within the university.

Sustainable design is not integral in part because we have just begun the process and collectively we have a lot to learn. It is necessary for individuals, programs and institutions to experiment, to discuss these experiments, to learn from them and to build on them. Fortunately there are a number of experiments underway around the world.

Azapagic and colleagues conducted a worldwide survey on the state of engineering students' knowledge about sustainable development [10]. The survey involved 40 universities with over 3000 students completing the questionnaire from 2000 to 2002. The students were asked to self assess their knowledge in a range of sustainable development areas. They found that the base knowledge level was not satisfactory and that significant gaps prevailed.

Huntzinger and colleagues reviewed sustainable

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thinking within a number of engineering schools (mostly US schools) [8]. They reflected on the level of integration ranging from, in their terms, ignorance (none), to bolted on, to built in and ultimately to redesign. They argue that active learning modes and a redesign approach to engineering education is necessary to achieve success in sustainable design education. McLaughlan explored the use of three active learning strategies (roleplay-simulation, online debates and scenario building) as means to help students develop an understanding of the multiple dimensions associated with sustainability in complex engineering activities [11].

TU Delft began pursuit of sustainable development within its engineering curriculum in 1994 [12]. They have subsequently developed an optional sustainable development graduation track available to students across disciplines. Students are able receive a sustainable development certificate by completing a colloquium, a number of courses from an elective list and a graduation project with sustainable development as an integral element. Carnegie Mellon has introduced a series of mini courses available to senior undergraduates and graduate students across all engineering disciplines [13]. The University of Kentucky has proposed a Sustainable Engineering curriculum model that starts in Year 1 of a bachelor's degree and extends to a doctorate program [14]. The curriculum would involve a partnership between the university, industry and government.

The University of Leeds has embedded sustainable design within their second year design course [15]. In a project based learning mode the students are required to imagine a larger scale system that is much more sustainable and then to develop a design for a component of that system that is needed for the vision to be realized.

The University of Guelph (Ontario, Canada) began modest integration of the concepts of sustainable development into the curriculum in Fall 2000. Engineering & Design II, a course common to all engineering programs, was selected for this integration. In Fall 2005, the level of integration deepened considerably. This paper will provide a description of the current approach, provide some observations on its effectiveness and share some thoughts regarding its continued evolution.

2. ENGINEERING DESIGN AT THE UNIVERSITY OF GUELPH

The University of Guelph provides a common sequence of four design courses—one for each year of every student's program. The first, second and third year courses all have a weighting that is 1.5 times a typical course while the final capstone design course has a double weighting. The sequence provides students the opportunity to build their design skills in tandem with their advancing engineering science capabilities.

Engineering & Design I (1st year, 1st semester) serves a number of purposes. Most heavily it introduces the students to the design process, constraints and criteria, project management and team work. The course welcomes students to engineering and engages them in fun and creative engineering design opportunities.

Engineering & Design II (2nd year) builds on the student's beginning design skills and their beginning engineering science skills. The course builds direct connections with Material Science and Engineering Systems Analysis (two other core engineering courses taken by students at the same time) to reinforce the integrating characteristics of engineering and design. Team skills, creativity and innovation, safety, computer aided design and sustainable design are important elements of the course.

Engineering & Design III (3rd year) continues the progression of engineering design skills. The projects are from external organizations (industry, government and non-profits). Students form their own teams, typically across disciplines. They select a project from an available list based on their team interests.

Engineering & Design IV (4th year, final semester) is the core capstone design course for all students. Students form teams of their choice. The structure of the course provides the students the opportunity to choose and control their design setting. The teams seek out potential problems or opportunities that fit their interests and desires. Some problems are heavily tied to external organizations and some design opportunities derive from the student's entrepreneurial spirit. In either case the students take ownership of the project and have the opportunity to control its direction.

3. ENGINEERING AND DESIGN II

Engineering & Design II (2nd year) emphasizes a number of elements: oral communication, team skills, computer aided design and sustainable development. The course has four major student assessments: a design-build-test project (45%), a computer aided design project (25%), individual oral presentations (10%) and a final exam (20%). Sustainable development and sustainable design are integrated into the course through the design-build-test project and through the complementing lectures that form the basis for the final exam.

The oral presentations and the computer aided design project do not directly serve to address sustainable design concepts. The oral presentations serve to provide individual students the opportunity to stand up in front of a room and a camera to deliver a technical communication in an effective manner. Practice and feedback is the most important elements of this dimension of the course. The computer aided design project provides an introduction to 3D computer modeling. Students are able to use this skill to produce parts within their design-build-test project.

The course has a common design-build-test project in which the students are required to pursue their design from a sustainability perspective. Completely opening up all of the complexities of sustainability is daunting. Indeed, experienced designers find sustainable design a daunting challenge. Second year students (early in their design experiences) can easily be overwhelmed by the challenges. However, it is valuable and potentially even essential for students to experience sustainable design challenges while in the formative stage of their design education.

Guelph's second year design project overcomes this apparent contradiction through limiting the design assessment to three individual and specific measures. The three measures echo the *Triple Bottom Line* and *3 P's*.

The Fall 2008 project will be used to illustrate the approach. Students in assigned teams of 4-5 were challenged to design, build and test a wheat grinder powered by wind energy alone. They were provided two small DC motors, provided access to a range of materials in the shop and able to purchase external items to a limit of $20 per team. The students were allocated half of the term to develop a paper design and then provided shop access and support to construct their design for testing and demonstration in the final week of the term. The final testing was conducted in the School's wind tunnel.

The design's performance was assessed based on minimizing raw material cost, maximizing recycled value and maximizing the mass of ground flour generated. The total raw material cost was the economic measure of the design. The raw material cost was the summation of the product of the mass of all system components and the raw cost of each material per unit mass. The raw cost per unit mass values for a range of common materials were provided to the students. Students wishing to use other materials could do so. In this situation, the onus was on the students to find a suitable cost value and to get this value approved for use. The value was then made public for all teams to use and to maintain consistency. This economic measure required students to track every item carefully and rewarded designs that chose materials wisely, kept items small and that stayed simple by eliminating unnecessary items.

The design's environmental performance was assessed based on maximizing recycled value. The recycled value was the summation of the product of the mass of all system components and their recycled values per unit mass. A material's recycled value per unit mass data were provided to the students. The values were largely based on local data that are publicly available [16]. The team disassembled their design following testing. Only items that were separated into a single material (a steel alloy was considered a single material) earned recycled values. This encouraged students to consider the design of their system from a disassembly perspective. A design that is easily disassembled is likely a design that is easier to recycle, easier to maintain and easier to originally fabricate. An additional dimension of this recycle value was to reward designs that use standard items. Items that are in 'as new' state following disassembly have a recycled value that matches the raw material cost (much greater than the recycled value per unit mass). Custom design and fabrication by the students needs to be limited to where innovation is really warranted.

Finally, the design's social performance is assessed by the measured mass of ground flour generated by the design. This is a simple performance to measure. However, it is not easy to estimate or forecast through a paper design exercise by students with second year engineering skills. It is necessary and valuable for students to realize that engineering science, engineering models and mathematical optimization aid design but frequently do not offer every piece of the puzzle.

The overall design's performance (grade) is then based on the combination of the performance against these three measures. For the economic performance, the team with the lowest cost earns 10 points. The median team earns 5 points. A straight line equation is generated relating cost and points based on these low cost and median cost values. The remaining teams in the class earn points for their cost performance based on this equation. The environmental performance is handled in the same manner with the team having the highest recycled value earning 10 points. The social performance provides the team having the most mass of flour with 10 points. Each team then receives three point values. One team could receive a maximum of 30 points and the lowest possible could be 0 points (negative points were not awarded in any of the three measures). The number of points is then translated into a grade for the design performance element of the project and course. A 'B' grade is for teams earning 15 points. The logic being a team that happens to be median by all three measures would be consistent with 'expected' skill levels. An 'A-' grade or better requires at least 19 points. A team at the top of two of the three measures and dismal in the third (0 points) is only marginally excellent. A solid 'A' grade requires attention to all three measures—top in one with median or better in the other two OR top fraction in all three measures. A solid 'A' grade requires a sustainable design.

The design performance score defines 20% of the grade in their design-build-test project. The remaining 80% of their project grade assesses the team's interim steps, the communication of their design (oral, written and drawings) and their design process. To encourage teams to take risks and to pursue creative solutions, the course included a potential for a 1.2 multiplier on the

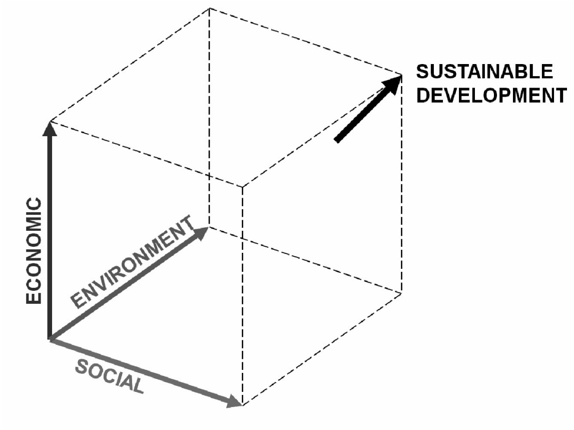

Fig. 1.

project's grade. This creativity element was judged by the course instructor with a multiplier different from 1.0 not assigned lightly.

The overall approach strives to encourage students to see the dimensions of sustainable development as three perpendicular vectors (see Fig. 1) rather than seeing them as direct contradictions (opposite ends of the same axis). This does not immediately make sustainable design easy but it begins to open their minds to the possibilities. Students begin to recognize that sustainable design success will rely on creativity and innovation in the same way that innovation has been essential to overcome other apparent engineering contradictions (strength vs. ductility in a typical TRIZ conflict table). Great engineering solutions are often associated with innovative means to overcome historical conflicts. The apparent conflicts associated with achieving sustainable designs are engineering's greatest innovation challenge. Society needs our success.

The approach also connects to the student's perspectives on interpersonal conflicts. It is possible for one party to worry only about their own needs. This situation rarely leads to a lasting relationship. This situation is rarely sustainable. It is possible for both parties to compromise. Both parties feel just a little bit dissatisfied. However, really successful teams over the long term are able to find the win-win for both (or all) parties.

The approach helps students recognize that there is no absolute 'sustainable design'. The three axes all go to infinity and there is nothing absolute about any particular origin for the axes. In this way they can see sustainable design in a relative context rather than an absolute context. There is no perfect design and there is no perfectly sustainable design.

Lectures on sustainable development and sustainable design complement the design project. The lectures provide an opportunity to look at the issues from a slightly broader view. The lectures try to convey sustainable development in ways that the students can relate to the concepts. One approach is to encourage the students to consider how they frequently make decisions reflecting economic, social and environmental factors within their own daily lives.

A range of unsustainable situations are discussed ranging from non-renewable resources to AIDS in Africa. These situations then seed a discussion of sustainability indicators. Sustainability indicators considered in the community of Guelph are reviewed and the students are asked to reflect on potentially appropriate national indicators. The students are then challenged to think about indicators that may be relevant for a developing country in Africa. It is hoped that the students are able to see the connections between indicators and the three measures associated with their design project. It is hoped that students can imagine the challenges and possibilities associated with considering their future designs from a sustainability perspective.

The evolution of the approach has heavily been driven by listening to the students: how their thinking about the design problem shifted as the problem setting shifted and their work assessment shifted. Initial efforts did not really move the students away from thinking about their designs from more than one dimension. A single measure easily dominates their attention. A single measure that they can readily calculate dominated their attention. The approach for the recycled value as something that is as readily calculated as the cost item dampened this dominance. However, many teams still make the decision based on one measure and just let the other measure fall where they may.

Some students approach the project from a purely grades centered mindset without seeing any connection to their field or reality. They see the 'formula' for grading and respond to the formula in a nearly disconnected manner. For these students, the $'s could be based on the number of brown items used and they would address the problem in the same detached manner.

Some students remain unconvinced that sustainable design has any relevance for them once they graduate. These students perceive that cost is all that really matters. That environmental, social and safety are only for tree huggers and the like. Many of our environmental engineering students remain trapped in the belief that environmental and sustainability are synonymous terms.

These observations require further assessment and analysis to support further enhancement of the course. It is anticipated that integrating numerous examples of successful and more sustainable designs from a breadth of engineering fields is a necessary element to add to the lecture component.

These challenging observations aside, there are a good proportion of the students who engage in the process and make the connections to the broader domain.

Ultimately success is not measured by events within a single course. Ultimate success comes in the form of subtle and not so subtle shifts in the design actions by graduates once they are in practice. However, assessment at that point is difficult and one is forced to wait for years to receive any feedback. The nature of the capstone design course at Guelph provides an opportunity for an initial assessment of how embedded the sustainable design perspective has become in our students. The students have considerable control in the choice and direction of their project. If sustainable design was deeply embedded in their individual design philosophies then it should be evident in their capstone project decisions.

A review of the student's capstone design executive summaries for the winter 2009 semester provides some initial feedback. Of these executive summaries, 30% claimed sustainability or used the sustainability word. However, like many in society, this buzz word is frequently used with little or no evidence to back up the usage. A number of teams only pursued environmental dimension without any indication of social or economic elements. Overall about 20% of the design projects appear to be driven by sustainable design objectives. This percentage is partially encouraging and partially discouraging. Morris and colleagues found that only 10% of students carried any form of sustainability thinking from a focused sustainable design project into a general design project that followed immediately after [17].

Our observations certainly indicate that further effort is needed in order to deeply embed sustainable thinking. The majority of students in the winter 2009 capstone design course took Engineering & Design II in Fall 2005 or 2006 depending on cooperative education and other factors. Fall 2005 and 2006 were the earliest efforts to embed sustainable design within the design-build-test project using the three vector approach. The approach has been adapted since then and it is hoped that the adaptations have been positive. It is expected that the percentage of teams pursuing sustainable design in the future grows well beyond 20%. It is appropriate to conduct a more thorough review of the capstone projects (beyond the executive summaries) to assess the degree of sustainable design efforts more accurately.

4. CONCLUDING REMARKS

The integration of sustainable design concepts, thinking and skill development into Engineering & Design II has been a work in progress for several years. The evolution has heavily been driven by listening to the students and listening to others. Simplifying the complex and multi-dimensional domain of sustainable development into three readily measured dimensions appears to be an effective approach for a large number of second year students. For some students additional approaches need to be developed.

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Warren Stiver is a Professor in the School of Engineering at the University of Guelph. He teaches courses in engineering design (Engineering & Design II), courses in Environmental Engineering and advised numerous capstone design teams over the years. He has been recognized as Professor of the Year (1997) by the students within the School and has received the Provost's Award for Teaching and Learning Innovation (2007). Professor Stiver has held an NSERC Chair in Environmental Design Engineering from 2001 to the present.